A STOCHASTIC SIMULATION OF THE STRATEGIC AIRLIFT SYSTEM

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Abstract

The Systems Analysis Office of the Assistant Secretary of Defense has been conducting studies to determine the most efficient strategic mobility system. A large-scale model, Simulation of Airlift Resources (SOAR), has been developed as a tool for analyzing the stochastic variations in the productivity of the airlift system. Programmed as a derivative of GASP, SOAR requires several minutes of computer (IBM 360/65) time per simular day to simulate the activities of up to 1500 flight crews, 700 aircraft, and 100 airbases. Employing statistics from a sequential factorial design, the objective is to determine marginal productivities for alternative strategic airlift systems.

1. THE STRATEGIC MOBILITY PROBLEM

The Systems Analysis Office of the Assistant Secretary of Defense has been conducting studies to determine the most efficient strategic mobility system. Elements of this system, concerned with the intercontinental movement of military personnel and their support equipment, include naval vessels, merchant marine ships, military airlift resources, civilian airlift augmentation, and the strategic prepositioning of personnel and equipment. Prepositioning is included in strategic mobility because its existence may imply a large ton-mileage extant at the start of any major contingency.

Each of these system elements requires sizeable support in terms of fixed installations (e.g., airbases, supply depots, and naval stations) and mobile, flexible resources (e.g., tanker ships, maintenance personnel, and crews) located at strategic sites throughout the Free World. The costs of maintaining each element must then reflect not only procurement costs but also the costs of their support.

Department of Defense decisions regarding the selection from among alternative strategic mobility systems rest upon a clear delineation of anticipated movement requirements: numbers of troops and tonnages of equipment required during successive time periods in a likely confrontation (or a set of simultaneous confrontations) in distant areas of the globe.

The resources available to meet these movement requirements are described in terms of productivities (usually as ton-miles per day) for each requirement. Resource mixes are determined on the basis of productivity-per-dollar ratios (i.e., cost/productivity). Linear programming* is applied in determining the least-cost mix of resources.

Nonetheless, sensitivity analyses revealed the need for more detailed studies of the productivity estimates used in the linear program. Both sealift and airlift productivities depend upon many subsystem variables, the interactions and effects of which are inappropriate for modeling by further linear programs. Thus, stochastic simula-

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* The linear programming model POSTURE is a set of mathematical expressions relating the various airlift, sealift, and prepositioning alternatives for movement requirements. The Research Analysis Corporation (RAC) programmed the model for the Office of Secretary of Defense (Systems Analysis).

tions were prepared for the sealift and airlift subsystems: (1) Simulation for Transportation Analysis and Planning* model (SITAP) and (2) Simulation of Airlift Resources** (SOAR). This paper reports on the application of the SOAR model to evaluate productivities for proposed and existing strategic aircraft by estimating marginal productivities of these aircraft as a function of their support resource levels.

2. THE STRATEGIC AIRLIFT PROBLEM

The strategic airlift system may be viewed as a set of time-phased movement requirements for troops, vehicles, and dry cargo, each constituting a demand for airlift resources. In performing their missions, aircraft move through a network of airbases, advancing from assigned aerial ports of embarkation (APOE), to enroute bases for refueling and flight crew interchanges, to a prescribed aerial port of debarkation (APOD), and returning, usually empty, to the APOE (See Figure 1). Variants in these mission cycles arise from a number of stochastic variables: weather conditions or enroute airbase congestion may force the aircraft to employ alternative routes; cargo weight may permit overflights of certain enroute bases; periodic maintenance requirements may arise and force the aircraft to return to their home bases outside the mission cycle; or, the aircraft may be assigned to a different movement requirement (and, hence, to a different network) in order to ensure the desired "marry-up" of troops and equipment at the contingency areas.

Support facilities at the airbases must include adequate maintenance capability (not only trained personnel but also spare parts and associated ground equipment), fuel storage and dispensing capabilities (trained personnel, refuel hydrants, and tanker trucks), the hard-surfaced parking capacity, a pool of trained flight crews, and the necessary equipment and personnel to support the landing/take-off operations of the base. At APOE's and APOD's, additional facilities include cargo handling capabilities such as loading/offloading crews, associated loading/offloading equipment, and cargo storage and removal capabilities. Any model of the strategic airlift system will of necessity incorporate the means for determining the effects of these airbase resources upon the system efficiency.

3. STRATEGIC AIRLIFT SYSTEM ANALYSIS: THE SIMULATION APPROACH

A useful model of the strategic airlift system requires that both the stochastic demands for support resources and the result of sporadic queueing for the resources (whenever demands exceed the available supplies) be incorporated into its logic. Stochastic demands and queueing are not easily incorporated directly into the logic of analytical models. In addition, an analytical study of the strategic airlift system is further complicated by the fact that airbases employed by strategic aircraft are seldom bases dedicated solely to the support of the airlift operations. Indeed, quite the opposite is true. Strategic aircraft are often regarded as "transients" at intratheater bases, the primary task of which is the support and maintenance of tactical aircraft. Consequently, a model of the strategic airlift system must incorporate competition for parking space and refueling resources at appropriate bases.

The complexity and importance of these factors precluded any attempt to construct a meaningful analytical model of the strategic airlift system. Consequently, the decision to construct a stochastic simulation of the system was made in December 1966.

A joint analyst/military working group was established and initially spent several months becoming familiar with the major aspects of the strategic airlift system. The task of the group, under the direction of the senior author, was to design a model to simulate deployments of up to 90 days and to estimate concomitantly:

(a) airlift productivity (by aircraft type),

(b) aircraft utilization rates (flying hours per day), and

(c) airbase throughput capacities (aircraft departures per day).

Through repeated applications of the model at adjusted resource levels, a fourth goal was to measure marginal productivities as a function of the support resource levels. Marginal productivity analyses of support resource levels are used to determine the cost-effectiveness of service program change requests.

4. ELEMENTS OF THE SOAR MODEL

This initial study revealed an important aspect of the strategic mobility model: its natural parsing into relatively independent modules. For example, the activities at any base were found to be capable of simulation by a subroutine which diminished base resource attributes as required by arriving aircraft's support requirement attributes. Thus, one module of the overall model was structured to handle only those ground acti-

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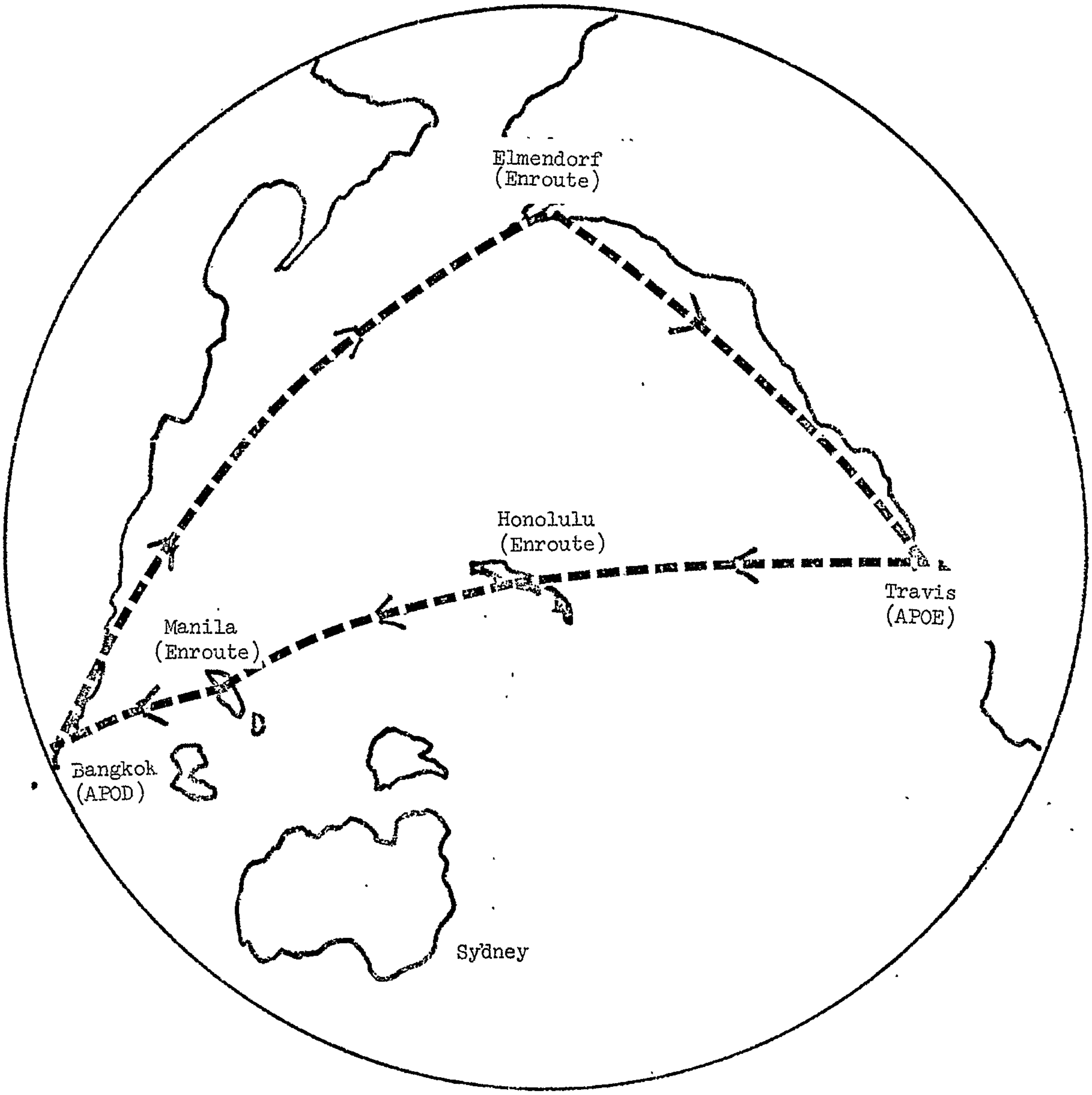
* Simulator for Transportation and Analysis (SITAP), Computer System Manual CSM SD 70-68, (National Military Command System Support Center, Washington, D. C., 1968).

** Simulation of Airlift Resources (SOAR), Under Contract DAHC 15 67 CO 187 (Planning Research Corporation, Washington, D. C., 1968).

Figure 1

Typical Strategic Airlift Mission



vities pertinent to the landing, servicing, and dispatching of any aircraft at any base, be it APOE, APOD, home base, or enroute station. This module was also designed to be useful as a separate model for simulating the activities of "ghost" aircraft. An example of ghost aircraft would be a C-130 (tactical aircraft) with home base at an APOD in the strategic airlift system. Thus, a by-product of the development of SOAR was a model for use in determining throughput capacities at any parameterized base. This type of useful logic parsing has not always evolved in the authors' previous experiences with simulation models.

In large-scale simulations, activities require varied lengths of time for their completion. Study of the strategic airlift system disclosed that the appropriate unit of simular time should be one minute. Only in one instance was a shorter unit considered desirable: the time required for the seizure of runways, usually 25-30 seconds. But, since the time of aircraft arrivals at bases could hardly be estimated with greater accuracy, the one-minute interval was selected. However, in order to permit two aircraft to employ any given runway within the same minute, the status of each runway was specified as an airbase attribute which maintained the time at which the runway was last in use; a negative sign on this attribute indicated that the second half of the specified minute was available for an arriving (or departing) aircraft's seizure of the runway.

The selection of the minute as the elementary unit was based upon the activities of the following entities which were critical to the successful simulation of the strategic airlift system:

(a) aircraft,

(b) flight crews,

(c) air bases,

(d) movement requirements.

Arrays were of course necessary for the recording of the attributes of these entities.

A number of additional arrays were used to maintain the parametric information for describing the strategic airlift system:

(a) networks of airbases and connecting legs,

(b) leg parameters, such as fuel requirements and flight times for each aircraft type,

(c) preferred routes for aircraft assigned to carry cargoes of specified weights through specific networks,

(d) aircraft type specifications, such as fuel consumption rate,

(e) maintenance and repair histograms, and,

(f) flight crew and scheduled maintenance policy parameters.

These additional arrays did not qualify as entities, since their elements (attributes) are not altered as a result of simulation activities.

As listed in Table 1, the magnitude of the SOAR program is reflected by the sizes of the entities and arrays employed in the initial design. Though the list of entities and arrays is not lengthy, model complexity is probably best measured by the relatively large number of attributes and array elements (columns).

The table of routes constitutes a quasi-entity in the SOAR model in that they might have been considered either as dynamic arrays or as attributes within the aircraft entities. More specifically, a desired feature of the model was to permit stochastic weather conditions to alter the prescribed route for an aircraft assigned to a payload of a given weight and destined for a specified APOD from a stipulated APOE. Thus, routes could have been indicated as a set of entities to which new entities could be added whenever route alterations were required. In this event, only one or two aircraft attributes would be necessary to indicate the aircraft's route. The selection of the alternative procedure of maintaining the aircraft's current route, as well as a separate and fixed table of preferred routes, was largely based on the availability of software at the time of the programming.

5. SELECTION OF THE GASP LANGUAGE

Candidates for computers and languages in mid-1967 were restricted to the IBM 7094 (GASP, GPSS, SIMSCRIPT I), the IBM 360/50 (GASP), and the CDC 6600 (GPSS, SIMSCRIPT I). Certain hardware/software combinations, such as IBM 360/GPSS and IBM 360/SIMSCRIPT, were then in various stages of development; others were not readily accessible to the Department of Defense agencies which would use the completed model. The attractiveness of newly increased computer speeds and the doubtful eventuality of larger random-access memories led to the elimination of the IBM 7094. The selection of the IBM 360/GASP combination was then predicted on the likelihood of this computer's augmented core storage capability. Further, the assumption was made that future analysts, requesting alterations in the SOAR program, would know FORTRAN (GASP is a collection of FORTRAN subroutines.) but not special-purpose simulation languages.(1)

Consultations with contracted programmers revealed the need, however, to modify the GASP language. The resulting GASP derivative was then

TABLE 1. SOAR ENTITIES AND ARRAYS

Entities

	Number	Attributes
Individual Aircraft	500*	35
Individual Flight Crews	900**	10
Airbases	100	162
Movement Requirements	20***	10

Arrays

	Number (or rows)	Columns
Networks	300	70
Legs	2000	4
Preferred Routes	1820	14
Aircraft Types	20	12
Histograms	400	10
Policy Parameters	50	5

* Currently at 700

** Currently at 1500

*** Soon to be augmented to 40.

compiled on the IBM 360/50; and the SOAR activity subroutines, written in FORTRAN IV/H, were programmed and added to the GASP routines.

As indicated previously, the selection of the GASP language led to the decision that routes be considered as tables, not entities, since this language did not readily provide a dynamic storage allocation capability.

6. EFFECTS OF DATA AVAILABILITY ON MODEL DESIGN

The simular effects of weather, from which the quasi-entity status of the routes arose, gave rise to another special problem. Hourly observations of ceiling, visibility, and crosswind strengths are available for a number of years at most of the airbases in the Free World. Any statistical analysis of these data, however, may have led to either or both of the following undesirable phenomena:

(a) successive random selections of weather conditions from a frequency histogram for a given base may produce substantially unusual weather patterns for the base, and

(b) concomitant random selection for bases relatively near one another would not be expected to provide the relative compatibility one would anticipate in their weather conditions.

Consequently, weather conditions were selected from a merged record of weather observations at the bases in the deployment scenario. All observations for a given hour were those recorded at the same (Greenwich Mean) time during some representative year. Randomness of weather data for the model is then ensured by the random selection of a starting point in the recorded weather data.

Though the collection and use of weather data was an issue easily resolved, other data requirements and availabilities led to some program alterations. Of particular importance was the effect of data availability on the design concepts surrounding maintenance requirements for aircraft and the application of maintenance resources to these requirements. Currently, it is quite difficult to ascertain whether maintenance requirements for strategic mobility aircraft are best described as a function of (1).

the number of landings; (2) the number of flying hours between maintenance activities; or (3) the base at which the aircraft is located. Even now, after having selected the "renewal"* process as a model for aircraft maintenance requirements, we are convinced that a thorough analysis of the maintenance data collection procedures and a significant study of the mechanisms determining aircraft malfunction is of vital importance to the analysis of the strategic airlift system.

7. MAN AND MACHINE REQUIREMENTS

The model logic was based upon discussions with appropriate military agencies for a 7 to 8-month period. The programming required the assistance of four experienced FORTRAN programmers for approximately 4 months. One of the programmers has been retained to assist both in improving the model and in assuring model operation in an environment of fluctuating computer operating systems.

A registry reveals that over 500 hours of IBM 360/50 and 360/65 computer time was required during the testing and programming. Each simular day, in a scenario involving the entire strategic airlift fleet, requires approximately 3 to 4 minutes of IBM 360/65 Central Processor time. Except for the terminal report generation subroutine, the program appears to be "compute-bound" (i.e., constrained by the calculation capability of the Central Processor).

8. MODEL ENCOUNTERS AND EXPERIMENTATION

Once the SOAR model had been programmed and tested with data representing the deployment of forces to a typical contingency scenario, major contingency scenarios, compatible with those employed in the linear program used to solve the more general strategic mobility problem in which aircraft compete for preference with naval vessels and prepositioned equipment, were defined. The data requirement for these worldwide scenarios delayed the projected target date of the simulation analysis. Nonetheless, the basic philosophy of experimentation with the model remained unaltered.

Each specification of SOAR input data (including random number seeds) defines a run of the model, or an encounter with the simulated environment. In order to ensure that the random effects of the model could be accurately measured, the model design incorporated the feature of permitting the model to restart with the same input data save the random number seeds (Though the random number seeds could be redefined for the subsequent encounter).

However, this approach was abandoned in the initial analyses in favor of an approach using intentionally confounded experimental design factors. Airlift productivity and utilization rate are functions of variables defining the scenario: route structures, numbers of aircraft, numbers of movements requirements, flight crews, and the many airbase support resources. By systematically altering subsets of these variables from their current levels (or predicted levels) to feasible augmented levels, estimates of the marginal productivities are provided by differences in the results of successive model encounters.

9. ANALYSIS OF OUTPUT DATA

A rather large number of variables are represented in the SOAR model. Determining the effect of each variable on productivity and utilization rate by a SOAR encounter for every combination of variables is infeasible because the number of combinations becomes exceedingly large. Instead, the effects of variables on productivity and utilization rates were estimated by using a somewhat heuristic, though analytical, technique. Analysis began by aggregating the variables in the system into 3 inclusive categories which were assessed to be the major determinants of airlift productivity and utilization rate. The three categories of variables were weather, cargo handling resources at the airbases, and all other resources at the airbases. Secondly, a 2^3 factorial design** was employed to determine the individual effects of the 3 categories of variables on their dependent variable, productivity.

For the first two encounters, all airbase resources were maintained at current levels and weather was varied between winter and summer. Each encounter begins weather conditions randomly within a season; in addition, seasonal winds may change aircraft "legs"***. Also, an increased frequency of bad weather may keep aircraft from flying and thus significantly affect aircraft productivity.

The second pair of encounters augmented all airbase resources by a fixed percentage. The two encounters were then: (1) augmented airbase resources under winter weather conditions; (2) augmented airbase resources under summer weather conditions.

Airbase resources were then divided into the two categories: cargo handling resources, and all other airbase resources. Airbase resources for cargo handling were augmented by a fixed per-

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* A renewal process is the repair of parts only upon actual failure, the repair constituting the equivalent of parts renewal.(2)

** $2^3 = 8$, the number of possible permutations of two levels of each of the three categories of variables.

*** For each aircraft type, inputs establish preferred winter routes and summer routes.

centage, and one encounter was simulated under winter weather conditions and one under summer weather conditions. Then, airbase resources for cargo handling were returned to their initial levels and all other airbase resources were augmented by the fixed percentage. Encounters for the augmented non-cargo resources were derived under winter weather conditions and then under summer weather conditions. Using zeroes to represent either winter weather conditions or current resource levels and ones to represent either summer weather conditions or augmented resource levels, Table 2 shows the 8 encounters, with productivities in ton-miles per aircraft-day and utilization rates in hours per aircraft-day, appropriately coded.

Applying the standard analysis of variance technique to the eight observations on utilization rate led to the results tabulated in Table 3.

Assuming that the sum of squares for interactions is an estimate of residual error, the analysis of variance reveals that weather and non-cargo airbase resources seem to contribute significantly to strategic airlift utilization rate whereas the effect of cargo-handling resources is insignificant. The standard F tests show that both weather and non-cargo resources are statistically highly significant (at the 0.01 level). We note in passing that these same results obtain in the analysis of variance for the productivity figures.

Results from our 2^3 factorial experimental design indicate that further experimentation should focus on the resources making up the category of non-cargo handling resources. Also, since weather conditions seem to be a significant contributor to productivity, it was decided to continue contrasting summer and winter weather conditions to determine more definitively the extent of their effect.

The non-cargo airbase resources were categorized either into runway and parking space resources, or into refueling and maintenance resources. Four additional encounters of the model were defined: (1) runway and parking resources augmented under both winter and summer weather conditions while refueling and maintenance resources were held at the "sunk cost" level; and, (2) vice-versa, under both winter and summer conditions.

The runway and parking spaces resources and the refueling and maintenance resources had already been simulated whenever the levels of the variables in the two categories had been compatible. Therefore, only the four additional encounters were needed: each new category of resources was simulated at its augmented level with the other category remaining at its standard level under both winter and summer weather conditions.

Table 4 shows the results of the encounters from Table 2 (Encounters 1, 2, 5, and 6) and the

TABLE 2. EIGHT (2^3) MODEL ENCOUNTERS FOR ANALYSIS OF WEATHER, CARGO-HANDLING RESOURCES, AND OTHER AIRBASE RESOURCES

		Airbase Resources			
Encounter (E)	Weather	Cargo-handling Resources	All Other Airbase Resources	Productivity (ton-miles/day)	Utilization Rate (flying hrs/day)
1	0	0	0	108.78	9.14
2	1	0	0	118.86	9.74
3	0	1	1	117.74	9.87
4	1	1	1	123.76	10.14
5	0	0	1	119.42	9.68
6	1	0	1	122.50	10.07
7	0	1	0	110.53	9.20
8	1	1	0	116.74	9.42

TABLE 3. ANALYSIS OF VARIANCE FOR 2^3 FACTORIAL EXPERIMENTAL DESIGN

Variable Category	Degrees of Freedom	Mean Square	F-value
Weather	1	0.325	23.21**
Cargo-handling Resources	1	0.002	.14
Non-cargo Resources	1	0.585	41.71**
Interactions	4	0.014	-

additional 4 encounters. Both productivities and utilization rates are tabulated, again appropriately coded.

The encounters employing cargo-handling resources at augmented levels were encounters number 3, 4, 7 and 8 (cf: Table 2).

Table 5 summarizes the analysis for the utilization rate estimates.

TABLE 4. EIGHT (2^3) MODEL ENCOUNTERS FOR ANALYSIS OF NON-CARGO AIRBASE RESOURCES

Encounter (E)	Weather	Other Airbase Resources Runway/Parking	Other Airbase Resources Refueling/Maintenance	Productivity (ton-miles/day)	Utilization Rate (flying hrs./day)
1	0	0	0	108.78	9.14
2	1	0	0	118.86	9.74
5	0	1	1	119.42	9.68
6	1	1	1	122.50	10.07
9	0	0	1	110.21	9.16
10	1	0	1	116.74	9.42
11	0	1	0	118.48	9.72
12	1	1	0	117.82	9.50

TABLE 5. ANALYSIS OF VARIANCE FOR SECOND 2^3 FACTORIAL DESIGN

Effect	Degree of Freedom	Mean Square	F-value
Weather	1	0.134	1.91
Runway/Parking	1	0.287	4.09
Refueling/Maintenance	1	0.001	0.014
Interaction (Residual)	4	0.070	

Though the effects of resource augmentations do not appear statistically significant in this analysis, the increase in runway/parking capabilities seems to be producing the corresponding change in aircraft utilization rates. Of especial interest was the result that the augmentation of refueling/maintenance resources throughout the scenario did not appear to affect the utilization rate significantly.

For this reason, our subsequent analyses centered about experimental designs in which the amount of competing aircraft traffic in the networks was varied. An additional variable was considered, that of the flight crew availability. This analysis, performed in a manner analogous to that precedent, revealed that the first of these factors was indeed statistically significant in the determination of aircraft utilization rates.

Presently, further experiments are being conducted to determine the relative contribution of other factors to airlift productivity. Problem formulations are being developed and model encounters defined for other potential contingency theatres as well.

10. VALIDITY AND UTILITY OF RESULTS

The simulation results seems reasonable and in concordance with estimates of aircraft productivities and utilization rates from other studies. Due to the difficulty of establishing a deterministic encounter, from which a validation run could be made and for which output information would be absolutely predictable, model validation was established by relying on the results of initial testing and debugging runs, as well as on the continuing check of the reasonableness of the outputs.

The simulation analysis has proved useful to both military planners and analysts by providing greater insight into the major factors affecting the strategic airlift system. Consequently, a number of important strategic airlift planning factors are being updated (i.e., new probable ranges are being established). In addition, it is anticipated that the military services will use this analysis (as well as continuations of the analysis) in supporting their program change requests as submitted to the Office of the Secretary of Defense.

The primary use of the SOAR model, however, will be in determining alternative allocations of resources in the strategic airlift system -- allocations which permit operational flexibility yet which maximize airlift productivity. The accomplishment of this goal will enable airlift to be evaluated more rationally in making comparisons with the productivities of the other major elements of the strategic mobility system: sealift and prepositioning.

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BIOGRAPHICAL SKETCHES

Dr. G. Arthur Mihram was the designer of the SOAR model during his two-year tenure with the Office of the Special Assistant for Strategic Mobility, Organization of the Joint Chiefs of Staff. His continued association, that of designing the simulation experiments reported herein, was maintained via Contract Number USAF: F44-620-69-C00005 with the University City Science Center, Philadelphia, for whom he is a part-time consultant while conducting courses and research in his primary capacity as a member of the Faculty of the University of Pennsylvania. His current interests include operations research, reliability studies, random processes, and stochastic simulation. Publications of Dr. Mihram have appeared in the *Journal of the American Statistical Association*, *Technometrics*, *Sankhyā: The Indian Journal of Statistics*, and the *I.E.E.E. Transactions on Reliability*.

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