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IMPACT OF C-130 RELIABILITY AND MAINTAINABILITY ON FUTURE THEATER AIRLIFT SYSTEM PRODUCTIVITY

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ABSTRACT

During the past few years, the US Air Force has been actively investigating the near-term acquisition of a new transport aircraft to provide improved intratheater airlift capability into the 21st century. The new transport aircraft will augment the current intratheater, or theater, airlift fleet, which is composed almost exclusively of C-130 aircraft. The new theater airlifter concept under consideration, referred to as the Enhanced Theater Airlifter, is to have reliability and maintainability attributes double that of a C-130E. This paper examines the impact of doubling the reliability and maintainability of generic C-130 fleets on a future theater airlift system's productivity.

1 INTRODUCTION

This paper assesses the impact of C-130 reliability and maintainability improvement on future theater airlift system productivity. Increasing the reliability and/or maintainability of an airlifter makes it more available. Increasing the availability of an airlifter fleet tasked with a heavy workload tends to increase the productivity of that fleet. Motivations behind this C-130 analysis are: to contribute to the Aeronautical Systems Division effort to evaluate a surrogate for the proposed Enhanced Theater Airlifter (ETA), and for the Directorate of Advanced Systems Analysis to exercise its theater airlift system analytic capabilities.

The methodology used for this effort is a multiparametric sensitivity analysis of a theater airlift system. The scenario is a conventional, 30-day war in Southwest Asia in the year 2010. The airlift fleet is moving primarily US Army cargo, and must move the cargo quickly and effectively in support of Army operations as defined by the Army's emerging AirLand Battle-Future doctrine. The total tonnage required to be moved in the scenario is a subset of what would be required in a real war; however, the cargo, amounts, timeliness, and destinations have been verified by both US Air Force and US Army organizations as representative of the cargo movement demands within the context of the scenario. The airlifters must occasionally fly into the surface-to-air threat in support of this doctrine, resulting in both attrition and battle damage.

The Generalized Air Mobility Model (GAMM) is the simulation tool used for this analysis. GAMM, developed over the past four years by the Directorate of Advanced Systems Analysis, is a tool unique to the airlift analysis community, in that with reasonably short run times it gives detailed information of the effectiveness of a theater airlift system. It simulates the entire system, including not only airland, airdrop, and airlifter ground operations, but also the ground transshipment facet of cargo movement. GAMM schedules the theater airlift assets within constraints such as the availability and characteristics of airbases; airlifter performance, ground turn operations, and survivability; and operational concepts to move the cargo in the most effective manner (GAMM 1989).

GAMM also accounts for airlifter reliability and maintainability, both of which are represented at the aircraft system level. Upon the completion of each sortie, the number of critical airlifter failures which occurred during the sortie is checked by randomly sampling from a Poisson distribution. (The term "critical failure" is synonymous with "grounding failure," as the failed system must be repaired prior to the airlifter's continued operation.) The rate λ for the Poisson process is the mean number of failures expected to have occurred during the sortie. λ is the quotient: sortie flight hours divided by the Mean Time (in hours) Between Critical Failures, *MTBFc*. *MTBFc*, an airlifter characteristic, is derived from failure rates of items on the airlifter's "Minimum Essential Systems List."

Repair time for each failure is taken from a lognormal random draw. The time required to effect a repair, at the airlifter system level, is the Mean Time To Repair, or *MTTR*. If the random draw for the number of critical breaks results in more than one failure, all repairs are performed simultaneously within the time of the longest repair. If the airlifter is at a main operating base (MOB), the maintenance crews and spare parts are assumed to be infinitely available and the repair action begins immediately. An airlifter which fails at a non-MOB is grounded until the crew(s) and part(s) can be transported to it; GAMM accounts for this "logistical pipeline delay" by adding a bias time to the repair time.

2 MULTI-PARAMETRIC SENSITIVITY ANALYSIS

This analysis varies the C-130's reliability, maintainability, force size, and logistical delay at non-MOB sites. The Directorate of Advanced Systems Analysis enlisted the assistance of the Deputy Chief of Staff for Acquisition Logistics, in determining the reliability and maintainability (R&M) characteristics of various C-130 models.

Reliability data was unavailable for the C-130E, but was available for the H; the Acquisition Logistics office advised that critical C-130H system failures be characterized by a *MTBFc* of 2.34 hours. Maintainability data for the E and H are not available separately, as they are confounded in the historical data; the Acquisition Logistics office also advised a *MTTR* of 2.4 hours (R&M Inputs 1990). As no C-130E-specific R&M data is available, either through the Acquisition Logistics office or the aircraft's manufacturer (LASC 1990), a single, generic C-130 model, referred to as the C-130, will be cited in this analysis.

The ETA is required to have both a reliability and maintainability double that of the C-130E. Since the specific R&M characteristics of the E model were unavailable, doubling the R&M of the generic C-130 (giving 4.68 hours for *MTBFc* and *MTTR* of 1.2 hours) most certainly exceeds that required of the ETA. The C-130 with doubled R&M is referred to as the C-130RM; it will be cited later in this analysis.

MTBFc is varied from 2 to 6 hours, and *MTTR* from 0.6 to 3 hours in this sensitivity analysis, ranges which easily encompass the actual *MTBFc* and *MTTR* for both the C-130 and the C-130RM.

The "logistical pipeline delay" for repairs at non-MOBs is varied as the third factor. No information on delay time specific to C-130s is available, but planning factors for the C-17 repairs at non-MOBs are used as guides. (The planned C-17 non-MOB logistical pipeline delay is 12 hours in peacetime, 6 hours in wartime (R&M Inputs 1990).) *Delay* is varied in this analysis from 5 to 12 hours.

Airlifter force size, *Force*, is the final factor. It is varied from four to ten squadrons, with each squadron sized at sixteen airlifters.

The measures of effectiveness (MOEs) used in this analysis are Tons Delivered (TD), Tons delivered On Time (TOT), utilization rate (UTE), and Non-Mission Capable (NMC) time. Note that cost is not accounted for in any of this analysis. TD is the total tonnage delivered during the thirty day scenario. TOT is a measure of the amount of cargo which is delivered by its desired, or requested time, and thus indirectly represents the ability of the airlift system to make timely deliveries to the user for effective prosecution of the warfighting effort. TD and TOT are our primary MOEs, and represent measures of productivity. UTE and NMC are not measures of productivity, and thus are not of primary interest for this effort. However, UTE and NMC allow valuable insight into airlifter usage and availability rates, two considerations which significantly influence fleet sizing deliberations.

UTE is the mean flight hours per airlifter per day. In real-world operations, UTE is limited by the availability of spares, rather than the airlift fleet's failure rate, repair time, force size, or other considerations. As the actual planning factor for Southwest Asian UTE is classified, it will not be referenced in this paper; rather, UTE differences will be addressed as they reflect the airlift system's requirement for its logistical tail. NMC time is the percentage of time the airlifters are unavailable due to grounding failures.

3 ANALYSIS

The multi-parametric sensitivity analysis is conducted using Response Surface Methodology (RSM). The entire RSM process, with the exception of the GAMM runs, was conducted using an automated procedure called PCRSM. PCRSM includes the experimental designs and multiple regression routines within a single software package (Meidt and Bauer 1990).

Four factors: *Force*, *MTBFc*, *MTTR*, and *Delay*, are varied in this analysis. The functional form for these factors in the response equations is expected to include second order effects; thus, a Central Composite Design was selected. No replications of either the "cube" or "star" points were made. While the lack of any design point replications prevents standard lack-of-fit tests, the number of GAMM runs is held to a minimum.

Five additional GAMM runs were made for response metamodel validation. The five runs form the extreme corners of a "cube," centered at the CCD center, with its side length one-half the length of the CCD "cube" side.

The points were selected such that any given point has each of the other four points diagonally opposite on each "cube face," at a coded distance of 0.707. Each metamodel is evaluated by examining its mean absolute percentage error in terms of an average departure from the actual responses of the validation runs.

The factors will be referred to as "ϕ_i"'s in the functional forms. They are coded as -1, 0, and +1 to preserve orthogonality in the design. The coded value of -1 corresponds to the "low" end of the actual range, 0 to the center, and +1 to the "high" end of the range. The terms "coded" and "uncoded" will be used frequently throughout the remainder of the paper. Refer to Table 1 for the variables and their coded and uncoded values.

Table 1: Analysis Variables, Ranges, and Coding

Factor		Uncoded Range			Coded Range		
ϕ_i	Name	Low	Mid	High	Low	Mid	High
1	*Force*	64	112	160	-1	0	1
2	*MTBFc*	2	4	6	-1	0	1
3	*MTTR*	0.6	1.8	3	-1	0	1
4	*Delay*	5	8.5	12	-1	0	1

3.1 Tons Delivered (TD)

The regression for the TD response showed that all linear terms and the second order term for *Force* were significant, and all other second order and all interaction terms were insignificant. The response's standard coded form, including each coefficient's standard error in parentheses, is shown in Equation (1).

$$\hat{TD}\Big|_{coded} = \underset{(189)}{24689} + \underset{(212)}{3499\phi_1} - \underset{(335)}{1392\phi_1^2} + \underset{(212)}{2060\phi_2} - \underset{(212)}{751\phi_3} - \underset{(212)}{1571\phi_4} \quad (1)$$

The statistical fit of the GAMM runs to the metamodel of Equation (1) was excellent: the regression's adjusted coefficient of multiple determination was 0.960, the Wilk-Shapiro normality test statistic was 0.932, and the predicted response and Rankits residual plots showed no evidence of departure from standard regression assumptions. The mean absolute percentage error for the TD metamodel was 4.86%, an acceptable accuracy for this R&M evaluation.

Figure 1 depicts the functional form for estimated TD (i.e., Equation (1)) graphically. Curves are plotted for estimated TD, as a percentage of the total tonnage demand, as a function of *Force* (ϕ_1), *Delays* (ϕ_4) of 6 and 12 hours, and R&M factors (ϕ_2 and ϕ_3) set to the appropriate values for the C-130 and the C-130RM. Observations regarding the information on Figure 1:

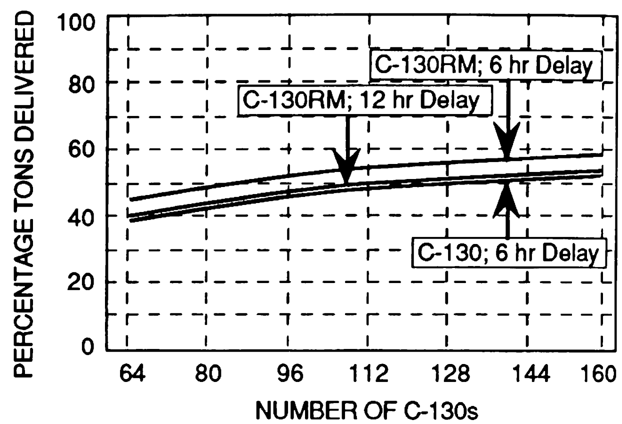

Figure 1: Percentage $\hat{TD}$ as Function of Force Size

1. Doubling the R&M characteristics of the C-130 yields approximately a 6% increase in the estimated percentage tonnage delivered for any given force level / logistical delay combination.
2. The number of C-130RM airlifters required to equal the productivity of 160 C-130s is approximately 97; this is a reduction of essentially four squadrons, or 39% less airlifters, at 53% tons delivered.
3. Doubling the logistical delay from 6 to 12 hours, for a given force of either the C-130 or the C-130RM, decreases the estimated percentage TD productivity by 5% of the requirement.

Partial derivatives of Equation (1) give the incremental change in estimated TD as a function of each factor. Equations (2) thru (5) give the partials for the four factors in coded variable form. Examining these partials at the extremes of the coded ranges indicates the effect of changes in estimated TD with change in that factor; Table 2 shows the partials' values at the extremes of the coded (i.e. -1, +1) ranges.

Each factor's relative effect on the estimated TD response is given by the partials' values of Table 2. *Force* has the strongest effect of the four factors at both its low and mid points, followed by *MTBFc*, *Delay*, and *MTTR* in order of decreasing effect. At the high end of its range, *Force* is the least significant of the four, demonstrating the same diminishing return for the larger forces that was graphically depicted in Figure 1.

$$\frac{\partial \hat{TD}|_{coded}}{\partial \phi_1} = 3499 - 2784\phi_1 \qquad (2)$$

$$\frac{\partial \hat{TD}|_{coded}}{\partial \phi_2} = 2060 \qquad (3)$$

$$\frac{\partial \hat{TD}|_{coded}}{\partial \phi_3} = -751 \qquad (4)$$

$$\frac{\partial \hat{TD}|_{coded}}{\partial \phi_4} = -1571 \qquad (5)$$

Table 2: Values of Coded $\hat{TD}$ Partials at Coded Range Extremes

ϕ	Name	-1	0	1
1	*Force*	6283	3499	715
2	*MTBFc*	2060	2060	2060
3	*MTTR*	-751	-751	-751
4	*Delay*	-1571	-1571	-1571

Working with the response metamodel in uncoded form is, in some cases, easier, as the calculations are made in the factors' original units. Table 3 gives the values for the uncoded partial derivatives of estimated TD at the low and high extremes (-1 and 1 in coded terminology) of each factor. The values in the table, given in units of tons delivered per each variable's unit, show the incremental change in estimated TD per unit change in the factor. For example, a C-130 fleet of 64 airlifters (coded as -1) will deliver 131 more tons for each additional C-130; or, a C-130 fleet will deliver 1030 more tons of cargo for an increase in *MTBFc* of one hour, independent of the original reliability of that fleet's airlifters.

Table 3: Values of Uncoded $\hat{TD}$ Partials at Coded Range Extremes

ϕ	-1	1
1	131 Tons/Airlifter	15 Tons/Airlifter
2	1030 Tons/Hour	1030 Tons/Hour
3	-626 Tons/Hour	-626 Tons/Hour
4	-449 Tons/Hour	-449 Tons/Hour

The uncoded partials are also quite useful for examining the relative merit of the four factors in forming the response. Two examples:

1. Increasing the C-130's reliability by one hour between critical failures is equivalent to increasing the fleet size from 64 to 72 airlifters. In other words, eight more airlifters, a 12% increase in fleet size, is equally productive in estimated TD to the original 64-airlifter fleet with each airlifter modified so as to increase its reliability by one hour between critical failures.
2. Increasing the C-130's reliability by one hour between critical failures is equivalent to improving its mean repair time by 1.65 hours. Conversely, a one hour improvement in repair time is equivalent to increasing the airlifter's reliability by 0.6 hours between critical failures. Thus, an incremental improvement in reliability time increases the estimated TD significantly more than the same incremental time improvement in maintainability. In other words, a more reliable fleet tends to be more productive than a more easily maintained fleet, since it experiences less failures. Critical failures are an especially big problem when frequently operating away from MOBs, as is the case for airlifters supporting AirLand Battle-Future operations in this Southwest Asia scenario.

The latter example, which described the relatively higher payoff for increased reliability over increased maintainability, is depicted graphically in Figure 2. The figure is a two-dimensional contour plot of percentage TD, and shows the relative effects of reliability and maintainability; *Force* and *Delay* are fixed at 112 airlifters and 6 hours, respectively. Clearly, the path of steepest ascent has a small, negative slope, meaning that more productivity is gained in moving to the right (increasing reliability) than in moving down the graph (increasing maintainability).

A final observation regarding tons delivered is that increasing an airlifter's R&M enhances productivity during cargo movement surge conditions. When a surge hits an airlift system with airlifters of relatively poor

R&M, they will be less available and therefore less productive; Figure 3 shows this exact condition, for Days D+18 through D+29. Whereas the C-130 does follow the changing daily demand, the C-130RM begins work on the surges more quickly, more extensively, and completes the surge's workload sooner. (Figure 3 is not a result of the estimated TD response; rather, it is a plot of data from two GAMM runs.)

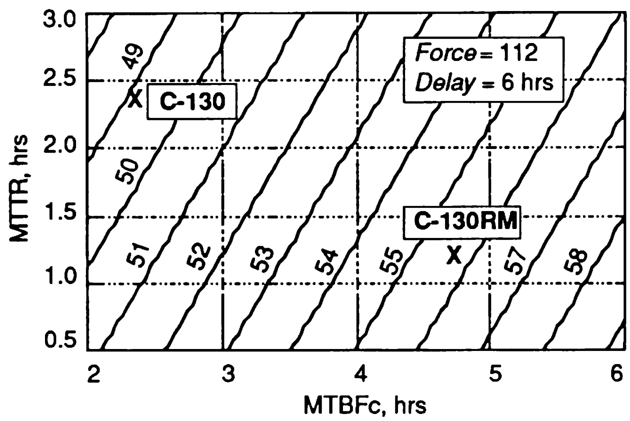

Figure 2: Percentage $\hat{TD}$ Isogram as Function of R&M

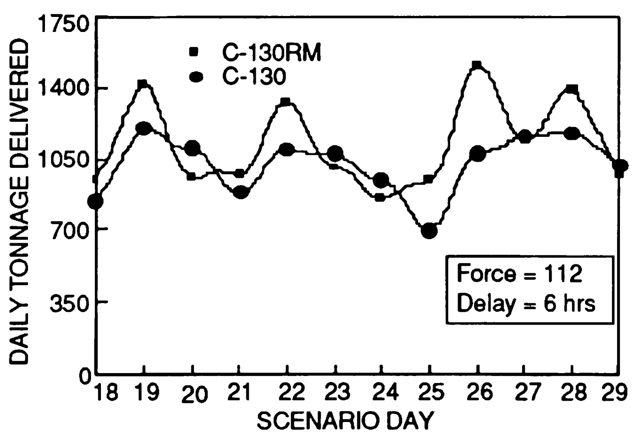

Figure 3: Improved R&M Increases Surge Capability

3.2 Tons On Time (TOT)

Multiple regression of the TOT responses showed all linear terms, *MTBFc*'s second order term, and no interactions to be significant; see Equation (6). Once again, the fit to the metamodel shown in standard coded form as Equation (6) was excellent: adjusted coefficient of multiple determination = 0.979, Wilk-Shapiro = 0.973, and the residual plots showed no evidence of departure from the regression assumptions. The mean absolute percentage error for the TOT metamodel was 4.37%, an accuracy acceptable for this R&M examination.

$$\hat{TOT}\Big|_{coded} = \underset{(96)}{13752} + \underset{(108)}{2482\phi_1} + \underset{(108)}{1275\phi_2} - \underset{(170)}{419\phi_2^2} - \underset{(108)}{429\phi_3} - \underset{(108)}{712\phi_4} \qquad (6)$$

Figure 4 depicts the estimated TOT responses graphically. Observations are basically identical to those made for the estimated TD responses on Figure 1. Note that the generic C-130 performs very poorly in TOT, delivering less than thirty percent of the required tonnage on time; the C-130RM does not perform much better. Southwest Asia is a very stressful scenario in the ability to make timely deliveries, largely due to the sparse airfield density and long flight distances involved.

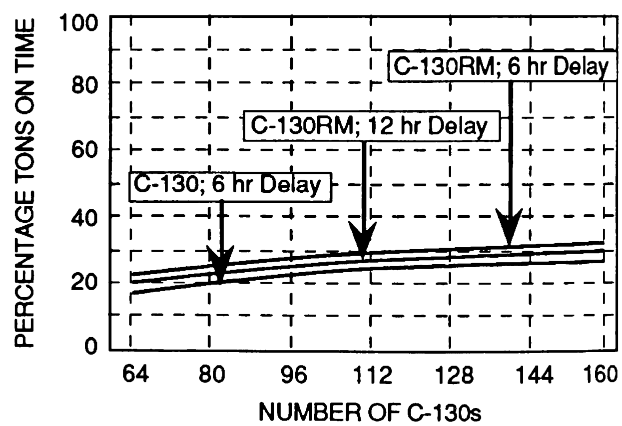

Figure 4: Percentage $\hat{TOT}$ as Function of Force Size

3.3 Utilization Rate (UTE)

Multiple regression of the UTE responses gave all four linear terms and two *Force* interactions as significant; see Equation (7). The UTE metamodel fit the responses excellently: adjusted coefficient of multiple determination = 0.973, Wilk-Shapiro = 0.995, and all residuals showed no evidence of departure from the standard regression assumptions. The mean absolute percentage error for the UTE metamodel was judged quite adequate for this examination at 3.15%.

$$\hat{UTE}\Big|_{coded} = \underset{(0.047)}{4.712} - \underset{(0.053)}{1.194\phi_1} + \underset{(0.053)}{0.359\phi_2} \quad (7)$$

$$- \underset{(0.053)}{0.226\phi_3} - \underset{(0.053)}{0.314\phi_4} - \underset{(0.083)}{0.586\phi_1\phi_2} + \underset{(0.083)}{0.516\phi_1\phi_4}$$

Estimated UTE is depicted as a function of *Force*, *Delay*, and C-130 type in Figure 5. Estimated UTE varies widely, quite low at the largest force sizes to much higher, but not necessarily unreasonably high, values for the small forces. Figures 1 and 4 showed that the small forces were reasonably productive, though they fell short of the larger forces.

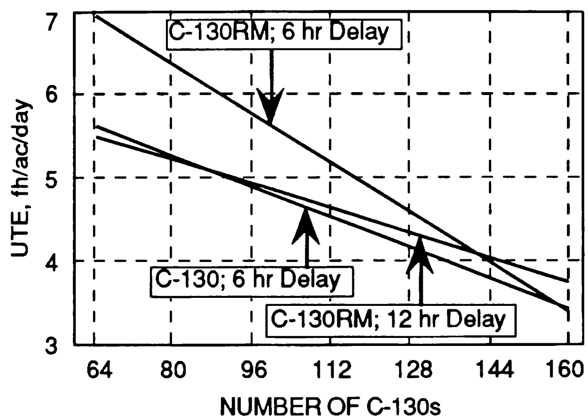

Figure 5: $\hat{UTE}$ as a Function of Force Size

Figure 5 shows that improving the reliability and maintainability of an airlifter fleet enables that fleet to sustain a higher UTE rate, thus enabling that fleet to be more productive, as previously seen in the sections on Tons Delivered and Tons on Time. From another aspect, an airlifter fleet with doubled R&M gives equal productivity to the generic C-130 fleet while using less total flight hours. This is due to the C-130RM airlifters being delayed at non-MOBs less often. A grounded airlifter cannot take on a new load and fly; another airlifter must be scheduled to fly in to pick up the load, resulting in a somewhat less efficient system. The combination of these additional sorties and the long flight distances of this Southwest Asia scenario significantly increase the total fleet flight hours. An airlifter fleet with not only less fleet flight hours, but also improved R&M, will require significantly less repair actions and fewer spare parts.

3.4 Non-Mission Capable (NMC) Time

GAMM reports the percentage of time the airlifter fleet is grounded due to critical failures. The percentage includes maintenance time and logistical pipeline delay time, and does not include time for effecting aircraft battle damage repair. All linear and three two-way interactions, plus *MTBFc*'s second-order term, were significant. Note the strong influence of *MTBFc* in forming the response; it is represented in four of the eight terms of the response sum. Adjusted coefficient of multiple determination is nearly unity, Wilk-Shapiro = 0.962, and the residuals showed no departure from standard assumptions. See Equation (8) for the standard form coded response function. The mean absolute percentage error, 7.26% for the NMC metamodel, was judged acceptable.

$$\hat{NMC}\Big|_{coded} = \underset{(0.050)}{21.160} - \underset{(0.056)}{4.753\phi_1} - \underset{(0.056)}{6.566\phi_2} \quad (8)$$

$$+ \underset{(0.088)}{2.294\phi_2^2} + \underset{(0.056)}{3.751\phi_3} + \underset{(0.056)}{4.625\phi_4}$$

$$- \underset{(0.088)}{1.754\phi_1\phi_4} - \underset{(0.088)}{1.831\phi_2\phi_3} - \underset{(0.088)}{1.924\phi_2\phi_4}$$

A preliminary set of requirements for the Enhanced Theater Airlifter specifies that it be "fully mission capable" (FMC) at least 75% of the time (ETA SORD 1990). Since the sum of FMC and NMC equals one hundred percent, FMC for the C-130 and C-130RM airlifters is readily obtained using Equation (8). Figure 6 shows the percentage FMC for the two airlifters as a function of force size. Three observations:

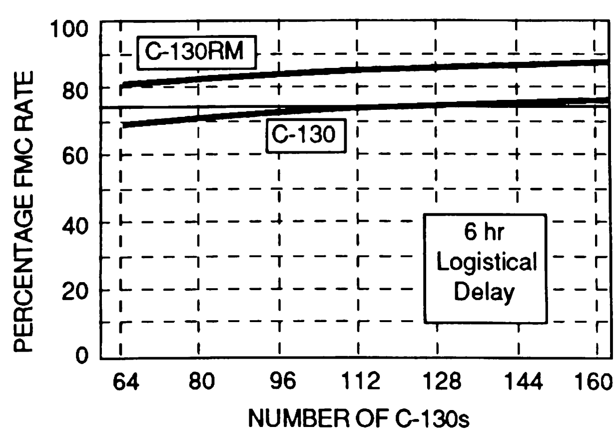

Figure 6: FMC as a Function of Force Size

1. The C-130RM exceeds the 75% FMC requirement at all force sizes in this scenario.
2. The C-130 also exceeds the 75% FMC requirement, although only for the larger force sizes in this scenario. Obviously, the commander has other options, besides the purchase of a new airlifter, in meeting a requirement such as FMC.
3. The only repair actions considered in this analysis are those which correct normal breaks. In an environment which has much threat exposure, airlifters will attrit and be battle damaged, further increasing the NMC rate.

4 SUMMARY AND CONCLUSIONS

Although this analysis was based upon notional C-130 airlifters, specific C-130s can be readily compared for the relative impact of their reliabilities and maintainabilities on theater airlift system productivity. However, the response analyses are based upon the performance characteristics of the C-130H, none of which were independent variables in this effort.

Response metamodels were derived for four measures of merit from the GAMM model: tons delivered, tons delivered on time, utilization rate, and non-mission capable rate. The analysis methodology used for this effort identified first and second order, and first order interaction terms, with each of those terms' significance judged through the examination of the quality of each regression. Each metamodel was validated through an examination of its mean absolute percentage error, which gave the amount of departure of the metamodel from actual GAMM runs. Specific highlights of this analysis are as follows:

1. Doubling the reliability and maintainability of the generic C-130 gives statistically significant benefits. Specifically, doubling the C-130's R&M: 1) increases its productivity by 6% in tons delivered and 4.5% in tons on time; 2) increases its responsiveness; and 3) increases FMC rate 12%.

   Although benefits are clearly attained through R&M improvements, they are of relatively small size and marginal utility. Similarly-sized benefits can be realized through relatively small increases in the number of C-130s in the scenario.

2. Improvements to the C-130's reliability contribute more to increasing its productivity than do improvements to its maintainability.

Remember that the C-130RM is not the same as the Enhanced Theater Airlifter; it almost certainly exceeds the reliability and maintainability that will be required of the ETA. Furthermore, airlifter designs proposed as an ETA may not meet the requirements of the ETA R&M specification, placing them even farther below the C-130RM productivities and efficiencies shown in this paper.

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