AN ANALYSIS OF THE EFFECT OF PRODUCTION QUANTITY AND INVENTORY SELECTION POLICY ON THE PROBABILITY OF MEETING A SPECIFIED LAUNCH SCHEDULE

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ABSTRACT

An analysis of the effect of two alternative inventory selection rules is performed to determine their effect on both cost per flight and schedule reliability for the planned Space Shuttle Program.

The major objective of the Space Shuttle Program is to achieve a low cost per flight while providing a capability to support a variety of scientific, defense, commercial and international space applications. Cost per flight is the average recurring cost for operating the shuttle. One aspect of cost per flight is related to the number of new motors required to complete the mission flight schedule.

The Logistics Simulation Model (LSM) of Schlagbeck and Giglieri (1) was employed to simulate the mission flight schedule. The two inventory selection policies considered were:

(1) When a motor is needed to make a flight select the available motor with the least number of previous flights (new logic).

(2) When a motor is needed to make a flight select the available motor with the most previous flights (old logic).

The study was performed using baseline parameters as supplied by the NASA program office. The number of new motors to be produced and the production schedule was varied over the range (80-90).

The study shows that the probability of meeting a specified launch schedule is greater and the refurbishment costs lower using the new logic over the entire feasible range of production quantities.

INTRODUCTION

The major objective of the Space Shuttle Program is to achieve a low cost per flight for space operations while providing a capability to support a variety of scientific, defense, commercial and international applications (2). The cost per flight as defined in reference (2) is the average recurring cost for operating the shuttle. Included are: manpower costs for recovering, repairing, refurbishing and maintaining the reusable hardware; manpower costs for launch and mission control; production costs for all expendable and partially reusable hardware; spares costs; and the cost of government furnished equipment to conduct the operational mission.

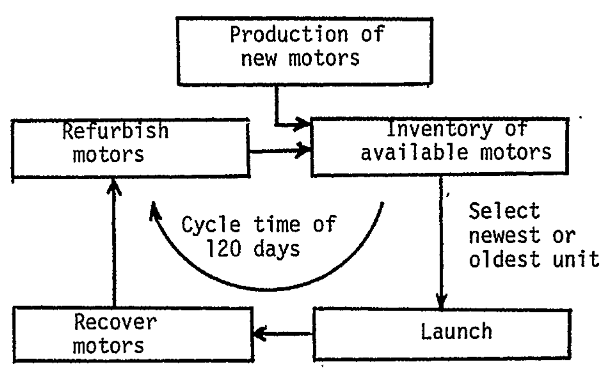
One aspect of cost per flight is related to the number of new motors required. In the next section it is shown that the number of new units required to achieve a given probability of meeting the launch schedule is smaller if the newest available motor is selected as opposed to the oldest available motor.

The Logistics Simulation Model, developed at NASA's Marshall Space Flight Center, is briefly described in the next section. Results obtained from the model are then presented and analyzed. Conclusions are drawn from the results and recommendations for further study are presented.

THE MODEL

The Logistics Simulation Model is a Fortran program which simulates the flow of hardware. New motors enter the inventory of available units according to a user defined production schedule. Upon recovery spent motors are refurbished and returned to the available inventory. The model simulates the launch, recover, refurbish and replace in inventory cycle. The hardware flow is as shown in figure 1.

FIGURE 1
Hardware Flow



TWO INVENTORY SELECTION POLICIES

The following parameters were supplied by NASA:

1. New motors arrive at a uniform rate as defined by the production schedule.

2. The Reburbishment Cycle equals 120 days in duration.

3. Launch dates are determined by the mission or traffic model. They are nearly uniformly spaced.

4. The overall probability of motor loss is 4%. It follows a 69% learning curve with an initial probability of loss of 50%.

5. The probability of a loss during a given year is the average loss rate for the flight numbers flown during the year.

ANALYSIS OF RESULTS

The input data and output for a typical case study simulated appears in figures 2-5. In order to determine the effect of the inventory selection policy on the probability of meeting a specified launch schedule two runs are performed with each data set. Figures 2-5 refer to the case in which the production quantity is 85, the only difference in input data being the OLD/NEW LOGIC indicator. If the indicator is set equal to zero the oldest (one with the most previous flights) available motor is selected to launch. If the indicator is set equal to one the newest available motor is selected.

Referring to figure 2, the input data includes the loss rate, the number of flights and the production quantity in each year of the mission model. The initial number of units produced is those available at the beginning of the first year. The total number of units produced is the sum of the initial number of units produced plus all those produced during the mission model. The total number of units produced was varied in order to determine its effect on the probability of meeting the given launch schedule. As previously stated the other parameter which was varied was the Logic indicator. For each total number of units produced and its associated production schedule one simulation was run using the old logic and another using the new logic. There are two motors required for each of the 445 flights in the mission model. The refurbishment time is assumed to be 120 days and the maximum number of flights before a motor is considered worn out is 20. The refurbishment and new units costs are assumed to be $840,000 and $1,200,000, respectively.

Referring to figure 3, the output includes the average and standard deviation for the following in each year of the mission model: lost units, worn out units, new units used, number of units in refurbishment, flights missed and days missed. In addition the extreme or maximum number of units in refurbishment is given for each year. This information would be useful in designing the necessary capacity for the refurbishment facilities. The number of units lost is a function of the loss rate and the number of flights per year. Neither of these parameters are varied in this study. Hence, this information is of little interest here. The number of units worn out is a function of the number produced and the inventory selection logic. It is interesting to note that for the case in which 85 units are produced and new logic is used (see figure 5) no units are worn out since older units are passed over when selecting a motor for the next launch. Using the old logic an average total of 20.92 units are worn out (see figure 3). They are distributed over the last six years of the mission model with by far the largest number of units being worn out in the last two or three years.

The new logic where no units are likely to be worn out has the advantage of maximizing the number of usable units. The number of usable units is the number produced minus those lost or worn out. Since, the number lost is independent of the logic and new logic minimizes the number worn out it maximizes the number of usable units. The disadvantage of the new logic is that when a unit is lost it is likely to have more remaining flights than when a unit is lost using the old logic. For example, compare the number of flights per lost unit. In figure 3, using the old logic, the average is 7.044 while in figure 5, using the new logic, the average is 5.44.

FIGURE 2
Input Data, 85 Units, Old Logic

Solid Rocket Motor Baseline Case 120 Day Turnaround
20 Uses Old Logic

Input Data

Yr	Loss Rate	Flights	Production
1	0.50000	1	20
2	0.17722	6	20
3	0.10502	11	20
4	0.07514	19	19
5	0.05632	36	0
6	0.04372	55	0
7	0.03611	60	0
8	0.03155	60	0
9	0.02851	60	0
10	0.02628	60	0
11	0.02456	60	0
12	0.02362	17	0

Initial Number of Units Produced =	6
Total Number of Units Produced =	85
Number of Units Required per Flight =	2
Total Flights in Mission Profile =	445
Refurbishment Time (Days)	120.00
Maximum Flights per Unit	20
Number of Days in Year	365
Simulations	50
Random Number Seed	11221
Old/New Logic (0=Old, 1=New)	0
Cost of Refurbishment (Thousands $)	840.00
Cost of New Unit (Thousands $)	1200.00

FIGURE 3

Output, 85 Units, Old Logic

Logistics Simulation Study Output

Yearly Results

Yr	Lost Units Avg	Lost Units Stdev	Worn Out Units Avg	Worn Out Units Stdev	New Units Avg	New Units Stdev	No. in Refurb Avg	No. in Refurb Stdev	No. in Refurb Extreme	Flights Missed (0/0) Avg	Flights Missed (0/0) Stdev	Days Missed Avg	Days Missed Stdev
1	1.10	0.71	0.0	0.0	2.00	0.0	0.90	0.71	0.90	0.0	0.0	0.0	0.0
2	1.86	1.20	0.0	0.0	2.64	1.24	1.71	0.19	2.00	0.0	0.0	0.0	0.0
3	2.40	1.40	0.0	0.0	6.18	1.47	5.15	0.39	6.00	0.0	0.0	0.0	0.0
4	2.82	1.61	0.0	0.0	8.54	1.43	10.60	0.48	11.96	0.0	0.0	0.0	0.0
5	3.90	1.87	0.0	0.0	13.42	1.57	19.75	0.52	21.86	0.0	0.0	0.0	0.0
6	4.78	2.36	0.0	0.0	18.56	2.45	32.64	0.75	35.80	0.0	0.0	0.0	0.0
7	4.04	2.09	0.34	0.52	8.54	2.31	38.11	0.69	39.76	0.0	0.0	0.0	0.0
8	3.58	2.18	0.20	0.40	3.86	1.90	38.70	0.65	39.82	0.0	0.0	0.0	0.0
9	3.36	1.80	1.79	1.05	4.98	1.99	38.33	0.64	39.86	0.0	0.0	0.0	0.0
10	2.84	1.66	3.54	1.49	6.36	2.30	37.93	0.67	39.82	0.0	0.0	0.0	0.0
11	3.46	1.91	6.34	1.98	8.04	3.19	36.39	1.27	39.40	1.67	3.18	0.0	0.0
12	0.98	0.89	8.80	1.90	0.02	0.14	14.63	1.70	36.64	0.12	0.83	0.0	0.0

Total Program Results

	Avg	Std Dev
Total Units Required	83.140	2.442
Total Units Lost	35.120	5.073
Total Units Worn Out	20.920	2.863
Flights per Lost Unit	7.044	0.905
Flights per Expended Unit	11.911	0.964
Units Remaining	28.960	3.440
Flights Remaining on Units	356.280	74.327
Attrition Rate	0.03946	

Cost Results

Total Cost of New Units (Thousands $)	102000.00
Total Cost of Refurbishment (Thousands $)	677762.25

The number of flights per expended unit is the total number of flights from lost and worn out units divided by the number of lost and worn out units. For the old logic (figure 3) the average is 11.91 and for the new logic (figure 5) the average is 5.44; the same as the number of flights per lost unit since no units are worn out.

As previously discussed the average number of units remaining 49.10 versus 29.96 (figures 3 and 5, respectively) is maximized using the new logic. The average number of flights remaining on those units 288 versus 356.28 is minimized using new logic since more flights are lost when a new unit is lost in recovery.

The total number of units required may be less than the number produced using old logic since a new unit is not selected unless there are no used units in inventory. It is noted in figure 3 that the average number of units required is 83.14. Since 85 were produced, the average number of units which were not required was 1.86.

The average number of units in reburbishment is generally greater using the new logic because there are more remaining units circulating in the hardware flow system. The average number of flights missed is generally smaller using new logic again because there are more remaining units circulating in the

FIGURE 4

Input Data, 85 Units, New Logic

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1	0.50000	1	20
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Initial Number of Units Produced =	6
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Simulations	50
Random Number Seed	11221
Old/New Logic (0=Old, 1=New)	1
Cost of Refurbishment (Thousands $)	840.00
Cost of New Unit (Thousands $)	1200.00

FIGURE 5
Output, 85 Units, New Logic

Logistics Simulation Study Output

Yearly Results

Yr	Lost Units		Worn Out Units		New Units		No. in Refurb			Flights Missed (0/0)		Days Missed	
	Avg	Stdev	Avg	Stdev	Avg	Stdev	Avg	Stdev	Extreme	Avg	Stdev	Avg	Stdev
1	1.08	0.72	0.0	0.0	2.00	0.0	0.92	0.72	0.92	0.0	0.0	0.0	0.0
2	1.92	1.31	0.0	0.0	12.00	0.0	1.73	0.18	2.00	0.0	0.0	0.0	0.0
3	2.26	1.38	0.0	0.0	22.00	0.0	5.19	0.40	5.96	0.0	0.0	0.0	0.0
4	3.16	1.54	0.0	0.0	38.00	0.0	10.49	0.44	11.92	0.0	0.0	0.0	0.0
5	4.36	2.40	0.0	0.0	11.00	0.0	19.65	0.67	21.82	0.0	0.0	0.0	0.0
6	4.36	2.18	0.0	0.0	0.0	0.0	32.66	0.65	35.78	0.0	0.0	0.0	0.0
7	4.14	1.86	0.0	0.0	0.0	0.0	38.23	0.54	39.82	0.0	0.0	0.0	0.0
8	3.64	2.08	0.0	0.0	0.0	0.0	38.77	0.67	39.86	0.0	0.0	0.0	0.0
9	3.40	1.82	0.0	0.0	0.0	0.0	38.86	0.58	39.94	0.0	0.0	0.0	0.0
10	2.88	1.75	0.0	0.0	0.0	0.0	39.03	0.53	39.90	0.0	0.0	0.0	0.0
11	3.80	1.85	0.0	0.0	0.0	0.0	38.75	0.55	39.92	0.07	0.47	0.0	0.0
12	0.90	0.91	0.0	0.0	0.0	0.0	18.39	0.41	38.62	0.0	0.0	0.0	0.0

Total Program Results

	Avg	Std Dev
Total Units Required	85.000	0.0
Total Units Lost	35.900	6.228
Total Units Worn Out	0.0	0.0
Flights per Lost Unit	5.440	0.606
Flights per Expended Unit	5.440	0.606
Units Remaining	49.100	6.228
Flights Remaining on Units	288.000	88.115
Attrition Rate	0.04034	

Cost Results

Total Cost of New Units (Thousands $)	102000.00
Total Cost of Refurbishment (Thousands $)	676200.00

hardware flow system. Figures 3 and 5 indicate the average number of flights missed in each of the first 10 years of the mission model is zero (assuming a total production of 85) for either new or old logic. For old logic an average of 1.67 flights out of the planned 60 flights are missed because of no available units. Using the relative frequency of flights missed divided by flights planned as an estimator of the probability of a missed flight we have the following estimated probabilities of missed flights using old logic in years 1 through 12.

$$\hat{p}(1) = \hat{p}(2) = \cdots = \hat{p}(10) = 0$$

$$\hat{p}(11) = \frac{1.67}{60} = .0278$$

$$\hat{p}(12) = \frac{.12}{17} = .0071$$

For the same problem (see figure 5) using new logic the estimates are:

$$\hat{p}(1) = \hat{p}(2) = \cdots = \hat{p}(10) = 0$$

$$\hat{p}(1) = \frac{.07}{60} = .0012$$

$$\hat{p}(12) = \frac{0}{17} = 0$$

A summary of the outputs for production quantities of 80-90 units is presented in figure 6. The estimated probability of a missed launch is presented for each production quantity for both Old and New logic. The data for the production quantity of 85 units is taken from figures 3 and 5 as was indicated. The data for other production quantities was taken from similar simulations.

The days missed refers to the number of days a flight was missed by due to the late arrival of a new unit(s) from the production facility. Zeros are entered under average days missed in all years after the production ceases. These columns are of no interest in this study since production ceases in an earlier year than any missed flights are recorded.

Under Cost Results the total cost of new units is $1,200,000 times the number produced. This number is the same for comparable cases; for example, see figures 3 and 5. The total cost of refurbishment is $840,000 times the number of refurbished units. The total refurbishment cost is generally lower for the new logic, for example see figures 3 and 5 where the refurbishment costs are 677,762,250 and 676,200,000, respectively. Lower refurbishment costs result from new logic because it is assured that all new units are used. Table 1 presents a comparison of refurbishment costs for production quantities 80-90 for new and old inventory selection logic.

FIGURE 6
Summary Data--Probability of Missing a Scheduled Launch

Probability of missing a Launch by year and logic*

Number Produced	Year 9 OLD	Year 9 NEW	Year 10 OLD	Year 10 NEW
80	0	0	.0250	.0011
81	.0157	0	.0622	.0033
82	.0005	0	.0112	.0235
83	0	0	.0133	.0028
84	0	0	.0012	.0078
85	0	0	0	0
86	0	0	0	0
87	0	0	0	0
88	0	0	0	0
89	0	0	0	0
90	0	0	0	0

Number Produced	Year 11 OLD	Year 11 NEW	Year 12 OLD	Year 12 NEW
80	.1528	.0083	.0553	0
81	.1433	.0078	.0829	0
82	.0850	.0322	0	0
83	.1013	.0045	.0829	0
84	.0478	.0118	.0206	0
85	.0278	.0012	.0071	0
86	.0217	0	0	0
87	.0178	0	0	0
88	.0105	0	0	0
89	.0078	0	0	0
90	.0055	0	0	0

*The probability of missing a launch in years 1 through 8 is zero for both OLD and NEW logic.

TABLE 1
A Comparison of Refurbishment Costs for New and Old Logic

Number Produced	Refurbishment Cost (in thousands) OLD	NEW
80	680,568	680,400
81	680,030	679,560
82	679,375	678,720
83	678,501	677,880
84	678,047	677,040
85	677,762	676,200
86	677,644	675,360
87	676,989	674,520
88	676,804	673,680
89	676,670	672,840
90	676,233	672,000

CONCLUSION AND RECOMMENDATIONS

Production quantity and inventory selection policy can be optimized to achieve low cost per flight while assuring a specified probability of meeting a launch schedule.

It appears as though new logic is preferrable to old logic if the same logic is to be used throughout the mission model. It is suggested that perhaps an even better procedure would be to use old logic in the first several years in the launch schedule and then switch to new logic for the last several years. Or one could use the rule of selecting the oldest unit which has fewer than a specified number flights (say 16 or 18). This would have the effect of keeping the old units in the hardware flow system.

Since the number in refurbishment is relatively small in the first several years while new units are being produced, it might be possible to use the same facilities for new production and refurbishment. While new production is at maximum levels refurbishment units might be stored. As new production diminished personnel and facilities utilization could be kept constant by phasing in the refurbishment of used units.

It would be useful to know when to quit refurbishing used units. For example, if enough new and refurbished units are in inventory or currently in refurbishment to complete the mission model then there is no need to input further recovered units to the refurbishment process. The number of units required to be in refurbishment or inventory would be equal to the number of remaining flights plus the expected number of units to be lost over the remaining flights plus some statistically based safety factor.

Much more work needs to be done to obtain improved estimates of the probability of meeting a given launch schedule. For example, the refurbishment cycle would not be exactly 120 days but would vary for each unit. The refurbishment time might vary with time because of facilities capacity and/or transportation system constraints.

The following economic tradeoffs would be of interest.

1. How much assembly and/or refurbishment plant capacity is optimum?
2. What is the optimum launch schedule?
3. Queue parameters such as average length, average idle time and average time in queue could be obtained for several alternative decision policies.

REFERENCES

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