DETAILED SIMULATION OF MILITARY AIRCRAFT OPERATIONS AND LOGISTICS

J. H. Keeney
The Boeing Company
Military Airplane Systems Division
Seattle, Washington

1.0 Introduction

Over half the life cycle costs of a weapon system goes toward supporting it after delivery. Since the costs of acquiring new weapon systems increases every year, support costs and ways of reducing them are receiving greater attention. Currently, the Department of Defense is spending $24 billion a year to operate and maintain previously procured weapon systems. Consequently, the Air Force is now asking aerospace firms to contract for support elements; for instance, failure rates, maintenance man-hours expended per flying hour (MMH/FH), spares costs, depot overhaul frequencies, system availability, sortie rates and 10-year operations and maintenance costs. Thus, when we design a new aircraft system, we are now obligated also to predict support elements and costs before the first aircraft is constructed.

One way of helping us predict these support elements and costs is through a simulation model. Experience shows that effective simulation programs are not developed quickly. Therefore, we in The Boeing Company approached model design and development as a research project with the idea to develop and maintain an operational and logistics simulation capability that could be adapted to varied aircraft systems with a minimum of programming revision.

This paper describes the resulting model which is programmed in GPSS/360 (General Purpose Simulation System) and is called GOALS (General Operations and Logistics Simulation). I would like to emphasize that the GOALS model is out of the development stage. It is an operational model, and has been verified against actual Air Force operations.

2.0 Description

The model is designed to evaluate and measure the impacts of various operational plans, logistics concepts, and resource levels (spares, people, etc.) as they apply to operating and supporting a specified number of military aircraft over a desired time span. All these elements or any one, such as resource levels, can be altered to determine the effects on operational effectiveness or life cycle costs. A cost model is an integral part of the overall simulation model, which takes the simulation output and transposes it into dollar values. Life-cycle costs are identified by several elements to provide a clear portrayal of the cost-sensitive elements as variations are introduced to the model.

The baseline model simulated the operations of a wing of B-52G aircraft for periods up to 2 months at a time. This configuration consists of 5000 card images of logic and data in core and data representing about 12000 maintenance tasks stored in an on-line device. One of the unique features of this model is its ability to handle a variable level of detail task data without affecting the logic of the model. The overall model description consists of two essential elements, logic and data, which are further described in the following paragraphs.

2.1 Model Logic

An initial step in running the baseline model required the preparation of a flying and maintenance schedule covering each aircraft over the time span to be simulated. This step is identical to scheduling techniques used in actual military operations. In the model, this schedule is represented by a packed word matrix. Also, the simulation incorporates the numerous tasks and interactions as experienced in real life to provide the personnel, spares, equipment, and other resources to support the overall flying and maintenance schedule.

During the simulation, the preparation phase for flying the aircraft includes the loading of applicable equipment, ground crew and air crew preflight, and accomplishment of those maintenance tasks discovered in the preparation routine. Aircraft are launched and flown on their specified missions, which may include training sorties, airborne alert, or simulated combat training missions of varied durations.

When missions are completed, aircraft are recovered and serviced. Required scheduled and unscheduled maintenance tasks are performed to return the aircraft to a ready status. Specific unscheduled maintenance tasks are determined by detection probabilities applied throughout the simulation cycle. Over 8000 possible on-equipment unscheduled maintenance tasks have been identified and are available for selection based on the probability factor applied. About 40 scheduled events such as preflight, postflight, and 24 phased inspection cycles are performed as required in actual operations.

Both organizational and field-level maintenance tasks can be simulated to varied levels of detail; i.e., one subsystem task or numerous tasks per subsystem dependent on detailed data available. In either case personnel, equipment, and spares and the time required to accomplish the tasks must be defined and placed in the model logistics data bank. During the simulation cycle, these resources are drawn upon to accomplish maintenance tasks. Each of these resources will result in queues if the required quantity is not available. If a required resource is not available, the maintenance task is delayed while other maintenance tasks are started for which resources are available. The manpower aspect is handled dynamically within the model on a shift basis. Personnel are assigned to a shift by speciality type and quantity. The current shift arrangement is 3 shifts per day 5 days a week, and 2 shifts per day over the weekend.

Tasks also queue work areas of the aircraft because of space limitations or task interference. Examples of these restricted work areas are wheel wells, cockpit, and fuselage compartments. Other limits may be imposed on task performance for realistic simulation. For instance, unscheduled maintenance can be restricted during refueling and weapon loading.

In regard to spares support, the following steps may occur during the simulation. If a maintenance task is unscheduled and requires the removal and replacement of a line replaceable unit (LRU), the serviceable unit is withdrawn from supply (if available) and the faulty unit is processed into a repair cycle if repairable. The LRU may be repaired on base and returned to supply stocks. If the spare is beyond the base repair capability, it is sent to a depot for overhaul. Base supply stock is replenished during the simulation. Replenishment item order and shipping time is a variable within the model, and may be structured to show current or desired supply pipeline times. The model can include any number of LRU's desired. The baseline model tracked 1555 LRU's for instance.

If the LRU is not available from base supply, one of several events can take place. The part can be repaired on base and reinstalled on the aircraft, a NORS (not operationally ready-supply) condition can occur and the part placed on priority order, or cannibalization may be accomplished under certain criteria to satisfy the requirement. Also, combinations of these actions can occur. During shop repair of an LRU, repair parts may be required, and repair may be delayed while awaiting parts. All these actions take place during a simulation run based on prior established probability factors and Monte Carlo selections occurring during simulation.

The capability to alter or update the model to new maintenance and operations concepts with ease was a key objective in the development of GOALS. Therefore, logic is constructed in a modular fashion, which permits routines to be removed and replaced individually as necessary. Thus, when a new situation is to be modeled, affected routines can be changed while others remain intact. A library of routines is built to simulate various known concepts, and as new concepts are defined they are programmed and added to the logic library. When a new aircraft is studied the library is searched for the applicable routines to be used, which are assembled in proper sequence to form the logic.

2.2 Input Data

One of the assets of this model is its flexible use of data storage for both organizational and intermediate level aircraft maintenance. In developing the model, steps were taken to simplify the simulation of a new aircraft system by paralleling the various stages of aircraft program development. During early stages of aircraft design, data necessary for simulation can be obtained from comparable systems on existing aircraft. Therefore, a data bank of various aircraft systems is constructed from historical data (AFM 66-1, Navy 3M) and/or an analysis effort, and then drawn on as required to satisfy new simulation requirements. The model is structured so the data input for maintenance tasks can cover a wide range of detail. The minimum number of on-equipment tasks to be simulated per system is one, and the maximum number can extend to the thousands. Shop tasks can be identified to ten levels for each LRU.

The method used to assemble data required for simulation is shown in Figure 1. Maintenance tasks identified to the aircraft system level for various aircraft are stored on disk. The aircraft to be simulated can then be assembled from comparable systems data from the various aircraft. When all the systems (pie segments in the figure) have been joined, the "paper" airplane, for simulation purposes, has been constructed. The applicable logic is then selected and simulation of a new aircraft system can be conducted in the early conceptual and design phase.

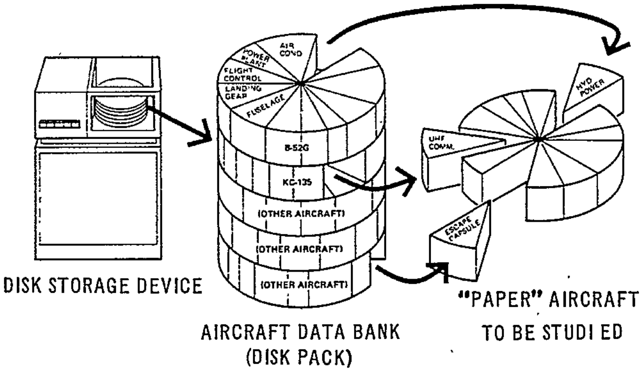

FIGURE 1. GOALS DATA BANK

As the aircraft design progresses and system details are established, the existing data can either be updated or replaced. These changes can be incorporated in small increments, as revisions are possible or necessary.

The primary source of maintenance data used for the baseline model development and validation was the AFM 66-1 (Air Force) data collection system. The baseline model simulates an existing aircraft system (B-52G) for which detailed maintenance data are available. The AFM 66-1 data used covered one year's operation for the entire fleet (189 aircraft) of B-52G aircraft for a total of 110,667 hours flown. These data were considered raw data to the model and came in the form of two flight line tapes, one shop tape, and one bit-and-piece tape.

A processing program was written to read these four tapes and extract the required information. During this processing, those work unit codes (items of aircraft equipment) with fewer than 25 maintenance actions during the reporting period were not included in the detailed input data. They were summarized by aircraft system, however. Processing programs also were used to produce the data files on disk in the required format, while simultaneously creating the cross-reference lists required to satisfy GPSS integer requirements.

Subsystem maintenance tasks are determined by a Monte Carlo selection process from individual functions assigned to each aircraft system. Task probabilities are computed from this same on-equipment data file processing program. This program punches function cards that indicate the probability of occurrence as the abscissa and the task numbers along the ordinate. The probability of task occurrence is computed from the maintenance frequencies derived from the AFM 66-1 data. The resulting functions are the cumulative distribution of all the individual maintenance task frequencies divided by the total hours flown to normalize them to a flight hour.

2.3 Special Features

Space does not permit detailed description of all the special features of this model. However, one is worthy of further comment. In GPSS/360 dynamic allocation of storage contents is not possible, which in turn requires special handling of utilization statistics for personnel.

The personnel utilization normally produced by simulation models does not take into account shift structuring upon the utilization statistics. To simulate the changing number of personnel available from shift to shift, a separate shift structuring subroutine in the model periodically alters a number of "dummy entries" to the personnel quantity indicators (storages) of each skill type. The addition or removal of these dummy entries serves to reduce or increase the remaining capacity of the storage, which in turn is the number of persons of the particular skill type available for the particular shift.

Because the normal GPSS utilization statistic from the model will reflect both dummy and "real" entries to the personnel quantity indicators (storages), the contribution (bias) of the dummy entries has to be discounted. When this is done, a statistic representative of the real utilization by skill type for the simulation period is computed. This is accomplished by subtracting the bias imposed by the dummy entries from both the numerator (average storage contents) and the denominator (storage capacity) of the personnel utilization expression. Therefore,

$$\text{Adjusted Utilization} = \frac{\text{Avg. Storage Contents} - \text{Avg. of the Bias}}{\text{Storage Capacity} - \text{Avg. of the Bias}}$$

Since the GPSS system numerical attribute SR_j (the utilization of storage j) is maintained in parts per thousand, and since the average of the bias, B_j is inputted to the model after multiplication by 100 (to achieve greater significance), the adjusted regular shift utilization (UA_j) for the jth skill code then equals:

$$UA_j = \frac{\frac{SR_j}{1000} * C_j - \frac{B_j}{100}}{C_j - \frac{B_j}{100}}$$

$$UA_j = \frac{SR_j * C_j - 10 * B_j}{1000 * C_j - 10 * B_j}$$

To express the utilization as a percentage (i.e., parts per hundred), the expression becomes,

$$UA_j = \frac{(SR_j * C_j - 10 * B_j) * 10}{100 * C_j - B_j}$$

3.0 Computer Requirements

The GOALS model is written in the IBM GPSS/360 language. The GPSS/360 execution module, DAG05, was modified to contain a help routine used to access maintenance data from disk storage. The help routine has been link edited with DAG05 and is "branched to" rather than "linked to" when it is called. This increased the size of DAG05 by approximately 25K bytes, but at the same time considerably reduced the occupancy time on the computer.

The GPSS/360 language was selected because the potential number of queues in this model was rather large which is ideal for GPSS. Also, the computer availability at Boeing favored a program either on the IBM 360 or CDC 6600 computers. At the time this model was begun there was no adequate simulation language compiler available for the 6600; this left the 360's, of which Boeing had an abundance with large main frames in the Seattle area.

The model uses FORTRAN Help routines to access data during the course of a simulation, prepare easily read output reports, and prepare input data to the cost program. A cost program written in FORTRAN IV produces life cycle cost data, and is an integral part of the GOALS job.

The GOALS model requires a region size of 570K bytes of core, and has been successfully run on IBM 360 models 65, 75, and 67 all with extended core of 1,000K bytes. The model has been executed only on systems with an MVT environment. Because of this, and variable loading of the model (i.e., different sorties flown, etc.) independent computer run times are difficult to estimate.

However, previous jobs yielded the following average run times for a 60-day simulation of one wing of aircraft with a 7-day initialization period:

IBM 360 Model 65		IBM 360 Model 75	
CPU	WAIT	CPU	WAIT
34.7 Min	24.2 Min	25.1 Min	19.5 Min

4.0 Validation

Validation of the model was an important milestone to our management, because if the GOALS model was to be accepted as a research tool, it first must be proven capable of producing correlated results. Previous models constructed either were not validated or no mention of validation was made. This did not instill much confidence in previous models. Consequently, confidence in results was equated to verification.

Actual field experience data previously documented on the B-52G aircraft were used to establish the baseline for validation. Field surveys to SAC bases to collect additional data to compare against the model results were also made. The model was run several times to de-bug subtleties within the logic, and when it appeared there was nothing remaining to de-bug, the results were compared to the field experience data. The results of the comparison produced approximately a 90 percent correlation for all areas. This was an acceptable correlation, and our management considered the model validated.

The GOALS baseline model which was simulating operations and maintenance for one wing of aircraft (15 aircraft) compared very favorably with averages for the entire fleet (189 aircraft). One example of this comparison in the area of subsystem maintenance is shown in Figure 2.

SYSTEM	B-52G ON-EQUIPMENT TASKS PER 1000 FH		B-52G MMH/FH FOR CORRECTIVE MAINT	
	ACTUAL FIELD EXPERIENCE	GOALS BASELINE (RUN NO. 16)	ACTUAL FIELD EXPERIENCE	GOALS BASELINE (RUN NO. 16)
1. AIRFRAME	827	819	2.224	2.241
2. COCKPIT	63	63	0.140	0.130
3. LANDING GEAR	162	156	0.762	0.665
4. FLT CONTROL	105	95	0.472	0.420
5. TURBOJET ENGINES	544	528	2.463	1.304
6. AIR CONDITIONING	40	45	0.183	0.194
7. ELECT. PWR	145	138	0.678	0.577
8. LIGHTING SYSTEM	132	123	0.139	0.156
9. HYD & PNEUMATIC PWR	126	139	0.409	0.400
10. FUEL SYSTEM	89	80	0.598	0.483
11. OXYGEN SYSTEM	29	34	0.101	0.110
12. MISC. UTILITIES	18	22	0.077	0.050
13. INSTRUMENTS	243	202	0.798	0.595
14. AUTO PILOT	50	49	0.309	0.292
15. (BLANK)	–	–	–	–
16. H. F. COMMUNICATIONS	32	27	0.226	0.135
17. UHF COMMUNICATIONS	39	40	0.277	0.258
18. INTERPHONE	30	34	0.088	0.083
19. IFF	9	7	0.071	0.049
20. RADIO NAVIGATION	33	38	0.266	0.233
21. RADAR NAVIGATION	19	20	0.125	0.112
22. BOMBING NAVIGATION	423	446	2.308	2.232
23. FIRE CONTROL	284	268	1.961	2.357
24. WEAPONS DELIVERY	32	37	0.140	0.215
25. ECM	391	375	1.720	1.668
26. PHOTO/RECON	4	6	0.015	0.016
27. EMERG. EQPT	4	8	0.012	0.013
28. DRAG CHUTE	9	11	0.076	0.068
29. AGM EQPT	20	9	0.178	0.048
30. EXPLOSIVE DEVICES	40	40	0.090	0.085
TOTAL	3942	3860	16.894	15.189

FIGURE 2. MAINTENANCE COMPARISON

5.0 Results

Experiments were designed to use the model for evaluating a variety of operational and logistics parameters. These experiments were grouped by general subject heading, and several runs made under each heading to derive the data necessary for the trends to be plotted. Space does not permit discussion of all experimentation accomplished with the GOALS model, but three sets of experiments are summarized as follows:

1) Effects of varied logistics support packages (spares, personnel, and support equipment) on operational availability;

2) Impacts of varied operational concepts on logistics requirements and operational readiness;

3) Benefits of improved reliability and maintainability criteria on logistics requirements and operational availability.

5.1 Variances in Logistics Support Packages

This experiment measured the impact caused by changing the level of resources available to support a constant flying schedule. The maintenance tasks, task times, and reliability criteria were held constant in this simulation series. The changes incorporated in the logistics elements from a cost viewpoint were incremental reductions from the baseline down 33 percent in initial spares, 26 percent in personnel, and 10 percent in support equipment.

As shown in Figure 3, the simultaneous reduction of spares, support equipment, and personnel quantities had the least impact on sortie completion rate (ratio of sorties completed versus scheduled). The operational ready rate was found to be most sensitive dropping 25 percent.

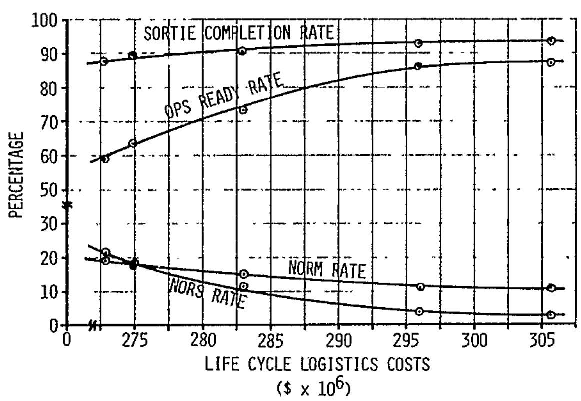

FIGURE 3. OPERATIONAL PERFORMANCE VERSUS SUPPORT COSTS

Also, Figure 3 shows that the reduced availability of resources increased the NORM (not operationally ready-maintenance) rate at a consistent rate from a low of slightly over 10 percent to a high of 19 percent. This increase was caused primarily by the queues that developed on personnel and repair tasks as fewer resources were available.

Decreasing the base spares stockage by 8 percent did not impair supply support. Further decreases in spares did increase the NORS (not operationally ready-supply) rate beyond that of the NORM rate. Translating this to a real world situation means that there are base investments wherein NORS is more important than NORM. Historically, the Air Force has set a 2 to 1 ratio of NORM to NORS rates, and this ratio may have been established in an arbitrary manner.

Figure 4 shows personnel data results from this simulation experiment. The chart reflects the relationship of the number of direct maintenance personnel to the number of times these people were not available to perform a task. For the 100 percent maintenance manning level (B-52G baseline), personnel were not immediately available to perform a required task slightly over 400 times for a total of 532 hours over the 61 days simulated. A decrease in the manning level to the percentages noted increased the total wait times sharply. Reduction in personnel, therefore, without improved reliability or maintainability criteria, or advances in other areas, will degrade the OR (operationally ready) rate because of the increasing queues on personnel resources.

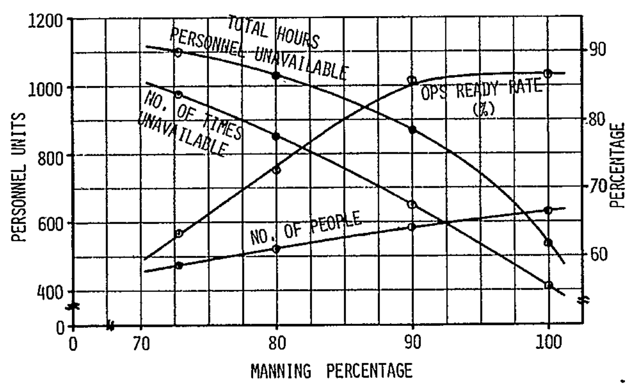

FIGURE 4. PERSONNEL EFFECTS ON SYSTEM PERFORMANCE

5.2 Variances in Operational Concepts

A series of simulation runs was made to evaluate the feasibility of supporting a wide range of operational considerations without changing the availability of logistics resources. For example, an airborne alert operation was simulated with sortie lengths ranging from 6 to 24 hours in duration. A constant number of aircraft flying airborne alerts was maintained, with two aircraft airborne at all times. An advanced bomber system was incorporated in the model to reflect the recovery and turnaround time spans projected for the advanced system. The number of maintenance tasks expected also reflected an advanced system, and the detailed subsystem tasks originally established in the model for the B-52G were retained to provide a realistic maintenance load.

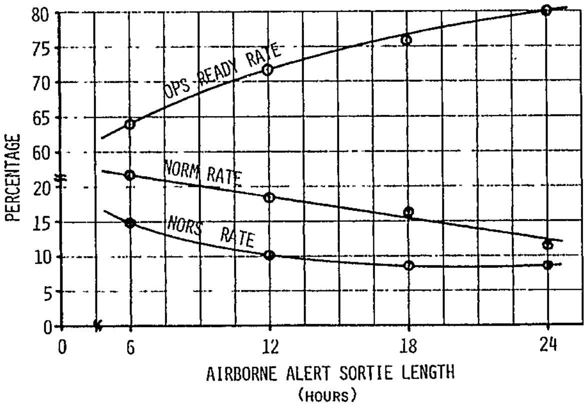

FIGURE 5. SYSTEM PERFORMANCE VERSUS SORTIE LENGTHS

Figure 5 shows the simulation output data for operational readiness, NORM and NORS rate trends as the sortie lengths were reduced from 24 to 6 hours, but with the airborne alert posture maintained constant. The decreasing OR rate is a direct result of the increasing maintenance and spares support required to support a greater number of sorties; i.e., landings and launches. In addition, the output reports revealed the on-equipment tasks increased 14 percent and the spares demands increased 13 percent between the 24-hour and 6-hour sortie. A significant factor was that without changing the logistics resources, the operational requirement for sorties was supported.

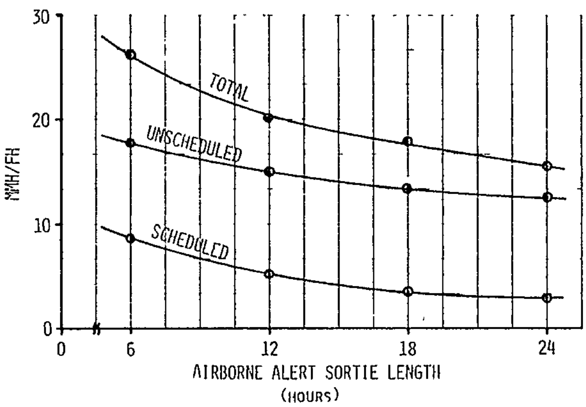

FIGURE 6. INCREASE IN MAINTENANCE TIME RESULTING FROM DECREASE IN SORTIE LENGTHS

Figure 6 shows the impact on MMH/FH (maintenance man-hours per flight hour) as the sortie length decreased, again with the alert posture maintained constant. As a result, total MMH/FH increased about 68 percent between the 24-hour and 6-hour sortie. This was mainly due to the sharper rise in scheduled maintenance requirements because of a greater number of sorties flown. This proves that the MMH/FH, which we are being asked to contract for, is not only a function of aircraft design, but also a function of the manner in which the aircraft are operated.

5.3 Improved Reliability and Maintainability

For several years, improvements in reliability and maintainability factors have been sought as a part of new aircraft programs. Measuring the overall impact of advances achieved or predicted in reliability and maintainability, however, has not been a simple task. The GOALS model has validated a capability for evaluating reliability and maintainability criteria impacts on a number of logistics and cost elements.

	BASELINE RUN	IMPROVED RELIABILITY AND MAINTAINABILITY RUN	PERCENT IMPROVEMENT
SORTIES COMPLETED	136	149	9.55
HOURS FLOWN	1679	1839	9.53
OPERATIONAL READY RATE (%)	81.85	88.46	8.07
NORM	9.90	6.29	36.46
NORS	8.25	5.25	36.36
MMH/FH	27.12	15.79	41.77
CORRECTIVE MMH/FH	16.02	8.74	45.44
UNSCHEDULED MMH/FH	20.59	11.95	41.96
SPARES DEMANDS	2103	1636	22.20
ON-EQUIPMENT TASKS	6875	5213	24.17
TASKS/FH	4.1	2.8	30.79
ABORTS	4	1	75.00
AVERAGE DOWNTIME (HOURS)	22.8	15.5	32.01

FIGURE 7. IMPROVED RELIABILITY AND MAINTAINABILITY RESULTS

Figure 7 shows the percentage improvements gained for major operational and logistics parameters when reliability factors for the B-52G subsystems were improved an average of 23 percent. At the same time, maintainability criteria was improved an average of 30 percent, and servicing task times were improved 55 percent. These improvements reflect feasible state-of-the-art objectives.

TOTAL 10 YEAR PROGRAM COST	%	$
MANNING	6.5	370 M
TRAINING	.5	28 M
SPARES	1.9	107 M
SUPPORT EQUIPMENT	-	2 M
DEPOT	6.0	339 M
AIRCRAFT	1.8	105 M
TOTAL PROGRAM	16.7	951 M

FIGURE 8. TOTAL PROGRAM COST SAVINGS

Figure 8 shows the total program cost savings anticipated by the reliability and maintainability improvements previously mentioned. One wing of aircraft was simulated and then extrapolated to the entire fleet of aircraft to arrive at these program savings. The personnel area indicates the largest cost savings, and represents a reduction in direct maintenance manpower from 645 to 425 people, or a 34 percent reduction. This, in turn, is equivalent to about a 500-man reduction per wing. This example shows the value of performing simulation and trade studies in the development phase of an aircraft system to measure the trend in manpower needs before establishing firm personnel requirements for a new system.

6.0 CONCLUSIONS

Based on the results achieved with the operation of the GOALS model to date, the conclusions reached on the value and application of the program are as follows:

a) The model is a validated simulation tool that can be used to measure the impact on aircraft operations of various availabilities of logistics resources.

b) The model can also be applied to define and measure the impacts on logistics requirements and costs caused by different levels of aircraft flying hours and varied basing concepts.

c) The model can be used to project the results from advances made or proposed in new design concepts.

d) The model can provide trade study data for optimizing the cost effectiveness of logistics investment in relation to operational concepts selected.

An example of a cost-effectiveness study performed with the aid of the GOALS model is shown in Figure 9. The problem addressed was that of finding an optimum or minimum cost system from an operational standpoint.

Total wing costs, excluding RDT&E, may be determined by adding investment costs to life cycle costs. By adding aircraft at a rate to maintain a constant availability, a curve of aircraft investment cost versus operational ready rate may be plotted. The life cycle logistics costs required to support various operational ready rates is also plotted in this figure.

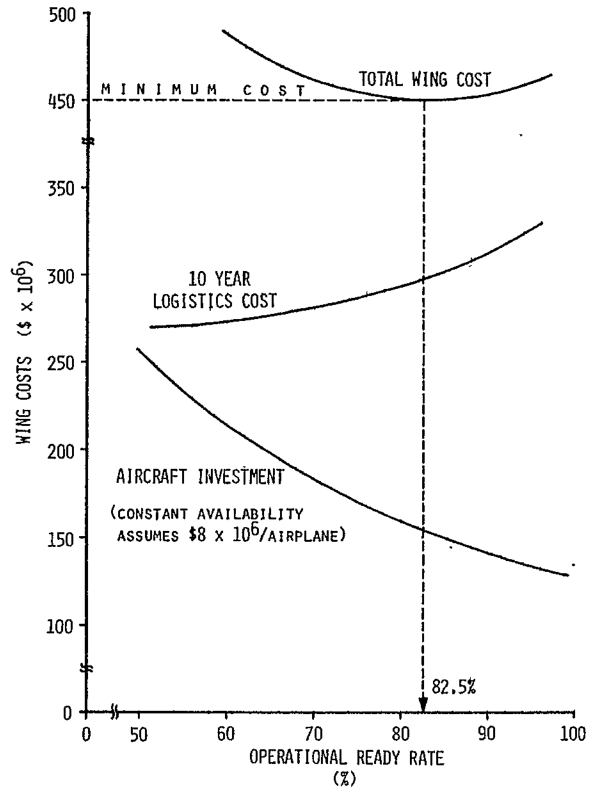

FIGURE 9. OPTIMUM SYSTEM DETERMINATION

The total wing costs curve was determined by adding the aircraft investment and 10-year logistics cost curves together. The resultant shows that there is an optimum (minimum cost) system at 82.5 percent operational ready. Thus for the B-52G, under the conditions simulated, it can be shown that attempting to improve the operational ready rate beyond 82 to 85 percent is not cost effective. This same analysis can be performed on a new aircraft system proposed early enough in the design process to have value in the ultimate design of the logistics system. The GOALS model was designed to accomplish this type of optimization, and this analysis proves that the model can accomplish one of its major design aims.