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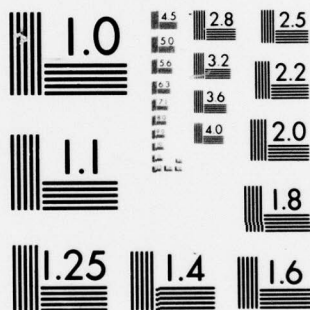
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SASPRO--SPARE AND SERVER PROVISIONING PROGRAM .

by

Donald Gross

Scientific rept.

Serial-T-371
26 April 1978

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The George Washington University
School of Engineering and Applied Science
Institute for Management Science and Engineering

Program in Logistics

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Abstract
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SASPRO--SPARE AND SERVER PROVISIONING PROGRAM

by

Donald Cross

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SASPRO--SPARE AND SERVER PROVISIONING PROGRAM

by

Donald Gross

1. Introduction

SASPRO, an acronym standing for *Spare and Server Provisioning*, is a versatile FORTRAN package that gives provisioning levels of spares inventory and repair capacity required to support a population of randomly failing items which, upon failure, are (1) dispatched to the repair facility, and (2) replaced by a spare if one is available. This paper describes in detail the problem environment, the program options, the input required to run the program, and the output provided by the program. Sample runs are also shown for each of the program options.

2. Problem Environment

A population of items containing certain key parts (for example, a fleet of aircraft, a fleet of ships, a group of machines) randomly fails and requires repair. Spare parts are also needed so that upon failure, the spare can be utilized to replace the failed part and the item put back into service. It is desired to determine how many spares and how many repair channels are required to support the system at a desired service level while minimizing costs.

The system is shown schematically in Figure 1. We consider only a single part-type at a time, which has its own spares pool and dedicated repair channels. For example, for a fleet of gas turbine propelled ships, the gas turbine engine has two components--a gas generator and a power turbine. Each must have dedicated repair channels and its own spares pool. Thus SASPRO would treat each component in turn, being utilized to provision first for a population of gas generators and then for a population of power turbines.

When a unit in the operating population fails, a spare is requested at the same time the unit is dispatched for repair. If a spare is not available, the request is backlogged and units coming out of repair are used in removing the backlog. When there is no backlog of requests for spares, units coming out of repair go into the spares inventory. Repair times as well as failure times are treated as random variables and with the proper assumptions (to be mentioned below), this stochastic process can be readily modeled as a finite source queueing system, often referred to as "the machine repair problem with spares," which, in addition, also fits a two-stage cyclic queueing model. Thus SASPRO uses a standard queueing model for the stochastic process [see GROSS, KAHN, and MARSH (1977)].

The assumptions required for using SASPRO are that times to failure and repair times are exponentially distributed random variables. These assumptions allow the employment of the standard finite source queueing theory to determine probabilities of various numbers of units in repair at any given time. From this, system service levels (number of units operating, availability of spares, etc.) can readily be computed.

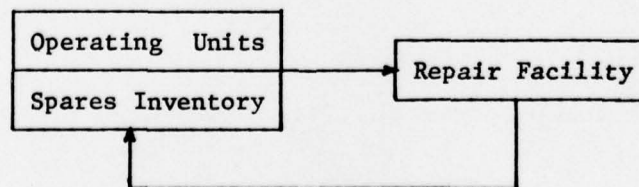


Figure 1. Problem environment.

In order to achieve a specified service level, certain combinations of spares and servers (repair channels) are required. Using costs associated with purchasing and holding spares, and costs associated with building and operating repair channels, SASPRO, through a heuristic optimization routine, finds the "best" combination of spares and servers that meets the service level constraint. [See Gross, *et al.* (1977) for specific details.]

3. Modes of Operation

The program has two modes of operation, dynamic and static. The former is advised for initial year provisioning when population sizes, failure rates, and repair times may be changing significantly. Population size changes may occur because units are put into operation gradually, thus building up to a full strength population over a period of several years. For example, it was anticipated to build a fleet of 256 gas turbine powered ships, starting in the first year with ten ships and building up to full strength over a ten-year period. Because of new technology, engines on ships introduced in the later years were expected to have smaller failure rates (be more reliable) while due to learning, repair times were also expected to be smaller in the later years.

In designing support systems for which it is necessary to determine the number and location of depots the static mode is useful [see GROSS and PINKUS (1978)]. In this situation the population is at full strength, technological advances and learning are complete, and conditions are very close to static. Running times and input requirements are greatly reduced when operating in the static mode.

The dynamic mode allows for changing population sizes, failure rates, and repair times, as well as for changing costs on a year by year basis. A set of input information is required for each year in the planning horizon. An item repaired and placed back into spares inventory (or operation) in year i is assumed to have the same failure rate as a new item introduced in year i .

All costs are turned into an equivalent beginning of year payment and then discounted according to where the year is in the planning horizon

so that at any year i the program gives the present worth of the cumulative sum of the discounted costs up to and including year i . The final value for the last year is then the present worth of the sum of discounted costs over the entire planning horizon.

The costs that are considered in SASPRO are purchase costs, salvage values, and annual operating costs associated with spares and repair channels; unit transportation and repair costs; and component improvement investment costs. Purchase costs and salvage values are in dollars per spare or repair channel, and salvage values are not realizable until the end of the planning horizon, even though spares or repair channels are retired prior to that. Operating costs of each channel and holding costs for spares are in dollars per year per spare or repair channel and any spare or channel purchased in year i is assumed to incur annual costs until the end of the planning horizon, even if retired earlier. Transportation and repair costs are in dollars per unit per repaired item and component improvement program (CIP) costs are in dollars per year.

The assumptions that salvage values are not received until the end of the planning horizon and that operating or holding costs are not reduced when spares or repair channels are retired early are necessitated by the heuristic optimization algorithm employed. Further, if a spare or repair channel is retired during the planning horizon and is required again a few years later, it must be repurchased. Again, this assumption is required because of the heuristic optimization algorithm.

In the static mode no such problems arise since spares and channels are not added or retired. Costs for this mode of operation are converted to expected equivalent end-of-year payments over the planning horizon.

4. Service Level Constraint Options

There are two options available for specifying service performance. The first, referred to as *spares availability*, sets a limit on the percentage of requests for spares that are met from on-shelf spares inventory (also called fill rate); that is,

$$\frac{\text{Number of Requests for Spares per Year Honored Immediately}}{\text{Number of Requests for Spares per Year}} \geq A, \quad (1)$$

where A is specified by the user and $0 < A < 1$.

The second criterion for service performance, called "*fleet*" *availability*, sets a level for the percentage of time a certain portion of the population desired to be in operation is actually operating; that is,

$$\Pr\{\geq \beta M \text{ units are up}\} \geq A. \quad (2)$$

Both β and A are specified by the user when $0 < \beta \leq 1$, and M is the population (fleet) size excluding spares.

Suppose, for example, we wish to have 100 machines in operation ($M=100$). When a machine fails, a spare machine is "plugged in" if one is available. We might specify that a service level constraint be (1) the percentage of requests for spare machines filled immediately from on-hand spares is at least 90% (option 1: $A=.9$), or (2) at least 95% of the machines are operating 85% of the time (option 2: $\beta=.95, A=.85$).

5. Input Data

Table I shows the data that are required as input for SASPRO.

Most input parameters are self-explanatory but a few require further comment. The A shown in Equations (1) and (2) is AVL, while BETA is the β shown in Equation (2).

The initial values $C0$ and $Y0$ must be read in for number of servers and spares, respectively. In the dynamic mode, after the first year the program uses the previous year's values for $C0$ and $Y0$ as initial values, even though a $C0$ and $Y0$ must be specified on the card set for every year in the planning horizon. The closer the initial values are to the final values (determined by SASPRO), the fewer iterations of the heuristic optimization algorithm are required. However, one may use $C0 = Y0 = 1$ if so desired.

TABLE I
INPUT REQUIREMENTS

Variable Name	Description	Symbol on Printout
AVL	Desired Availability	AVL
BETA	Desired Percent of Population Up	BETA
C	Initial Value--Number of Repair Channels	CO
CIC	Carrying Cost per Spare (\$/yr/spare)	CIC
CIPC	Component Improvement Cost (\$/yr)	CIPC
CPSER	Repair Channel (Server) Purchase Cost (\$/channel)	CPSER
CPSP	Spare Purchase Cost (\$/spare)	CPSP
H	Operating Hours per Year per Item (hrs)	H
KEYWD	Mode Option Indicator { =1: Dynamic #1: Static	KEYWD
KZ	Service Criterion Option Indicator { #1: Spare Avl =1: Fleet Avl	KZ
NYEARS	Planning Horizon Length (yrs)	YEARS
OCSPSER	Operating Cost of a Channel (\$/yr/channel)	OCPSER
R	Yearly Interest Rate	RATE
RM	Population Size	M
RMTBR	Mean Time Between Removals (hrs)	MTBR
ST	Average Turn Around Time (days)	1/MU
SVSER	Salvage Value of a Channel (\$/channel)	SVSER
SVSP	Salvage Value of a Spare (\$/spare)	SVSP
URC	Unit Repair Cost (\$/unit)	URC
UTC	Unit Transportation Cost (\$/unit)	UTC
Y	Initial Value--Number of Spares	YO

A set of cost inputs (CIC, CIPC, CPSER, CPSP, OCSPSER, SVSER, SVSP, URC, UTC) is required for each year in the horizon in the dynamic mode. This allows one to account for inflation and technological innovations. The Component Improvement Program Cost (CIPC) is the annual expenditure required to achieve a given MTBR schedule (the MTBR which must

be inputted for each year in the horizon) for the dynamic mode of operation, or to maintain the MTBR achieved when operating in the static mode.

The MTBR value is the actual mean time to failure of each unit when operating continuously. If items do not operate continuously but are required for, say, only H hours per year on the average, the mean failure rate actually used in the queueing model portion of SASPRO is lowered accordingly. If items do operate around the clock, $H = 365 \times 24 = 8760$. If, for example, a population of items has an MTBR of 1000 hours but is called upon to operate, on the average, only half the time ($H = 4380$ hours), the effective MTBR used in the program is raised to 2000 hours (failure rate cut in half). The user specifies H and MTBR and SASPRO automatically makes the adjustment. The reader is referred to BARZILY, GROSS, and KAHN (1977) for a discussion of the adequacy of this procedure to account for noncontinuous operation. The above reference also discusses the SASPRO assumptions, when operating in the dynamic mode, that (1) the population attains instantaneous steady-state each year at average values, and (2) the population consists of nonidentical units (with respect to mean failure and repair time), which are treated as identical by weighted averaging.

The parameters KEYWD and KZ are the option flags. Setting KEYWD=1 puts SASPRO in the dynamic mode; otherwise it operates in the static mode. Designating KZ=1 sets the service level on fleet availability; otherwise the service level constraint is on spares availability. A β must be specified when KZ=1.

Table II and Figure 2 give the card layout required for the input information. There are eight cards needed for the static mode and six plus two cards for each year in the planning horizon required for dynamic mode operation. The input requirements for static mode operation are similar to those required for a one-year planning horizon dynamic run. However, the output cost values given in the static mode are the expected end of year payments adjusted over an NYEAR life, while the costs of a single year dynamic mode run are the present worth of expenditures for that year.

TABLE II
CARD LAYOUT FOR INPUT

Card Number	Input Data Parameter(s)	Format	Columns
1	Title (any desired by user)	--	1-80
2	NYEARS	I2	1-2
3	R	F8.5	1-8
4 ^a	AVL, BETA	F8.5, F8.5	1-8, 9-16
5 ^b	KZ	I2	1-2
6 ^c	KEYWD	I2	1-2
7 } 8 }	See Figure 2: One set required for each year in dynamic planning horizon; one set only for static mode.		

^aFor Spares Avail Option, BETA may be set at any value.

^b $KZ = \begin{cases} 0 \rightarrow \text{Spares Availability} \\ 1 \rightarrow \text{Fleet Availability} \end{cases}$

^c $KEYWD = \begin{cases} 0 \rightarrow \text{Static Mode} \\ 1 \rightarrow \text{Dynamic Mode} \end{cases}$

6. Output from SASPRO

SASPRO gives the heuristic optimum combination of spares and repair channels needed to meet the service level constraint and also provides the costs associated with this solution. For the static operation mode there is a single line of output with the total costs shown being the expected equivalent annual expenditure over the NYEAR system life. For the dynamic mode of operation there is a line of output for each year, the cost outputted being the expected present worth of the cumulative sum of discounted costs up to and including that year. Also given as output are the heuristic optimum combinations of servers and spares; the average system failure rate, which in the static mode is the same as the

M	Y0	C0	MTBR	1/MU	H	CIPC	CPSER	CPSP	URC	UTC
1	89	1617	2425	3233	4041	5051	5859	6364	7071	7576
F8.0	F8.0	F8.0	F8.0	F8.0	F10.0	F8.0	F5.0	F7.0	F5.0	F5.0

SVPSE	SVPSP	OCPSER	CIC
1	56	1213	1718
F5.0	F7.0	F5.0	F5.0

Figure 2. Format for card set 6,7.

inputted failure rate calculated from the MTBR and H values read in, and in the dynamic mode is a weighted average of the units in the population which were introduced and repaired in various years at different values;¹ the average number of units repaired; and the actual availability achieved (always $\geq$ AVL). Another output quantity shown is ASTAR, the percentage of time the population is called upon to operate ($ASTAR = H/8760$); this serves as a check on the H value put in. The output quantities with definitions are shown in Table III.

TABLE III
OUTPUT QUANTITIES

Name	Description
YR	Actual year represented
M	Population size year i (from input)
FR	Failure rate of a unit purchased or repaired in year i (failures/day = $\frac{1}{MTBR} \cdot \frac{H}{8760} \cdot 24$)
FRBAR	Average failure rate of a typical unit (failures/day = weighted average of various units purchased or repaired in all years up to and including i)
ASTAR	Average percent of time population is called upon to operate ($H/8760$)
C	Heuristic optimum number of repair channels required in year i
Y	Heuristic optimum number of spares required in year i
RBAR	Average number of units repaired in year i
COST	Costs expended in year i dynamic mode or equivalent yearly average expenditure in static mode
PRES WORTH	Present worth of sum of discounted costs up to and including year i, dynamic mode; same as COST for static mode

¹See Gross, Kahn, and Marsh (1977).

7. Sample Runs

We illustrate the model by showing sample runs for each mode (dynamic and static) for each service level option (spares availability and fleet availability). The first run is a dynamic, fleet availability, 20-year planning horizon case. Following this, a similar dynamic run is performed for spares availability. Next a static, 20-year system life spares availability situation is considered. Finally, a static, 20-year system life fleet availability case is run.

A listing of the input cards for these runs is given in Figure 3. For the four cases, there are a total of 108 data input cards ($2[6 + 2 \times 20] + 2[8]$).

The associated output for the cases is given in Figure 4.

8. Intermediate Output and the Heuristic Optimization Algorithm

Also provided as output are intermediate values of Y and C which "step up" from Y_0 and C_0 showing the operation of the algorithm at each iteration. Briefly, the algorithm works as follows.

First, a C_1 and C_2 are computed, where C_1 is a function of the purchase cost, operating cost, and salvage value of a repair channel and C_2 is a function of the purchase cost, carrying cost, and salvage value of a spare. In the dynamic mode, the functions for C_1 and C_2 , year i , are

$$\begin{aligned} C_1 &= \text{CPSPER} + \text{OCSPER} \left[\frac{(1+R)^{K-i+1} - 1}{R(1+R)^{K-i+1}} \right] - \text{SVSER} \left[\frac{1}{(1+R)^{K-i+1}} \right], \\ C_2 &= \text{CPSP} + \text{CIC} \left[\frac{(1+R)^{K-i+1} - 1}{R(1+R)^{K-i+1}} \right] - \text{SVSP} \left[\frac{1}{(1+R)^{K-i+1}} \right], \end{aligned} \quad (3)$$

where K is the total number of periods in the dynamic planning horizon, i the current year, R the interest rate, and the costs are as defined

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32, 203, 32
SAMPLE RUN 2

20	
0.10	
0.90	1.00

32. 205.35
SAMPLE RUN 5

20	
0.10	
0.40	1.00

32. 205.35
SAMPLE RUN 4

20
0.10
0.40 0.95

0	32.	250.	205.35	10.	130.12.	4000.	55.	2037.14	0.	90.	1020.44	44.	0.
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Figure 4. Sample run output.

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INPUT DATA	M	AVL	BETA	YO	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
20	.100	.250	.050	.95	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10. 137.
OUTPUT DATA																	
YH	2	FR	FRHAW	ASTAR													
85	250	0.00062015	0.00062015	0.232550	0.232550	13											
INPUT DATA	M	AVL	BETA	YO	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
20	.100	.250	.050	.95	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10. 137.
OUTPUT DATA																	
YH	4	FR	FRHAW	ASTAR													
86	250	0.00062015	0.00062015	0.232550	0.232550	13											
INPUT DATA	M	AVL	BETA	YO	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
20	.100	.250	.050	.95	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10. 137.
OUTPUT DATA																	
YH	4	FR	FRHAW	ASTAR													
87	250	0.00062015	0.00062015	0.232550	0.232550	13											
INPUT DATA	M	AVL	BETA	YO	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
20	.100	.250	.050	.95	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10. 137.
OUTPUT DATA																	
YH	4	FR	FRHAW	ASTAR													
88	250	0.00062015	0.00062015	0.232550	0.232550	13											
INPUT DATA	M	AVL	BETA	YO	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
20	.100	.250	.050	.95	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10. 137.
OUTPUT DATA																	
YH	4	FR	FRHAW	ASTAR													
89	250	0.00062015	0.00062015	0.232550	0.232550	13											
INPUT DATA	M	AVL	BETA	YO	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
20	.100	.250	.050	.95	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10. 137.
OUTPUT DATA																	
YH	4	FR	FRHAW	ASTAR													
90	250	0.00062015	0.00062015	0.232550	0.232550	13											
INPUT DATA	M	AVL	BETA	YO	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
20	.100	.250	.050	.95	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10. 137.
OUTPUT DATA																	
YH	4	FR	FRHAW	ASTAR													
91	250	0.00062015	0.00062015	0.232550	0.232550	13											
INPUT DATA	M	AVL	BETA	YO	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
20	.100	.250	.050	.95	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10. 137.
OUTPUT DATA																	
YH	4	FR	FRHAW	ASTAR													
92	250	0.00062015	0.00062015	0.232550	0.232550	13											
INPUT DATA	M	AVL	BETA	YO	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
20	.100	.250	.050	.95	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10. 137.
OUTPUT DATA																	
YH	4	FR	FRHAW	ASTAR													
93	250	0.00062015	0.00062015	0.232550	0.232550	13											
INPUT DATA	M	AVL	BETA	YO	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
20	.100	.250	.050	.95	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10. 137.
OUTPUT DATA																	
YH	4	FR	FRHAW	ASTAR													
94	250	0.00062015	0.00062015	0.232550	0.232550	13											

Figure 4.--continued

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SAMPLE RUN 2

DYNAMIC MODEL 1 SPARES AVAIL OPTION

INPUT DATA	M	AVL	BETA	YU	CU	MTOM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
13 MATE	20	.100	1.00	1.00	1.00	3500.	65.000	1800.	90.	817.	49.	0.	0.0	32.	123.	10.	82.
OUTPUT DATA	FM																
75 10	0.00147186	0.00147186	0.214646	5	Y	5.3											
INPUT DATA	M	AVL	BETA	YU	CU	MTOM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
13 MATE	20	.100	1.00	1.00	1.00	3500.	62.500	1948.	90.	709.	49.	0.	0.0	32.	142.	10.	95.
OUTPUT DATA	FM																
76 20	0.00152455	0.00152455	0.222330	5	Y	15.3											
INPUT DATA	M	AVL	BETA	YU	CU	MTOM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
13 MATE	20	.100	1.00	1.00	1.00	4250.	60.000	2122.	90.	815.	38.	0.	0.0	32.	163.	10.	109.
OUTPUT DATA	FM																
77 50	0.00130767	0.00130767	0.242192	5	Y	20.4											
INPUT DATA	M	AVL	BETA	YU	CU	MTOM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
13 MATE	20	.100	1.00	1.00	1.00	5500.	57.500	1989.	90.	881.	40.	0.	0.0	32.	176.	10.	117.
OUTPUT DATA	FM																
78 82	0.00094101	0.00094101	0.227106	10	Y	37.2											
INPUT DATA	M	AVL	BETA	YU	CU	MTOM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
13 MATE	20	.100	1.00	1.00	1.00	6500.	55.000	1959.	90.	951.	42.	0.	0.0	32.	190.	10.	124.
OUTPUT DATA	FM																
79 121	0.00082509	0.00082509	0.223624	12	Y	45.3											
INPUT DATA	M	AVL	BETA	YU	CU	MTOM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
13 MATE	20	.100	1.00	1.00	1.00	7500.	55.000	1966.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FM																
80 156	0.00071831	0.00071831	0.224471	15	Y	51.8											
INPUT DATA	M	AVL	BETA	YU	CU	MTOM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
13 MATE	20	.100	1.00	1.00	1.00	8500.	55.000	1976.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FM																
81 182	0.00063699	0.00063699	0.225602	13	Y	53.9											
INPUT DATA	M	AVL	BETA	YU	CU	MTOM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
13 MATE	20	.100	1.00	1.00	1.00	9000.	55.000	2002.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FM																
82 208	0.00060941	0.00060941	0.226527	14	Y	56.3											
INPUT DATA	M	AVL	BETA	YU	CU	MTOM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
13 MATE	20	.100	1.00	1.00	1.00	9000.	55.000	2002.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FM																
83 229	0.00061725	0.00061725	0.231467	15	Y	58.3											
INPUT DATA	M	AVL	BETA	YU	CU	MTOM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UTC	SVPSEM	SVPSP	UCPSEM	CIC
13 MATE	20	.100	1.00	1.00	1.00	9000.	55.000	2002.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FM																
84 251	0.00062296	0.00062296	0.233012	15	Y	61.6											

Figure 4.--continued

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INPUT DATA	M	AVL	BETA	YU	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UIC	SVPSEM	SVPSP	OCPSM	CIC
13 456	256	.900	1.00	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FR		FR		ASTAR		15	Y	RR		CUST	PR-MONTH					
85 256	0.00062015		0.00063767		0.232556		15	Y	RR	61.6	2463.55	30671.44					
INPUT DATA	M	AVL	BETA	YU	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UIC	SVPSEM	SVPSP	OCPSM	CIC
14 456	256	.900	1.00	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FR		FR		ASTAR		14	Y	RR		CUST	PR-MONTH					
86 256	0.00062015		0.00063767		0.232556		14	Y	RR	60.7	2467.43	31522.24					
INPUT DATA	M	AVL	BETA	YU	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UIC	SVPSEM	SVPSP	OCPSM	CIC
15 456	256	.900	1.00	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FR		FR		ASTAR		14	Y	RR		CUST	PR-MONTH					
87 256	0.00062015		0.00063767		0.232556		14	Y	RR	60.0	2401.14	32287.32					
INPUT DATA	M	AVL	BETA	YU	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UIC	SVPSEM	SVPSP	OCPSM	CIC
16 456	256	.900	1.00	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FR		FR		ASTAR		14	Y	RR		CUST	PR-MONTH					
88 256	0.00062015		0.00063767		0.232556		14	Y	RR	59.5	2381.28	32977.04					
INPUT DATA	M	AVL	BETA	YU	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UIC	SVPSEM	SVPSP	OCPSM	CIC
17 456	256	.900	1.00	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FR		FR		ASTAR		14	Y	RR		CUST	PR-MONTH					
89 256	0.00062015		0.00063767		0.232556		14	Y	RR	59.2	2366.19	33000.18					
INPUT DATA	M	AVL	BETA	YU	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UIC	SVPSEM	SVPSP	OCPSM	CIC
18 456	256	.900	1.00	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FR		FR		ASTAR		13	Y	RR		CUST	PR-MONTH					
90 256	0.00062015		0.00063767		0.232556		13	Y	RR	58.8	2353.51	34163.54					
INPUT DATA	M	AVL	BETA	YU	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UIC	SVPSEM	SVPSP	OCPSM	CIC
19 456	256	.900	1.00	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FR		FR		ASTAR		13	Y	RR		CUST	PR-MONTH					
91 256	0.00062015		0.00063767		0.232556		13	Y	RR	58.6	2344.56	34673.79					
INPUT DATA	M	AVL	BETA	YU	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UIC	SVPSEM	SVPSP	OCPSM	CIC
20 456	256	.900	1.00	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FR		FR		ASTAR		13	Y	RR		CUST	PR-MONTH					
92 256	0.00062015		0.00063767		0.232556		13	Y	RR	58.4	2337.85	35156.32					
INPUT DATA	M	AVL	BETA	YU	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UIC	SVPSEM	SVPSP	OCPSM	CIC
21 456	256	.900	1.00	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FR		FR		ASTAR		13	Y	RR		CUST	PR-MONTH					
93 256	0.00062015		0.00063767		0.232556		13	Y	RR	58.3	2332.68	35555.87					
INPUT DATA	M	AVL	BETA	YU	CU	MTM	1/MU	M	CPSEM	CPSP	UNC	CIPC	UIC	SVPSEM	SVPSP	OCPSM	CIC
22 456	256	.900	1.00	11.	8.	9000.	55.000	2037.	90.	1027.	44.	0.	0.0	32.	205.	10.	137.
OUTPUT DATA	FR		FR		ASTAR		13	Y	RR		CUST	PR-MONTH					
94 256	0.00062015		0.00063767		0.232556		13	Y	RR	58.2	2328.71	35936.63					

Figure 4.--continued

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SAMPLE RUN 3

STATIC MODEL: SPARES AVAIL OPTION

INPUT DATA	M	AVL	BETA	YU	CU	MTBR	17MU	M	CPSEM	CRSP	UNC	CIPC	UTC	SVPSM	SVSP	UCPSEM	CIC
YRS WALE	20	.100	.250	.900	1.00	11.	8.	4000.	55.000	2037.	44.	0.	0.0	32.	203.	10.	137.
OUTPUT DATA	75	250	0.00062015	0.00062015	0.232556	0.232556	ASTAN	C	Y	RRAR	COST	PM-MURTH					
								13	14	57.9	6361.81	6361.81					

SAMPLE RUN 4

STATIC MODEL: FLEET AVAIL OPTION

INPUT DATA	M	AVL	BETA	YU	CU	MTBR	17MU	M	CPSEM	CRSP	UNC	CIPC	UTC	SVPSM	SVSP	UCPSEM	CIC
YRS WALE	20	.100	.250	.900	1.00	11.	8.	4000.	55.000	2037.	44.	0.	0.0	32.	203.	10.	137.
OUTPUT DATA	75	250	0.00062015	0.00062015	0.232556	0.232556	ASTAN	C	Y	RRAR	COST	PM-MURTH					
								12	1	56.1	2960.50	2960.50					

Figure 4.--continued

in Table I. The first bracket term brings the annual costs, OCSPER and CIC, to a beginning of year i equivalent cost, while the second bracket term brings the salvage value to a beginning of year i equivalent term; that is, the bracket terms are the present worth factors for a series payment and end of horizon payment, respectively. Note it is assumed that if a spare or repair channel is purchased in year i , the annual costs are incurred through the end of the planning horizon and salvage cannot be obtained until the end of the horizon, even if removal occurs sooner.

The algorithm forms a ratio (call Δ) of C_1/C_2 or C_2/C_1 , depending on the relative magnitudes in such a way that the ratio is ≥ 1 . Then given a pair of values C, Y (to start year i , C_{i-1} and Y_{i-1} are used) the availability is computed. If it is below the desired level and if $\Delta = C_1/C_2$, then for an equal dollar expenditure Δ repair channels or one spare can be added. Availability is calculated for both cases (adding Δ repair channels or one spare) and the case yielding the higher availability becomes the new C, Y pair. The algorithm repeats until the desired availability is met. Upon exceeding the desired availability, a backoff procedure is utilized. If feasibility was reached by adding Δ channels, the algorithm first attempts to remove a spare and then channels are removed one at a time to see if a cheaper solution exists near the boundary. If feasibility was reached by adding a spare, again one-at-a-time removal of channels is tried. Had $\Delta = C_2/C_1$, the words channel and spare would be reversed in describing the algorithm.

When the initial values of C and Y for year i exceed the availability desired, the algorithm immediately goes into a backoff mode, trying to remove spares and channels one at a time, starting with the more expensive (larger C_i value) first.

The algorithm uses only C_1 and C_2 . The other costs are used in calculating the total year i expenditures even though they are not used in the algorithm. The costs URC, UTC, and CIPC are assumed year end expenditures and are multiplied by $1/(1+R)$ to bring them back to

a year beginning cost. The URC and UTC costs are multiplied by $\bar{R}$ and then added to $C_1 \times (\text{number of new channels added}) + C_2 \times (\text{number of new spares added}) + \text{CIPC}$ to yield the total beginning of year cost for year i (call T_c) which is outputted. Letting $\alpha = 1/(1+R)$, the discounting factor, the final cost figure given in the output for year i is the present worth of the cumulative sum of equivalent beginning of year costs, up to and including year i ; namely, $\sum_{j=1}^i \alpha^{j-1} T_j$.

In the static mode the algorithm works in the same way, except the functions C_1 and C_2 are changed to reflect all costs as average expenditures per year. Thus, the purchase costs and salvage values are multiplied by sinking fund and capital recovery factors, namely,

$$\begin{aligned} C_1 &= \text{CPSER} \left[\frac{R(1+R)^K}{(1+R)^K - 1} \right] + \text{OCSPER} - \text{SVSER} \left[\frac{R}{(1+R)^K - 1} \right] \\ C_2 &= \text{CPSP} \left[\frac{R(1+R)^K}{(1+R)^K - 1} \right] + \text{CIC} - \text{SVSP} \left[\frac{R}{(1+R)^K - 1} \right]. \end{aligned} \quad (4)$$

In this mode total equivalent expenditures per year are calculated simply by adding $(\text{URC} + \text{UTC})\bar{R}$ and CIPC to $C_1 \times (C) + C_2 \times (Y)$. This is then the value which shows as both COST and PRES WORTH on the output, the PRES WORTH column being meaningless in the static mode.

A sample of intermediate output is shown in Figure 5 for the first year of sample run 1. Shown are the failure rate for year i (RLAM), average population failure rate for year i (AMTBR), average turn around (repair) time (ST), availability for the particular combination of C and Y , average queue size at repair depot (LQ), and average number of units in repair (L).

9. Acknowledgments

The computer programming was originally performed by H. D. Kahn and modified by F. Ghotb and M. Y. Wong. Their excellent assistance was invaluable in yielding the SASPRO package.

M=	10.0	C=	1.0	Y=	1.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.38615D	00	LQ=	0.1610D	01	L=	2.4129
M=	10.0	C=	8.0	Y=	1.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.76002D	00	LQ=	0.1538D-07	L=		0.9266
M=	10.0	C=	1.0	Y=	2.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.49112D	00	LQ=	0.2000D	01	L=	2.8293
M=	10.0	C=	15.0	Y=	1.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.76002D	00	LQ=	0.0	L=		0.9266
M=	10.0	C=	8.0	Y=	2.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.92963D	00	LQ=	0.5208D-07	L=		0.9484
M=	10.0	C=	15.0	Y=	2.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.92963D	00	LQ=	0.0	L=		0.9484
M=	10.0	C=	8.0	Y=	3.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.98395D	00	LQ=	0.1332D-06	L=		0.9549
M=	10.0	C=	7.0	Y=	3.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.98395D	00	LQ=	0.2655D-05	L=		0.9549
M=	10.0	C=	6.0	Y=	3.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.98394D	00	LQ=	0.4001D-04	L=		0.9549
M=	10.0	C=	5.0	Y=	3.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.98387D	00	LQ=	0.4669D-03	L=		0.9553
M=	10.0	C=	4.0	Y=	3.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.98305D	00	LQ=	0.4328D-02	L=		0.9590
M=	10.0	C=	3.0	Y=	3.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.97552D	00	LQ=	0.3331D-01	L=		0.9868
M=	10.0	C=	2.0	Y=	3.0	RLAM=0.147186D-02	AMTBR=0.0014719	ST=	65.000	AVAIL=0.93769D	00	LQ=	0.2403D	00	L=	1.1875

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Figure 5. Intermediate output--sample run 1--first year.

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CHARLES HOOK TOMPKINS, DOCTOR OF ENGINEERING
BECAUSE OF HIS ENGINEERING CONTRIBUTIONS TO THIS UNIVERSITY, TO HIS
COMMUNITY, TO HIS NATION, AND TO OTHER NATIONS.

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1955

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