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IMPACT OF THEATER AIRLIFTER CHARACTERISTICS ON FUTURE THEATER AIRLIFT SYSTEM PRODUCTIVITY

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ABSTRACT

The US Air Force is examining deficiencies in its current theater airlift capability and reviewing the need to establish requirements for the theater airlift system of the future. An important aspect in satisfying those future requirements is specifying the nature of the system's inherent theater airlifter. Because the characteristics of a theater airlifter are too numerous to examine with rigor in all their possible and reasonable combinations, this paper proposes the use of designed simulation experiments, which screen groups of variables, to determine how airlifter characteristics influence the efficacy of the theater airlift system.

1 INTRODUCTION

Whereas strategic airlift moves personnel, supplies, and equipment, to, from, or between theaters of operations, it is the mission of theater airlift to move this cargo within a designated region of operations. On occasion, US Army helicopters are used for logistical cargo movement about the theater, and could be considered as part of the theater airlift fleet. For this analysis, we ignore the helicopter assets, and concentrate on the contribution of US Air Force airlifters.

The fundamental objective of theater airlift is to provide the user, which is usually the Army, with the capability to conduct a cargo movement mission when there are no other means available to do the job. Theater airlift provides the Army with increased mobility without reliance upon "ground lines of communication." It affords a degree of maneuver that may otherwise be impossible due to the lack of roads, rail lines, or major airfields within a theater of operations (Shine 1988). The maneuverability and responsiveness afforded by theater airlift are integral components of the US Army's vision of its role in future conflicts.

The US Army is continuing the development of AirLand Operations (ALO), its newest warfighting doctrine. Under ALO, the concept of the battlefield has drastically changed. It will consist of nonlinear operations that engage lighter, more mobile US Army combat units with enemy forces in "pockets" of combat. US combat forces will press the fight with the enemy and exploit the element of surprise to take advantage of unprepared enemy units and their vulnerable support areas. Those US forces carrying out the relatively deep attacks will be heavily dependent upon the theater airlift system for their initial employment, resupply, and extraction. As ground lines of communication will be either nonexistent or unreliable, an effective theater airlifter is likely to be a necessary ingredient for the successful prosecution of the ALO doctrine.

We propose a means of assessing the productivity of the theater airlift *system* based on the characteristics of the theater airlift *aircraft*. Our intent is to determine which combinations of aircraft characteristics provide the most desirable levels of theater airlift capability. The approach consists of:

1. Establishing a sufficiently detailed theater airlift scenario which allows for meaningful simulation.
2. Grouping the numerous aircraft characteristics into logical sets that can be treated as composite variables.
3. Designing a set of experiments to support development of a hypothesized metamodel.
4. Conducting a set of sequential experiments, as in a Response Surface Methodology study, modifying the experimental designs and subsequent metamodels as appropriate.

The result of such an approach should reveal which composite variables materially influence the effectiveness of the theater airlift system. Further work can identify the specific aircraft characteristics that are most important by conducting similar experimentation on the aircraft characteristics included in the composite variables found to be significant.

2 BACKGROUND

The primary theater airlifter in the current US Air Force inventory is the C-130 Hercules aircraft, which became operational in the 1950s. Many of those in use today need to be replaced or refurbished as they are approaching the end of their useful service life. The C-17, a transport aircraft suitable for theater airlift use, will soon be added to the inventory. While the C-17 will have short field performance similar to the C-130, it is intended primarily to augment the C-5 and C-141 strategic airlift fleet, and occasionally deliver critical cargo directly into forward operating locations. To assist Headquarters, Air Mobility Command (AMC) in assessing theater airlift systems of the future, the Aeronautical Systems Center (ASC) is conducting the most comprehensive analysis of theater airlift capability ever carried out by the US Air Force through the Future Theater Airlift Studies (FTAS) project.

The FTAS project has developed a computer simulation model to analyze the effectiveness of theater airlift systems representative of future wartime scenarios. The Generalized Air Mobility Model, or GAMM, simulates the entire theater airlift system's movement of cargo from its source to its ultimate destination. It does not purport to assess the outcome of a campaign, but quite capably measures the effectiveness of the theater airlift system in meeting the operational demands of a given scenario. The model requires information concerning the cargo to be moved, the transportation system network, and the characteristics of the airlifters to be used. In addition to airlifter flights, GAMM simulates airdrops, airlifter ground operations, transshipment of cargo by US Army assets, and the survivability of the cargo in its various modes of transportation.

A rather detailed set of data is required for GAMM's use: the airlifters' in-flight and on-ground characteristics; information on all airfields; information on all entry and destination sites; the nature of the linkages between the airfields and entry/destination sites; and full dimensional information, timing, and location requirements for each piece of cargo to be moved.

Three scenarios have been constructed for analyses using GAMM: a central European war; a drive by the former Soviets south through Iran to the Persian Gulf; and an invasion of Honduras and El Salvador by Nicaraguan forces. Although considered classic wars, these scenarios are now outdated due to the drastically altered world situation. However, they continue to be used within the theater airlift analysis community because they represent a widely varied mix of significant theater characteristics such as: combat intensity; threat level; flight distances; pressure/altitude requirements; airfields; cargo; and on-ground infrastructure. The key aspect of these scenarios, which is critical for theater airlift system analysis, is their corresponding sets of "representative" airlift jobs. The job set for each scenario was developed through the use of working groups, with wide representation from the US Air Force, industry, and especially the US Army.

The Central American scenario was selected for use in this effort, as it has many similarities to the type of conflict that might be faced in a country of particular interest to one of the authors: Australia's Region of Direct Military Interest (RDMI). One of the likely contingencies which could require the involvement of the Australian Defence Forces in the future is an escalated low level conflict. While some aspects of the Central American scenario created for GAMM are peculiar to US strategies, tactics, and equipment, the terrain and infrastructure of the Central American theater is very similar to that of Northern Australia and other countries within Australia's RDMI. These regions have tropical climates, very few roads, almost no railway systems, a very limited number of major airfields, and many short, unprepared airfields. Therefore, the resulting analysis of a Central American theater airlift system will provide useful insights for theater airlift considerations of the Australian Defence Force.

A number of representative airlift jobs were developed to accompany the Central American scenario. The jobs require the movement of approximately 10,000 short tons over the course of 30 days. The jobs include the five general mission categories defined by the US Air Force for theater airlift:

- *Deployment* is the movement of forces to their initial area of operation in theater.
- *Employment* is the movement of forces around a theater after their initial deployment.
- *Sustainment* is the movement of replacement personnel and supplies in support of deployed forces.
- *Retrograde* is the use of aircraft, typically on the return leg of a mission, for withdrawing personnel, civilians, equipment, or enemy prisoners of war from the combat area.
- *Air Evacuation* usually requires a specially configured aircraft (Shine 1988).

The fleet of airlifters used in this Central American scenario consisted of 16 C-130Hs and two C-17s. The C-17s were restricted to using only a handful of airfields, due to the limited load-bearing capacity of the airfields in the scenario. The C-130Hs were able to operate into many more airfields, but were also restricted in their operations into many of the airfields due to load-bearing capacity constraints.

3 MEASURES OF EFFECTIVENESS

Measures of effectiveness historically used for theater airlift systems include: rate of cargo movement; average aircraft flying time per day, or utilization (UTE) rate; departure reliability; and the ratio of hours flown to hours scheduled to be flown (Bryant and Gordon 1984). Studies by McManus (1988), Shine (1988), Wourms (1990), and Bryant and Gordon (1984) have concluded that these measures are not very useful in measuring either the capability or effectiveness of theater airlift.

Rate of cargo movement is a good measure for evaluating simple throughput. *Tons per Day* is commonly used to characterize strategic airlift effectiveness. However, the nature of the theater airlift system and how it supports combat forces requires that we consider its effectiveness in forms other than simple throughput, such as:

- Timeliness of deliveries, particularly in the case of emergency resupply;
- Effectiveness in making multi-flight deliveries within narrow time and location constraints, such as combat unit move insertion;
- Ability to move large, "oversize" items; and
- Impact of operating in threat environments.

Similarly, UTE rate is a limited measure of theater airlift's effectiveness. UTE rate is a function not only of the airlifter's characteristics, but also the distances of each mission. Large theaters and long average mission distances tend to have high UTE rates, whereas airlifters in small theaters flying short missions will have low UTE rates. Taken to an extreme, consider the case of two airlifters, equal in every way except for cruise speed: the faster airlifter will have a lower UTE rate, as it spends proportionally less time in flight.

Departure reliability has little to do with the theater airlift system's effectiveness. The ratio of hours flown to hours scheduled gives little, if any, insight into theater airlifter effectiveness, as this ratio is impacted by external factors such as weather and airfield closures.

These historical measures of theater airlift capability are primarily efficiency measures that do not take into consideration the ability of theater airlift to meet the user's needs. Bryant and Gordon (1984) succinctly state: "The fact that tactical requirements are often determined by the user as a result of changing combat situations makes response to these requests more important than the need to efficiently use the aircraft."

The primary measures of effectiveness used for this analysis are *Ratio Delivered* and *Ratio on Time*; these refer to the percentage of the total cargo demand which (1) was delivered, and (2) was delivered on time, respectively. Both of these measures indicate the responsiveness of the theater airlift system. Four secondary measures were examined in the thesis by Pappas (1991); they are not detailed herein.

4 ANALYSIS METHODOLOGY

The classical approach to dealing with uncertainties in a simulation model's inputs is the use of sensitivity analysis. Sensitivity analysis gives a one-dimensional representation of the sensitivity of the system being modeled to the parameter being varied. As an alternative, one could consider a multi-dimensional sensitivity analysis which varies multiple parameters concurrently. The formal methodology for multi-parametric sensitivity analysis is referred to as Response Surface Methodology (RSM). RSM operates on the simulation model by determining the experiments, or cases, to be run in accordance with statistically designed experiments, and characterizes the resulting output as a mathematical function using regression techniques. It is important to note that the functional representation of the response, referred to as the "metamodel," is an approximation which provides insight into the simulated system's behavior. In general, the metamodel is not a substitute for the simulation itself.

An analysis of the C-130H was conducted early in the FTAS project to identify specific airlifter-related problems that would prevent or impede the delivery of the required throughput on future battlefields. This study, known as the "C-130H Deficiency Analysis," evaluated the C-130H's characteristics individually and found that no single deficiency significantly affected the C-130H's airlift capability (Wourms 1990). (A previous study, carried out at ASC using RSM techniques, attempted to screen the C-130H's characteristics individually for significant effects. This study was inconclusive and was never published.) While it was not intended as a screening analysis, the deficiency analysis was the only previous study which attempted to identify significant theater airlifter characteristics.

For this analysis, a two-level full factorial design was selected. The experimenter must select appropriate values for the high and low levels of the variables being assessed. The chosen values must be far enough apart to identify major trends in the response, such as the slope, but they cannot be so far apart that major features of the response, such as inflection points, are ignored. The final consideration in selecting the variables' values for this study was that they be selected around the C-130H baseline, so that significant findings could be directly related to the C-130H's capabilities.

The high and low levels were derived by multiplying the C-130H's characteristics by 4/3 and 2/3, where the high level of each characteristic was the C-130H multiple which was expected to increase the airlift system's operational effectiveness. In other words, the high and low levels of the variables, respectively represented by +1 and -1 in the experimental design, may at times be opposite the change in the parameter's actual value.

A two-level full factorial design assessing k variables requires 2^k experiments. Testing all airlifter parameters in GAMM using such a design would require 2^{69} experiments. Since this is not practical, the number of parameters was reduced in two steps:

1. The number of parameters was reduced by holding characteristics relating to the concept-of-operations constant; and
2. The remaining parameters were grouped into six functional sets.

The second parameter reduction step is referred to as group-screening, which is the key to our approach to evaluating the influence of theater airlifter characteristics. The group screening strategy reduces the number of variables in the full factorial design from the number of individual parameters to the number of functional sets or groups of parameters. In this case, the airlifter parameters were grouped into five functional sets. Adding airlifter fleet size as the sixth variable resulted in a full factorial design requiring a far more manageable 64 runs. The five functional sets are: Field Performance; Cargo Cabin; Inflight Performance; Ground Flotation/-Wheel Loading; and Servicing/Loading/Unloading. The parameters contained in these sets are listed in Table 1.

The groupings were determined by combining parameters that were closely related in airlifter function or purpose. For example: cargo cabin size is directly proportional to *Cargo Bay Width, Height,* and *Length.* In addition, the size of the cabin influences the size of the airlifter (i.e., *Aircraft Spot Factor*) more strongly than most any other design factor. Generally, as aircraft increase in size, all cabin dimensions will increase and the aircraft's *Maximum Cabin Payload* will also tend to increase. Similarly, the times to load, unload, and service directly affect the airlifter's turn time.

However, grouping the parameters confounds any analysis concerning individual parameters, because the effect of any single parameter would be combined with the effects of the other parameters within its set. This limitation was accepted because the primary purpose of this experiment was to screen the chosen parameter groups to determine which were significant. If significant groups were found, the next step in the analysis might be to carry out a more detailed examination of the individual parameters that comprised the significant sets. The parameters in the sets that were not significant could be disregarded with some level of confidence.

The results of the two-level factorial experiment were fit with least squares estimates. Five replications were chosen for the simulation runs; their averages were accurate to within 2% at a 95% confidence interval.

5 ANALYTIC FINDINGS

Ratio Delivered varied from a low of 26% to a high of 98%; *Ratio on Time* varied from 12% to 49%. The results of the regressions for the two responses fit the data extremely well: adjusted coefficient of determination exceeded 0.995 in both cases. Qualitative examination of residual and normal probability plots indicated that the extremely accurate statistical metamodels developed from the regressions conformed to standard assumptions.

Table 1: Functional Parameter Sets

Field Performance (F)
Takeoff at Max Useful Load (ft)
Landing at Max Useful Load (ft)
Takeoff at Mid Useful Load (ft)
Landing at Mid Useful Load (ft)
Takeoff at Zero Useful Load (ft)
Landing at Zero Useful Load (ft)
Cargo Cabin (C)
Cargo Bay Width (in)
Cargo Bay Height (in)
Cargo Bay Length (in)
Max Useful Load (lbs)
Mid Useful Load (lbs)
Aircraft Spot Factor (No.)
Maximum Cabin Payload (lbs)
Cargo Threshold for Relocation (lbs)
Inflight Performance (I)
Cruise Speed (kts)
Cruise Fuel Flow (lbs/hr)
Maximum Ferry Fuel (lbs)
Takeoff/Landing Fuel Bias (lbs)
Ground Flotation/Wheel Loading (G)
Load Classification Number at Max Useful Load
Load Classification Number at Zero Useful Load
Servicing/Loading/Unloading (S)
Mean Time to Service (hrs)
Mean Time to Load (hrs)
Mean Time to Unload (hrs)

These initial regressions were reviewed with the intent of generating *parsimonious* metamodels, that is, metamodels with the smallest number of terms that still provide an adequate representation of the response function for each measure of effectiveness. The parsimonious metamodels were generated by removing a term or two that were least significant from the current metamodel, then repeating the regression to assess the quality of the statistical fit without those terms. The final, parsimonious, metamodels include only Cargo Cabin (C), Ground Flotation/Wheel Loading (G), and their interaction term (CG). To illustrate the form of the metamodels, the estimated response for *Ratio on Time* is shown as Equation 1. All coefficients for the two equations were positive, meaning that when either variable is changed from a low to a high level, the value of the response will increase, and if both variables are increased, the response will increase by an even greater amount due to the interaction term. Adjusted coefficients of determination exceeded 0.970 for both revised metamodels; residual and normal probability plots were considered quite reasonable.

$$\hat{Y} = 0.239 + 0.078C + 0.074G + 0.033CG \qquad (1)$$

The effects of the two variables, *C* and *G*, on the results for the *Ratio on Time* are shown in Figure 1. The top line in the figure represents the high level of the variable *C*, which corresponds to a large theater airlifter. The lower line therefore represents a small theater airlifter. The effect of the interaction is clearly seen. Increasing the size of the cargo cabin results in a much greater increase in the ratio of cargo delivered on time when the flotation/loading variable, *G*, is at a high level rather than a low level.

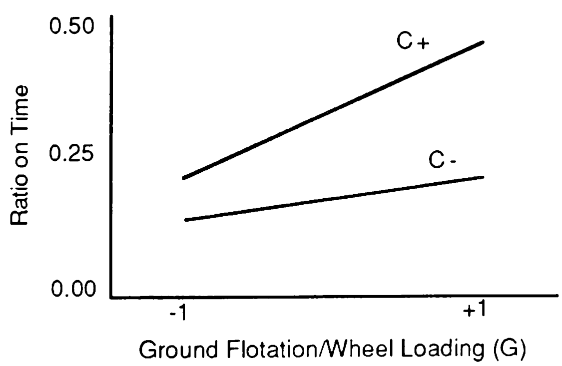

Figure 1: *Ratio on Time* as a Function of Cargo Cabin (*C*) and Flotation/Loading (*G*)

A similar result is shown in Figure 2 for *Ratio Delivered*. While there are still indications of the effect of the interaction, it is not as pronounced as for *Ratio on Time*. However, the figure does show that significant increases in the ratio of cargo delivered occur when either variable is increased from its low level to its high level, and the greatest increase occurs when both variables are set to their high levels.

It is interesting to find the presence of the interaction term, *CG*, in both responses. The reason for this interaction is due to a significant link between the two variables *C* and *G*. The flotation/loading term, *G*, contains only two terms, both of which quantify airfield load bearing capacity requirements for the airlifter in terms of Load Classification Number (LCN). One of the flotation/loading terms specifies the airlifter's LCN at its *Maximum Useful Load* and the other at zero useful load. The LCN ratings of an airlifter are very important in a region such as Central America, where airlifter performance is decreased because of poor airfields. GAMM interpolates between the airlifter's LCN values to determine the maximum load that can be supported by a given airfield. The cargo cabin term, *C*, includes the value for *Maximum Useful Load*. Thus, the significant interactions between *C* and *G* are due to the common impact of *Maximum Useful Load*.

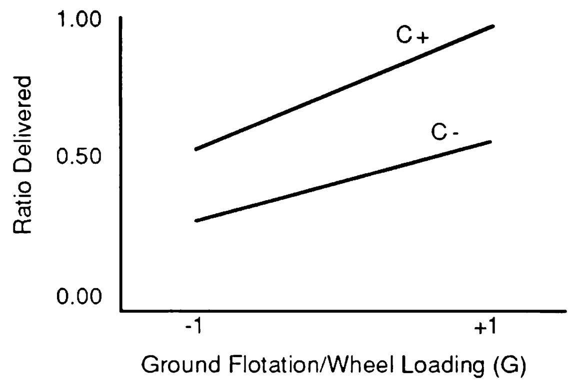

Figure 2: *Ratio Delivered* as a Function of Cargo Cabin (*C*) and Flotation/Loading (*G*)

For the two primary measures of effectiveness, *Ratio on Time* and *Ratio Delivered*, it is clear that using airlifters with the characteristics of the *C* and *G* groups set to high levels results in a significant improvement in the theater airlift system's productivity. The exact characteristic or combination of characteristics which cause the increase in throughput could be sought through further study.

Clearly, we are primarily interested in determining the parameter groups which are of prime importance in forming the response. In developing the final, parsimonious metamodels, parameter groups were discarded for one of two reasons: either they were statistically insignificant; or they were statistically significant but were relatively unimportant in forming the response. In this analysis, only the sixth factor, Fleet Size, was discarded due to statistical insignificance. Previous theater airlift system studies have always shown fleet size to be very important below some point of diminishing return. Further review of our experimental setup indicates that the range of values for Fleet Size probably did not reach low enough. Recall our discussion in the ANALYSIS METHODOLOGY section: "The chosen values must be far enough apart to identify major trends in the response...." We have evidently selected both our high and low values in a range where very little change in response occurs.

6 CONCLUSIONS AND RECOMMENDATIONS

The study proposed a means to identify the theater airlift *aircraft* characteristics that materially influence the effectiveness of the theater airlift *system*. We showed that designed experiments and group-screening are powerful and efficient approaches to initiating sequential experimentation efforts with a simulation model. In terms of specific results, however, we've only taken a first step. Our analysis is restricted to one of three generic scenarios, and it only examined the impact of groups of related airlifter characteristics on the theater airlift system. Results concerning other scenarios and the influence of individual aircraft characteristics on the theater airlift system could be readily obtained through additional steps in the sequential experimentation process.

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