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PRODUCTIVITY ESTIMATES OF THE STRATEGIC AIRLIFT SYSTEM BY THE USE OF SIMULATION

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ABSTRACT

Although the strategic airlift system is under continuous analysis, C-5A problems provided impetus to analyze the airlift system productivity function by using a large-scale simulation model. Development of the simulation model (Simulation of Airlift Resources—SOAR) was initiated by the Office of Secretary of Defense (Systems Analysis) in 1966. SOAR had barely become operational in time for the study in November 1968.

Since limited verification and validation tests had been performed on the simulation model, the design of experiments was of critical importance. The experimental design had to be flexible enough to salvage the maximum amount of information possible upon the discovery of either a verification or validation error. In addition, the experimental design was required to accommodate the estimation of a large number of possibly changing independent variables.

The experimental design developed for the analysis was full factorial design sets for a finite number of factors. Initial analysis began with aggregated sets of factors at two levels, and information gained from experiment execution was used to parse the sets. The process was sequential and parsing continued until the major explanatory independent variables were identified or enough information was obtained to eliminate the factor from further direct analysis. This design permitted the overlapping of simulation runs to fill out the factorial design sets.

In addition to estimating the airlift productivity function several other findings are reported which tended to disprove previous assumptions about the nature of the strategic airlift system.

PRODUCTIVITY ESTIMATES OF THE STRATEGIC AIRLIFT SYSTEM USING SIMULATION

Computer simulation was used in a recent Department of Defense study designed to evaluate the impact of strategic airlift system characteristics on the productivity of the military airlift system.* Although the system is under continuous analysis, budgetary pressures and adverse reaction to the C-5A cost increases prompted the formation of a joint OSD/Air Force study group to evaluate a proposal

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*The Mobility Forces Division of Systems Analysis in the Office of the Secretary of Defense performed the analysis with Headquarters, United States Air Force.

The simulation analysis of the strategic airlift system is one component of an optimization/simulation framework for the analysis of strategic mobility. For a description of the framework see R. L. Nolan and M. G. Sovereign, "A Recursive Optimization and Simulation Approach to Analysis with an Application to Transportation Systems," Management Science (August 1972). For a description of the simulation analysis of the strategic sealift component, see R. L. Nolan and M. G. Sovereign, "Simulation of the Strategic Sealift System," *Proceedings of 1971 Summer Computer Simulation Conference*, pp. 1184–1191.

to reduce procurement of the controversial Lockheed transport aircraft. The hypothesis had been made that with a marked increase in the daily utilization rate (i.e., flying hours per day) of aircraft in the transport force, wartime deployment capability could be maintained at the required level with significantly fewer C–5As. A controversy developed over the feasibility of operating the military aircraft force at the proposed higher utilization rate under conditions of a wartime rapid deployment. Of particular concern was the uncertainty over the potential contribution to higher utilization rates of increases in airlift support resources. Previous tests and analytical efforts to determine feasible utilization rates were inconclusive in resolving the question of increased resources or in supporting or rejecting the hypothesis.

A useful analysis of utilization rates, and its derivative productivity, must consider not only the factors affecting utilization rates, but factor interactions and combined impact on the airlift system. Because of the number of variables and the complexity of the system, simulation emerged as the most appropriate method of analysis. In 1966 the Office of Assistant Secretary of Defense (Systems Analysis) had initiated the development of several computer models to aid strategic mobility planning and analysis. One of these models was a Simulation of Airlift Resources (SOAR), a computer simulation of intertheather airlift operations under conditions of rapid deployment which had been designed and developed within the Office of Joint Chiefs of Staff (SASM).†

The complexity of the system and the decision to use simulation posed two different problems in the design of the analysis:

1. Model verification and validation.
2. Experimental design.

The proper resolution of both problems is key to developing useful conclusions. Complete verification of a large simulation model such as SOAR is almost impossible. Validation in the sense of testing the "goodness of fit" of the model with real world data was infeasible for the following reasons:

1. SOAR is one of the largest computer simulations designed.
2. The strategic airlift system has never been exercised in an intertheater rapid deployment.
3. Data from previous exercises of the strategic airlift system are (a) incomplete, and (b) obsolete.
4. Field test data on parts of the system are difficult to interpret because they were not collected for the purposes at hand, as well as the fact that environmental conditions are rarely controlled in such tests.

The task of verification and validation was redefined within the constraints outlined. The objective of the "verification and validation" process is to develop a "threshold of confidence," which can be conveyed to decisionmakers, that the model is a sufficient abstraction of reality to be used as a basis for decisions. A number of techniques are available for building this level of confidence. One of the most important was the involvement of operations managers in the design of the model and interpretation of model-generated results. In addition, statistical analysis of the model results provided a measure of consistency and inherent variability in the model itself.*

† Office of the Joint Chiefs of Staff (Special Assistant for Strategic Mobility).

* Naylor and Finger together with a critique by McKenney state the validation problem and summarize the approaches to it. See Thomas H. Naylor and J. M. Finger, "Verification of Computer Simulation Models," *Management Science* (October 1967), and James L. McKenney, "Critique of Verification of Computer Simulation Models" in the same issue.

SOAR Model

SOAR is programmed by using a derivative of the GASP simulation language, which is, in turn, a derivative of FORTRAN. It can simulate up to 1,000 aircraft, 100 airbases, and 1,500 air crews. Approximately 6 to 7 minutes of computer (IBM 360/65) time are required to simulate the activities of 1 day.

In SOAR the important categories of variables in the strategic airlift system are represented. Air traffic density is a function of the number of mission aircraft (C-141 and C-5A) and the competing aircraft (Civil Reserve Air Fleet (CRAF), tactical airlift, fighters, reconnaissance). Weather effect is simulated by specifying the effect of seasonal enroute winds on leg flying time, fuel requirements and allowable cabin load. In addition, hourly weather observations for each base in the simulation can close a base when conditions of ceiling, visibility, or crosswind dictate. All base resources, comprising a third category of resources, are treated in detail. This category includes the personnel and equipment for cargo handling, maintenance, and refueling, aircrews, parking space, and airfield acceptance data. Airfield acceptance data specify base IFR (Instrument Flying Rules) minima and the number of aircraft per hour which can be managed by approach and landing controllers. A fourth category of variables addressed by the computer model includes those aircraft characteristics (e.g., speed, fuel consumption rates, parking "shadow") which impact system performance. Other system characteristics which may have an effect such as crew staging policies, routing policies, scheduled maintenance policies, and warning time are addressed both in problem formulation and in ordering of input data.

Each aircraft to be simulated is located at a specific base and given a starting time. The cargo to be moved is identified by weight and its location at bases. The effect of cargo density is described by a cumulative frequency distribution which essentially describes the probability of a C-5A or a C-141 being loaded at a given weight. Levels of maintenance, refueling, cargo handling, and aircrew capability are specified for each base. With the scenario and system defined, initialization is begun.

During initialization, the input data are checked for internal consistency and completeness, and the random number generator is used to establish the initial values of those aircraft, aircrew and resource attributes which are stochastic in nature. Following these actions, the simulation is ready to begin.

In SOAR, there are four types of bases (home, onload, enroute, and offload), and at each base are located resources consistent with its function. For instance, at onload and offload bases there can be found aerial port crews needed to process cargo; at home bases, a large pool of aircrews and the facilities necessary for all maintenance short of depot-level; at all bases, of course, are parking spaces, transient maintenance and fuel. The simulation begins with each aircraft at its home base. There the aircraft is checked to ascertain that it has no maintenance problems, an aircrew is ready, and adequate fuel is aboard. If weather permits, the aircraft departs for the airfield that has the highest priority cargo awaiting pick-up. On the aircraft's arrival at the onload base, the model selects the route to be taken from this onload base to the cargo destination (offload base). The route selection is based on factors, such as weight of the cargo, fuel requirements, weather, and the availability of resources at the bases in the several candidate route networks. With the route selected and the cargo now placed aboard, a check is made to assure that the aircraft is still operationally ready in terms of maintenance, aircrew, and fuel. Deficiencies are corrected, and the aircraft departs on its next leg weather permitting.

The procedure is repeated as the aircraft moves through its enroute bases and arrives at the delivery point. After cargo is offloaded, the model determines which onload base has an appropriate load of cargo to be picked up by this aircraft. Again necessary maintenance and fuel servicing is performed, a rested aircrew replaces the one aboard if required, a weather check is performed and the aircraft departs for its next onload base to recommence the cycle.

As an aircraft moves through the airlift system, from home to onload through a series of enroute bases and finally to offload, it makes demands on the resources available at these bases. Where demands exceed the capability of the bases to meet them, queues form adding to ground time reflecting the penalties resulting from system saturation. Some of the demands are deterministic; aircrews are replaced if duty time will exceed 18 hours, fuel requirements are based on flying time and fuel consumption rates, and the parking area used is the result of "parking shadow" of the aircraft itself.

Other demands are stochastic: maintenance failures are generated randomly from a distribution as a maintenance man-hours required to repair the failure, the routes themselves are selected by the random process which determines the weight of the cargo loaded on each aircraft. Still others are a combination in which a random number generation selects an entry value in a table which then is processed in a deterministic manner.

However arrived at, it is these demands and the ability of supporting systems to satisfy them which are key elements of the airlift simulation. Since only the lack of one or more of the essential resources will hold aircraft on the ground, SOAR is well designed for the evaluation of the impact of changing levels of system resources and demands on aircraft utilization rates.

Design of the Experiments

SOAR is typical of the large-scale simulation model. It consists of many instructions, complex logic, and is expensive to run. Eventually, the model grows beyond the ability of the analyst to comprehend all of the interactions between the components. Hunter and Naylor* suggest the use of a two-stage experimental design for analysis on the large scale simulation model. The first stage can be termed exploratory. The exploratory stage is intended to discover the major contributing independent variables to the response, or dependent variable. Techniques such as factorial analysis are especially useful along with other tools such as regression analysis, analysis of variance, and linear mathematical models. The exploratory stage is followed by an optimization stage which is intended to optimize the response variable, or at least improve it, by adjusting the controllable independent variables.

The experimental design reported in this paper focuses on the exploratory stage. The response variable is aircraft utilization and aircraft productivity, each defined for the C-5A and C-141. In general the response variables (Y) are a function of the factors (X_i),† that is

$$Y = f(X_1, X_2, \ldots, X_{23}),$$

* J. S. Hunter and Thomas H. Naylor, "Experimental Design," in Thomas H. Naylor, editor, *The Design of Computer Simulation Experiments* (Durham, North Carolina: Duke University Press, 1969), pp. 39-58. Much has been written in general on experimental design techniques. See for example, D. R. Cox, *Planning of Experiments* (New York: John Wiley and Sons, 1961), W. Mendenhall, *Introduction to Linear Models and the Design and Analysis of Experiments* (Belmont, California: Wadsworth Publishing Company, 1968), and Ken Chen Peng, *The Design Analysis of Experiments* (Reading, Mass.: Addison, Wesley, 1967). Only relatively recently have the design of experiments for computer simulation experiments been discussed in the literature. The special problems are focused around the expense of making large scale computer simulation experiments and the model verification/validation problem.

† Since the analyst may only set levels of controlled variables, the response is characterized as a function of the controlled variables.

where the X_i are the variables listed in Table 1. For any given computer run the variables take on specific values x_i:

$$X_1 = x_1, X_2 = x_2, \ldots, X_{23} = x_{23}.$$

TABLE 1. *SOAR Model Variables*

Variable number	Variable description
1	Mission aircraft
2	Competing aircraft—other tactical aircraft, fighters, etc.
3	Personnel for cargo handling
4	Equipment for cargo handling
5	Maintenance personnel
6	Maintenance equipment
7	Refueling personnel
8	Refueling equipment
9	Air crews
10	Aircraft parking space at a base
11	Airfield capacity
12	Weather data—including the effects of seasonal enroute winds, fuel requirements, allowable cabin load
13	Hourly weather data about the conditions at a particular base
14	Aircraft speed
15	Aircraft fuel consumption
16	Aircraft parking-landing requirements
17	Aircraft maintenance data
18	Crew staging policies at bases
19	Routes and routing policies
20	Scheduled maintenance policy
21	System alert warning time
22	Airbase locations and descriptions
23	Other miscellaneous data

These factors may be considered the independent variables. Indeed, the factors may not be truly independent; their values may be altogether constrained by some other limiting function (i.e., total resources, or an annual budget). Nevertheless in the exploratory stage, the analyst usually accepts the independency assumption and then challenges it with the benefit of more information in the optimization stage. In the optimization stage, appropriate constraints can be employed for searching to define explicitly the experimental region.

In the initial exploratory stage with a model like SOAR, the number of computer runs can cost a prohibitive amount. An experimental design is required that will provide information on all the variables of main interest, but can be executed to unfold successively more information about the more significant variables. The factorial experiment can be used to do this.

The first step in the design of the SOAR experiments was to eliminate from consideration variables of indirect interest, or variables that could be analyzed by use of other means. "System alert time" and "miscellaneous data" were thereby eliminated leaving 21 variables to be considered. The second step was to decide on the levels to be assigned to the variables. For exploratory purposes, each variable was assigned a base or normative level and an augmented level except for the aircrew variable which was assigned a base level and a decremented level. Each combination of variable levels produced a design point. A full factorial experiment requires computer runs for each design point. Enough information is provided to determine the effects of changing the level of each variable and the effects of variable interactions. However, the information advantage in the SOAR analysis of the full factorial was clearly offset, and infeasible, by the cost of making the computer runs to satisfy the full factorial design. The number of runs included in a full factorial experiment with 21 variables each at two levels is 2^{21}, or 2,097,152.

Two alternatives to the full factorial experiment were examined: fractional factorial, and factor aggregation. The fractional factorial experiment is to make computer runs on a subset of the runs required for a full factorial. The analyst selects a sequence of runs with the factors at various base and augmented levels. Although the problem of factor choice during an experiment is well documented in the literature,* it poses a difficult problem for the analyst at the outset. Thus, it was decided to employ a factor aggregation method.

The factor aggregation method is to group similar variables which are then all set at base levels or augmented levels during any one run. A full factorial experiment is run using these variables groupings as if they were variables themselves. In the SOAR analysis, variables were initially grouped into three categories and full factorial experiments were satisfied. Figure 1 illustrates the general design set. The zero (0) entry indicates the base level and a (1) entry indicates the changed level.

In Figure 2, the same design is shown with the actual variables and levels of a specific case substituted for the general notation. Weather is Variable One, with winter weather representing the (0) entry and summer weather the (1) entry. Variable Two is now All Resources, with (0) being the "base case" and (1) the changed (augmented) case. Variable Three is Air Traffic. In the base case (0 level),

Encounter	Variable One	Variable Two	Variable Three
1	0	0	0
2	1	0	0
3	0	1	0
4	1	1	0
5	0	0	1
6	1	0	1
7	0	1	1
8	1	1	1

FIGURE 1. General Design Set

Encounter	Weather	All Resources	Traffic
1	Winter	Base level	MAC+CRAF
2	Summer	Base level	MAC+CRAF
3	Winter	Augment 50%	MAC+CRAF
4	Summer	Augment 50%	MAC+CRAF
5	Winter	Base level	MAC+CRAF+TAC
6	Summer	Base level	MAC+CRAF+TAC
7	Winter	Augment 50%	MAC+CRAF+TAC
8	Summer	Augment 50%	MAC+CRAF+TAC

FIGURE 2. Typical Experimental Design Set

*John L. Overholt, "Factor Selection," in Thomas H. Naylor, editor, *op. cit.*, pp. 59–79.

only CRAF airframes compete with mission aircraft for resources; in the augmented case (1 level), TAC (Tactical Air Command) activity is added to the MAC (Military Air Command) and CRAF traffic.

The impact of the categories, or independent variables, on the dependent variable, either aircraft utilization rate or productivity, was assessed by applying a standard analysis of variance technique. Three factor analysis of variance with interactions shows the statistical significance of the change in resource level and the effect of factor interaction.

The statistical analysis of the 2^3 factorial experiment* is used to determine whether further experimental analysis of a category is warranted. If a category is statistically significant, a second experimental design is then formulated to test that category again with other categories. Alternatively, the category may be parsed into two or more less aggregated variables in order to discover the actual variables that are contributing to the dependent variable. On the other hand, statistically insignificant categories may be temporarily dropped from further analysis.

For instance, as it became obvious that the variable All Resources had a significant impact, it was necessary to determine which particular resource types were the most important marginal contributors. Therefore Refueling and Maintenance were grouped in a separate category as were Aircraft Acceptance Rates and Parking Space. These two categories were then run in a subsequent design set with Weather providing the third variable. If the experiments demonstrated that a particular variable had no significant effect, it was not included in future sets. The same procedure was used when it was determined that enough information had been gathered about a particular variable. For example, in the SEAsia case Weather was a variable in 16 runs. In the last six runs (a total of 22 SEAsia encounters were run in the experiments) only winter weather was used since it was deemed that enough information concerning the marginal contribution of seasonal weather changes had been collected.

SOUTHEAST ASIA ANALYSIS

Twenty-two computer simulations were made with the SOAR model for the SEAsia case. In these runs, the objective was to quantify the impact on the airlift system of such variables as weather, base resources, competing traffic, aircrews, and mission aircraft. The impact of changes in the levels of the variables was measured in terms of their effect on utilization rates and productivity. Three different tools of statistical analysis were employed: three factor analysis of variance† was used primarily to test the level of significance of the changes in the dependent variables caused by the factors and interactions being evaluated; paired comparisons were used to identify the marginal contributions of the variables; and regression analysis was used to examine the relationship of utilization rate to productivity.

Figure 3 illustrates the independent variables which were changed during the 22 SEAsia runs.

In the first experiment, the three factors were Weather, Cargo-handling Resources and Other Base Resources; for Weather, the base level was winter; the changed level was summer. For the

*$2^3 = 8$, the number of possible combinations of two levels for each of the three factors being tested. Each SOAR run is equivalent to one observation in the 2^3 factorial experiment.

†The use of three factor analysis of variance is an unconventional use of a familiar statistical technique. Among statisticians, there is a difference of opinion as to whether this technique is appropriate to the purpose to which it was applied. The adequacy of eight observations (SOAR runs) to test the three variables and their interactions is the point in question. The eight observations provide a total of seven degrees of freedom. Of these, one each is used for each variable and interaction. The remaining one degree of freedom is applied to experimental error which also includes the high order interaction. Many statisticians would insist on more than one degree of freedom for experimental error. The point in question is the power of the test, the level of confidence one may place in the results of the test.

Run	V_1	V_2	V_3	V_4	V_5	V_6	V_7
1	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0
3	0	1	1	1	0	0	0
4	1	1	1	1	0	0	0
5	0	0	1	1	0	0	0
6	1	0	1	1	0	0	0
7	0	1	0	0	0	0	0
8	1	1	0	0	0	0	0
9	0	0	1	0	0	0	0
10	1	0	1	0	0	0	0
11	0	0	0	1	0	0	0
12	1	0	0	1	0	0	0
13	0	0	0	0	1	0	0
14	1	0	0	0	1	0	0
15	0	1	1	1	1	0	0
16	1	1	1	1	1	0	0
17	0	0	0	0	1	0	−1
18	0	1	1	1	1	0	−1
19	0	0	0	0	1	1	0
20	0	1	1	1	1	1	0
21	0	0	0	0	1	1	−1
22	0	1	1	1	1	1	−1

FIGURE 3. SEAsia Experiments

two other categories, the base level consisted of those men, equipment, materiel, facilities, or capability assigned to each airbase. In the changed case, the base level of resources was augmented at every airbase by a constant percentage, usually 50 percent. The results of the first experiment are shown in Figure 4 for the C–141 and C–5A.

The presence of the word "none" in Figure 4 indicates that the factor or interaction was not statistically significant and that any impact thought to be associated with it most likely occurred by chance. In fact, the level of significance indicates the probability that the effect being measured occurred by chance. Thus, the smaller the number, the more confident we can feel that the factor being tested actually was associated with the impact that was reflected in utilization rates or productivity. For example, looking at C–5A utilization rate, the 0.08 level of significance indicates a probability of 8 percent that the impact occurred through random effects and a 92 percent probability that it may be attributed to weather. Furthermore, by consulting the Marginal Contribution chart, one sees that the mean difference between summer and winter weather was 0.75 hours (45 min per aircraft day). Other Base Resources also affected utilization rates; the effect was statistically significant at the 0.05 level. Only Cargo-handling seemed to have no significant impact on C–5A rates. The C–5A rates were also relatively sensitive to the interaction of the variables, although there was a good chance that such an impact could have occurred through random effects (25 to 37 percent).

The C–141, on the other hand, was not sensitive to any changes in the factors or interactions. With the single exception of the effect of weather on productivity, there is reason to believe the differences which were registered actually occurred by chance.

In Experiment 1, Cargo-handling was shown to have a negligible impact on both aircraft. Weather and Other Base Resources, however, had an important effect on C–5A utilization rates and a strong indication for C–5A productivity. Therefore Weather was retested in Experiment 2. Other Base Re-

Marginal contributions

Category	C-141		C-5A	
	Utilization rate (hours per day)	Ton-mile productivity per day (000)	Utilization rate (hours per day)	Ton-mile productivity per day (000)
A. Weather	0.11	1.32	0.75	10.05
B. Cargo-handling Resources	0.12	0.42	0.04	−0.57
C. Other Resources	0.19	1.04	0.77	10.98

Levels of significance

Category	C-141		C-5A	
	Ute rate	Productivity	Ute rate	Productivity
A. Weather	0.75	0.50	0.08	0.25
B. Cargo-handling	0.75	None	None	None
C. Other Resources	0.75	0.75	0.05	0.25
AB. Interaction	0.60	0.75	0.25	None
AC. Interaction	None	None	0.37	0.75
BC. Interaction	0.75	0.75	0.25	None

FIGURE 4. Experiment 1

sources was subdivided into two more definitive categories: (1) Refueling and Maintenance, and (2) Airfield Acceptance Capability and Parking. The results of Experiment 2 are shown in Figure 5.

With the possible exception of Airfield Acceptance Capability and Parking, none of the categories in Experiment 2 were shown to be significant at a meaningful level. This evidence appeared to confirm the indications of Experiment 1 that the levels of resources in the base case were too high for the level of demand. As a result it was decided to stress the system by increasing demand.

In Experiment 3, Weather was tested once again. All Base Resources was the second variable tested (it actually was the second test for this category since in Experiment 1, Cargo-handling Resources and Other Base Resources add up to All Base Resources). The third category was Competing Aircraft. In the base case, competing aircraft consisted of commercial carriers (CRAF) only. In the augmented case, the deploying tactical air forces (TAC) were added to CRAF. Results appear in Figure 6.

Once more, the experiment illustrated the relative insensitivity of C-141 to changes in the operating environment. The increased competition for resources probably had such a negligible effect that it was entirely overcome by random effects which produced an *increase* in utilization rates and productivity for the C-141. The highest utilization rate for all 22 SOAR runs was recorded in this set; the C-141s averaged 15.19 hours in the Summer case having augmented resources and the fully augmented level of competing aircraft.

The greatest impact for the categories being tested were found in C-5A productivity. All of the factors and interactions were determined to have a statistically significant impact at levels ranging from 0.005 to 0.10. The addition of competing aircraft resulted in the loss of an average of 1.17 hours and 6,690 ton miles per aircraft per day.

Marginal contributions

Category	C-141 Utilization rate (hours per day)	C-141 Ton-mile productivity per day (000)	C-5A Utilization rate (hours per day)	C-5A Ton-mile productivity per day (000)
A. Refuel/Maintenance	−0.24	0.08	0.09	1.96
B. Weather	0.08	0.85	0.12	7.38
C. Airfield/Parking	0.29	1.81	0.53	8.97

Levels of significance

Category	C-141 Ute rate	C-141 Productivity	C-5A Ute rate	C-5A Productivity
A. Refuel/Maintenance	0.50	None	None	0.75
B. Weather	None	0.75	0.50	0.33
C. Airfield/Parking	0.50	0.40	0.40	0.25
AB. Interaction	None	None	None	None
AC. Interaction	0.50	None	0.75	0.75
BC. Interaction	0.75	None	0.75	0.40

FIGURE 5. Experiment 2

Marginal contributions

Category	C-141 Utilization rate (hours per day)	C-141 Ton-mile productivity per day (000)	C-5A Utilization rate (hours per day)	C-5A Ton-mile productivity per day (000)
A. All Resources	0.62	2.79	1.36	16.39
B. Weather	0.12	1.26	0.56	7.41
C. Competing Aircraft	0.28	1.37	−1.17	−6.69

Levels of significance

Category	C-141 Ute rate	C-141 Productivity	C-5A Ute rate	C-5A Productivity
A. All Resources	0.25	0.25	0.40	0.005
B. Weather	0.75	0.50	0.75	0.05
C. Competing Aircraft	0.50	0.50	0.50	0.10
AB. Interaction	None	None	0.50	0.10
AC. Interaction	0.50	0.50	0.75	0.05
BC. Interaction	0.50	0.50	None	0.05

FIGURE 6. Experiment 3

In Experiment 4, Weather was dropped from further consideration because sufficient data had been accumulated: it accounted for an average marginal increase in productivity for "C-5As" of 6,333 ton miles per day and 1,771 ton miles per day for C-141s. In order to observe the system under maximum stress, Mission Aircraft was evaluated as a variable. In the base case, the number of C-5As and C-141s were 67 and 157, respectively; in the augmented case, the C-5As were increased to 96 and the C-141s to 224. The second category tested was All Base Resources. Flight Crews constituted the third category. In the base case, 1,464 crews were used; in the changed case (decremented, this time) the number was 1,246. The results of Experiment 4 are shown in Figure 7.

Marginal contributions

Category	C-141		C-5A	
	Utilization rate (hours per day)	Ton-mile productivity per day (000)	Utilization rate (hours per day)	Ton-mile productivity per day (000)
A. All Resources	0.87	3.70	2.20	23.64
B. Flight Crews	−0.16	−0.64	−0.18	−1.56
C. Mission Aircraft	−0.89	−3.94	−0.84	−21.23

Levels of significance

Category	C-141		C-5A	
	Ute rate	Productivity	Ute rate	Productivity
A. All Resources	0.10	0.20	0.15	0.20
B. Flight Crews	0.50	0.75	0.75	None
C. Mission Aircraft	0.15	0.20	0.30	0.20
AB. Interaction	0.75	0.75	0.35	0.75
AC. Interaction	None	None	None	0.50
BC. Interaction	0.50	None	None	None

FIGURE 7. Experiment 4

As expected, the increased demand generated by the additional mission aircraft caused the category "All Base Resources" to register a more impressive impact. It was statistically significant at levels ranging from 0.10 to 0.20. Changes in the levels of "All Base Resources" accounted for a variation of 2.20 hours and 23,640 ton miles per day for each C-5A. Even the relatively insensitive C-141 varied an average of 0.87 hours and 3,700 ton miles per day in response to changes in "All Base Resources."

The addition of more mission aircraft caused a decline in utilization rates and productivity per aircraft. This is a further illustration of the effect of queueing brought on by increased competition. It is also an indication that airlift forces productivity is not directly proportional to the number of aircraft applied. That is, the productivity of one C-141 may be 60,000 ton miles per day, but the productivity of 100 C-141s is probably less than 6 million ton miles (i.e., 100 × 6,000).

EUROPE/AFRICA ANALYSIS

Twenty computer simulations were made with the SOAR model for the simultaneous deployments to Europe and Africa. Because these runs were made after the SEAsia runs had been completed, they were designed with the benefit of more experience with the computer model and a better understanding of system behavior. Thus, it was possible initially to focus these experiments on specific resources. In addition, after the first design set, augmentation was limited to those resources or capabilities which could reasonably be expected to be dramatically improved. In the dual deployment, 15 C-5A and 105 C-141 aircraft were allocated to the African deployment; the remaining 52 C-5As and 42 C-141s were assigned to European requirements. Figure 8, a summary chart of the 20 SOAR encounters, shows the variables tested in the Europe/Africa runs.

Run	V_1	V_2	V_3	V_4	V_5	V_6	V_7
1	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0
3	0	1	1	1	1	1	0
4	1	1	1	1	1	1	0
5	0	0	0	0	0	0	1
6	1	0	0	0	0	0	1
7	0	1	1	1	1	1	1
8	1	1	1	1	1	1	1
9	0	1	1	0	0	0	0
10	1	1	1	0	0	0	0
11	0	0	0	0	1	0	0
12	1	0	0	0	1	0	0
13	0	1	1	0	1	0	0
14	1	1	1	0	1	0	0
15	0	0	0	1	0	0	0
16	0	1	0	0	0	0	0
17	0	1	0	1	0	0	0
18	0	0	1	0	0	0	0
19	0	0	1	1	0	0	0
20	0	1	1	1	0	0	0

V_1: Weather; 0 = Winter, 1 = Summer.
V_2: Refueling; 0 = Base level, 1 = augmented level.
V_3: Maintenance; 0 = Base level, 1 = augmented level.
V_4: Cargo-Handling; 0 = Base level, 1 = augmented level.
V_5: Parking; 0 = Base level, 1 = augmented level.
V_6: Other Resources; 0 = Base level, 1 = augmented level.
V_7: Flight Crews; 0 = 963 crews, 1 = 1187 crews.

FIGURE 8. Europe/Africa Case

As before, eight SOAR encounters were used to provide the observations for the 2^3 factorial design sets. Three experiments were executed. In Experiment 1, the variables tested were: Weather, Flight Crews, and All Airbase Resources. Once again, the base Weather level consisted of winter wind factors and airfield observations; summer provided the changed level. For Flight Crews, the programmed 4.42 crew ratio was used for the base level; the changed (augmented level) was a 5.42 crew ratio. For the base level for All Airbase Resources, the study group's best estimate of men, equipment, materiel, and capability available at the system's airbases was used. For the augmented level, these resources were increased system-wide by a flat percentage, usually approaching 50. The results of Experiment 1 are shown in Figure 9.

Marginal contributions

Category	C-141		C-5A	
	Utilization rate (hours per day)	Ton-mile productivity per day (000)	Utilization rate (hours per day)	Ton-mile productivity per day (000)
A. Crews	0.01	−0.25	−0.30	−0.31
B. Weather	−0.01	0.59	−0.15	−1.1
C. All Airbase Resources	3.27	13.49	3.59	48.69

Levels of significance

Category	C-141		C-5A	
	Ute rate	Productivity	Ute rate	Productivity
A. Crews	None	None	0.10	None
B. Weather	None	0.75	0.20	None
C. All Airbase Resources	0.05	0.05	0.005	0.05
AB. Interaction	None	None	0.05	0.50
AC. Interaction	0.75	None	0.10	None
BC. Interaction	0.75	None	0.05	None

FIGURE 9. Experiment 1

The results of the paired data tests used to compute marginal analysis indicate that seasonal changes in weather had little effect on utilization rates. Since one might anticipate a significant effect from weather in northern Europe, the suspicion arises that the weather enroute to Africa somehow dampened or washed out the effects of European weather. This hypothesis was supported by a separate analysis of weather effects by geographical area.

The negative effects of the addition of one extra flight crew per aircraft may be attributed to random effects. Apparently the base level crew ratio was sufficient to support airlift activity at the levels tested; the additional crews were neither required nor used. Therefore, the net effect was that of additional runs of the base cases with random effects providing a negligible variation in results. Augmentation of All Airbase Resources resulted in a dramatic increase in both utilization rates and productivity. The impact was significant at levels ranging from 0.05 to 0.005. The important increases resulting from the augmentation of All Base Resources indicated that a more detailed examination of this aggregated category might be productive. Accordingly Experiment 2 was designed to test at two levels the following variables: Base Parking Space, Refueling and Maintenance (combined), and Weather. All other variables were set at base levels. Results of Experiment 2 appear in Figure 10.

The evidence shown in Marginal Contributions for Experiment 2 reinforces the indications from Experiment 1. The important contribution made by All Airbase Resources in Experiment 1 is essentially duplicated by the combined contribution of Refueling/Maintenance and Parking. The aggregate category, Refueling/Maintenance, is shown to be an important marginal contributor; the average difference between the base level productivities and the augmented level of productivities is shown to be

Marginal contributions

Category	C-141		C-5A	
	Utilization rate (hours per day)	Ton-mile productivity per day (000)	Utilization rate (hours per day)	Ton-mile productivity per day (000)
A. Refuel/Maintenance	2.88	11.59	2.73	33.88
B. Weather	0.05	0.49	0.17	1.61
C. Parking	0.17	1.44	0.62	7.87

Levels of significance

Category	C-141		C-5A	
	Ute rate	Productivity	Ute rate	Productivity
A. Refuel/Maintenance	0.08	0.05	0.08	0.10
B. Weather	0.50	0.75	0.75	0.75
C. Parking	0.75	0.25	0.25	0.35
AB. Interaction	0.60	None	0.50	0.60
AC. Interaction	0.50	0.25	0.75	0.75
BC. Interaction	None	0.75	0.75	0.75

FIGURE 10. Experiment 2

Marginal contributions

Category	C-141		C-5A	
	Utilization rate (hours per day)	Ton-mile productivity per day (000)	Utilization rate (hours per day)	Ton-mile productivity per day (000)
A. Refueling	2.59	10.66	2.42	29.64
B. Cargo-handling	0.06	0.61	0.06	0.00
C. Maintenance	−0.03	−0.21	−0.23	−8.80

Levels of significance

Category	C-141		C-5A	
	Ute rate	Productivity	Ute rate	Productivity
A. Refueling	0.025	0.01	0.05	0.08
B. Cargo-handling	0.40	0.20	0.75	None
C. Maintenance	None	0.50	0.40	0.50
AB. Interaction	0.40	0.20	0.90	None
AC. Interaction	0.25	0.10	0.75	0.75
BC. Interaction	0.75	0.35	0.75	0.75

FIGURE 11. Experiment 3

11,590 ton miles per aircraft day and 33,880 ton miles for the C–141 and C–5A, respectively. The impact of this change is statistically significant at levels ranging from 0.10 to 0.05. The marginal contribution of additional parking space is slight, indicating that the amount of parking presently available would not be a serious constraint on utilization rates ranging from 8.88 hours to 13.46 hours.

Once again Weather was found to be a negligible factor. Therefore, Weather was not tested in the third and last experiment. Because of its slight impact, Parking was also dropped from further consideration. But Refueling and Maintenance were separated with each providing one variable in Experiment 3. The third variable was Cargo-handling. The results of the third Experiment appear in Figure 11.

In Experiment 3, all experiments were run with winter weather. With the exception of those variables being tested, all resources and capabilities were held to the base levels. The results indicate that Refueling capability is the key variable in the Europe/Africa depolyment. Experiment 1 identified the important and significant contribution played by All Airbase Resources. In Experiment 2, the identity of the critical resource was narrowed down to the aggregate category Refueling and Maintenance. In Experiment 3, it was revealed that Refueling was the single most constraining factor in the system. The next logical step in the analytical process would be to identify those key bases in the network at which refueling is a serious problem. It could well be that the addition of a dozen or so refueling trucks, relatively easy to deploy, could eliminate the choke point and make possible significant increases in airlift effectiveness. Also, a change in the number or scheme for recovery bases may alleviate the problem.

CONCLUSION

The simulation findings were instrumental in arriving at the joint OSD/Air Force determination that while some increase in aircraft utilization rates could be achieved by improvements in system support resources, it would not be feasible to operate the airlift force at the proposed utilization rate during a wartime deployment. The simulation was especially valuable in identifying constraints in the system and in estimating the kinds and levels of resource augmentation required to relieve the constraints.

In addition to the analysis of the effect of individual resources, an examination of several relationships commonly assumed to exist between measures of airlift effectiveness and certain system variables was conducted. Two of the most interesting findings concerned the assumptions of direct proportionality between productivity and utilization rate and between productivity and numbers of aircraft.

Productivity is generally recognized as the key measure of effectiveness because of its obvious, direct impact on mission accomplishment. The relationship between productivity and utilization rates (an interim, easily quantifiable measure), has long been assumed to be one of direct proportionality. Regression analysis was employed to determine the relationship between the two variables. The relationship was shown to be linear within the range of the values tested. The assumption of direct proportionality, however, was shown, by the presence of a constant, to be an incorrect one. The size and sign of the constant were, in turn, found to be a function of aircraft type and deployment area. The regression equations suggest the existence of an appropriate predictive expression for each aircraft type and specific contingency area. The development and use by contingency planners of a family of predictive equations would result in more accurate estimates of productivity, closure dates, and airframe requirements.

Direct proportionality has also been assumed between the productivity of an airlift force and the numbers of aircraft in that force. Thus, if the daily productivity of one C–141 is 54 kiloton miles, then the productivity of 10 is 540 kiloton miles and the productivity of 100 is 5,400 kiloton miles. The assumptions underlying such calculations are that marginal increases per aircraft are uniform regardless of the size of the airlift force. As expected, this assumption has been found to be incorrect. As aircraft are added to the base programmed level, total productivity rises, but per aircraft productivity declines. The important point here is the provision of a method to quantify an alternative assumption to the direct proportionality assumption.

With the capability to cope with extremely complex aspects of dynamic systems that are clearly beyond the capability of most mathematical models, simulation has been demonstrated to be a valuable technique for airlift system analysis. The key to controlling a large simulation analysis, such as the SOAR analysis, resides in a carefully constructed experimental design which provides information in a structured manner and which, at the same time, permits the flexibility for the analyst and decision-maker to test new hypotheses developed from additional information that comes available during the analysis. A useful technique developed for this analysis is to design experiment sets for a finite number of factors. Initial analysis begins with aggregated sets of factors, and information gained from experiment execution is used to parse sets and ultimately identify major explanatory independent variables. Moving from aggregate to the individual variables also permits overlap of computer runs for experiments. Thus, the technique facilitates obtaining the maximum information from the minimum number of computer runs.