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Platform Design for Fleet-Level Efficiency: Application for Air Mobility Command (AMC)

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Preface & Acknowledgements

Welcome to our Tenth Annual Acquisition Research Symposium! We regret that this year it will be a “paper only” event. The double whammy of sequestration and a continuing resolution, with the attendant restrictions on travel and conferences, created too much uncertainty to properly stage the event. We will miss the dialogue with our acquisition colleagues and the opportunity for all our researchers to present their work. However, we intend to simulate the symposium as best we can, and these *Proceedings* present an opportunity for the papers to be published just as if they had been delivered. In any case, we will have a rich store of papers to draw from for next year’s event scheduled for May 14–15, 2014!

Despite these temporary setbacks, our Acquisition Research Program (ARP) here at the Naval Postgraduate School (NPS) continues at a normal pace. Since the ARP’s founding in 2003, over 1,200 original research reports have been added to the acquisition body of knowledge. We continue to add to that library, located online at www.acquisitionresearch.net, at a rate of roughly 140 reports per year. This activity has engaged researchers at over 70 universities and other institutions, greatly enhancing the diversity of thought brought to bear on the business activities of the DoD.

We generate this level of activity in three ways. First, we solicit research topics from academia and other institutions through an annual Broad Agency Announcement, sponsored by the USD(AT&L). Second, we issue an annual internal call for proposals to seek NPS faculty research supporting the interests of our program sponsors. Finally, we serve as a “broker” to market specific research topics identified by our sponsors to NPS graduate students. This three-pronged approach provides for a rich and broad diversity of scholarly rigor mixed with a good blend of practitioner experience in the field of acquisition. We are grateful to those of you who have contributed to our research program in the past and encourage your future participation.

Unfortunately, what will be missing this year is the active participation and networking that has been the hallmark of previous symposia. By purposely limiting attendance to 350 people, we encourage just that. This forum remains unique in its effort to bring scholars and practitioners together around acquisition research that is both relevant in application and rigorous in method. It provides the opportunity to interact with many top DoD acquisition officials and acquisition researchers. We encourage dialogue both in the formal panel sessions and in the many opportunities we make available at meals, breaks, and the day-ending socials. Many of our researchers use these occasions to establish new teaming arrangements for future research work. Despite the fact that we will not be gathered together to reap the above-listed benefits, the ARP will endeavor to stimulate this dialogue through various means throughout the year as we interact with our researchers and DoD officials.

Affordability remains a major focus in the DoD acquisition world and will no doubt get even more attention as the sequestration outcomes unfold. It is a central tenet of the DoD’s Better Buying Power initiatives, which continue to evolve as the DoD finds which of them work and which do not. This suggests that research with a focus on affordability will be of great interest to the DoD leadership in the year to come. Whether you’re a practitioner or scholar, we invite you to participate in that research.

We gratefully acknowledge the ongoing support and leadership of our sponsors, whose foresight and vision have assured the continuing success of the ARP:



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Logistics Management

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Platform Design for Fleet-Level Efficiency: Application for Air Mobility Command (AMC)

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Abstract

The approach presented here combines techniques from multidisciplinary design optimization and operations research to improve energy efficiency-related defense acquisition decisions. The work focuses upon the acquisition of new aircraft for the U.S. Air Force Air Mobility Command missions. Air Mobility Command is the largest consumer of fuel in the Department of Defense, making this a relevant example application. The approach here builds upon previous efforts that examined fleet-level acquisition decisions for commercial airline-related problems, so the paper describes changes necessary to use the problem decomposition strategy of the previous applications in the context of Air Mobility Command. With many of these changes made, the approach is used to simultaneously select requirements for a new cargo aircraft; predict size, weight, and performance of that new aircraft; and also allocate the new aircraft along with existing aircraft. The fuel efficiency of the resulting fleet provides a metric for comparison. The approach, with the abstractions and assumptions used, successfully provides a description of a new cargo aircraft that impacts fleet-level metrics. Results in this study consider a simplistic three-route network and two larger networks, all informed by actual Air Mobility Command data captured by the Global Air Transportation Execution System.

Introduction

The *Energy Efficiency Starts with the Acquisition Process* factsheet (DUSD[AT&L], 2012) states, “Neither current requirements or acquisition processes accurately explore tradeoff opportunities using fuel as an independent variable.” The factsheet also states, “Current processes undervalue technologies with the potential to improve energy efficiency.” Studies conducted by the Institute for Defense Analyses, the Defense Science Board, Energy Security Task Force, and JASON have all alluded to the significant risk and operational constraints that energy efficiency issues pose on military operational flexibility. The consumption and transport of fuel across a combat theater, throughout the life cycle of operational systems, poses significant operational risk, strategic vulnerability, and increased monetary cost in supporting forward-force assets. Additionally, increasing fuel consumption shifts focus to the acquisition of an increasing number of “tail units” in maintaining forward-force assets. Aviation fuel contributes the largest percentage of energy consumption in the



Department of Defense (DoD), with the Air Mobility Command (AMC) being the single largest consumer (Allardice, 2012). This makes an air mobility-related application relevant for the current research effort.

AMC is a branch of the United States Air Force that is responsible for a wide range of airlift missions that span its global theater of operations. AMC's mission profile mainly consists of worldwide cargo and passenger transport, air refueling, and aeromedical evacuation. AMC also provides transports for humanitarian supplies for major natural disaster around the world. Platforms in operation include C-5 Galaxy, C-17 Globemaster III for long range strategic missions, C-130 Hercules for tactical missions, KC-135 Stratotanker, and KC-10 Extender for aerial refueling missions, and various VIP transport platforms including Air Force One. AMC also utilizes Civil Reserve Air Fleet contractually committed from U.S. airlines (Air Mobility Command, 2013).

The complex logistics involved in the transportation of various cargos across its service network requires effective deployment of its fleet of cargo aircraft in meeting daily cargo delivery requirements, while minimizing fuel consumption and subsequent costs. These fuel costs are naturally driven by the choice of aircraft design and individual flight legs flown by the AMC fleet, in meeting cargo obligations within a prescribed schedule timeframe. The identification of cost-saving measures in minimizing fleet-wide fuel consumption is thus intuitively tied into the design of the aircraft itself, and the structure of the routes flown. However, the characteristics of aircraft flown dictate the kind of network that the fleet can serve, thus making it a closely coupled problem.

The objective of this work is to provide a decision-support framework that assists acquisition practitioners in identifying optimal characteristics of new assets (here, aircraft) that can minimize fuel dependency of the entire system architecture in which they serve (here, the fleet of cargo aircraft). This context is driven by the coupled nature that an aircraft design has on fleet operations. The framework in this paper provides a process that can examine how acquisition (and pre-acquisition) decisions describing the requirements for a new aircraft might be made to directly reduce fleet-level fuel usage/cost, considering the operational network and other existing assets along with the potential new (or modified) platform. Consideration of the aircraft design and fleet allocation problems simultaneously presents many decision variables—a condition where the size of the problem rapidly exceeds the mental capability of the designer. Hence, a computational approach becomes necessary to address the complexities associated with the coupled problem. This research will advance the knowledge on how to perform trade-offs with fleet-level fuel consumption as one of the quantities of interest and will enhance understanding about what features this kind of process should entail.

Problem Statement

Previously research at Purdue University has used decomposition strategies that allow a direct connection between the design of a new system (here, an aircraft) and its operations along with other existing systems (here, a fleet of aircraft). The result is an approach that can maximize or minimize a fleet-level objective function by searching for a set of decision variables that describe the new system design and describe the allocation of the new and existing systems to perform operational missions. While a single, monolithic problem statement can reflect this kind of problem, solution of the resulting mixed-integer, non-linear programming problem (MINLP) is difficult, if not impossible. The decomposition strategy breaks down the computational complexity of the decision space into a series of smaller subproblems controlled by a top-level problem. The decomposition approach addresses the issue of tractability, of solving a monolithic, mixed discrete non-linear programming problem, and has yielded better “design solutions” across a set of aviation



applications including commercial airlines, fractional management companies, and air taxi services (Mane & Crossley, 2006, 2012; Mane, Crossley, & Nusawardhana, 2007). The motivation of these prior works in identifying cost- and fuel-saving characteristics of a new, yet-to-be-acquired aircraft bears great similarity to the U.S. Air Force Air Mobility Command (AMC) problem. This paper presents a process that allows investigation of trade-offs between fleet-level fuel usage, performance metrics, and acquisition alternatives for a conceptual problem that resembles missions of the AMC.

AMC's automated air transportation management system, Global Air Transportation Execution System (GATES), is managed by USTRANSCOM and has very detailed information on palletized cargo and personnel transported by the AMC fleet. Cargo transported by the strategic fleet, consisting of C-5 and C-17 aircraft, and the Boeing 747 Freighter (747-F) from the Civil Reserve Air Fleet (CRAF) for long-range missions, are considered as a representative measure of typical cargo flow on the AMC service network. Each data item entered in "GATES Pallet data" represents cargo on a pallet or a pallet-train that was transported. Each pallet data entry item has detailed information about the pallet, such as pallet gross weight, departure date and time, arrival date and time, mission distribution system (MDS), tail number, aerial port of embarkation (APOE), aerial port of debarkation (APOD), pallet volume, pallet configuration, and so forth. These data enable the reconstruction of the route network, pallet demand characteristics, and existing fleet size for our allocation problem.

In this paper, the following assumptions are made on operations of the fleet, based on the available dataset:

In this paper, the following assumptions are made on operations of the fleet, based on the available dataset:

1. The filtered route network from the GATES dataset is representative of all AMC cargo operations.
 - a. Demand for the subset served by C-5, C-17, and 747-F (75% of all pallets in the GATES dataset)
 - b. Fixed density and dimension of the pallet, representing the 463L pallet type
2. The aircraft fleet consists of only the C-5, C-17, and 747-F. The model is indifferent to variants of these aircraft types.
3. Aircraft operate on a round trip between each base pair to avoid time-of-day scheduling issues and the need for flow balance constraints. A round trip consists of a trip from the hub airport to the outlying base airport and a return trip from the outlying base airport to the hub airport. This assumption played an important role in simplifying the previous work for passenger airline problems and was reasonable for scheduled passenger service. This assumption does not appear as acceptable for AMC cargo operations; however, work to date has not removed this assumption.

Example Baseline Three-Route Problem

We motivate our study with a very simple, illustrative "baseline" problem for AMC operations. In this scenario, a representative route network, consisting of three routes with one shared base, is drawn from the GATES dataset for 2006. A schematic of the sample problem network appears in Figure 1. The three aircraft operated on these routes are the C-5, C-17, and the Boeing 747-F (the latter of which is assumed to be operated as a chartered



aircraft). In this simplified problem, we make the assumption that the aircraft operates on a round trip basis and that the amount of palletized cargo between each base and the Hub base is symmetrical. Route 1 has a range of 2,495 nautical miles with 2,775 pallets transported each way in one year. Route 2 has a range of 325 nautical miles with 2,115 pallets transported. Route 3 has a range of 1,101 nautical miles with 2,199 pallets transported in 2006. The maximum distance of the three chosen routes is 2,495 nautical miles, which allows all three types of current strategic airlift aircraft to provide service on these routes without refueling. The intent is to allocate aircraft to the three routes to satisfy all cargo demand.



Figure 1. Schematic of Three-Route Allocation Problem

Aircraft Sizing and Costs

When determining which aircraft to allocate to the network routes, the problem formulation will require estimates of the cost, block time, and fuel consumed by each aircraft type in the fleet. A Purdue in-house aircraft sizing code, written in MATLAB, provides these estimates. Jane's Aircraft database (Jackson, Peacock, & Munson, 2004) provided the input parameters for the three existing aircraft types (C-5, C-17, 747-F) used in this study, as shown in Table 1.

Table 1. Existing Aircraft Characteristics

Parameter	C-5	C-17	747-F
Range (nmi)	2,982	2,420	4,445
Pallet Capacity	36	18	29
W/S (lb/ft ²)	135.48	161.84	137.34
T/W	0.205	0.263	0.286
AR	7.75	7.2	7.7

Direct operating cost (DOC) estimates for commercial aircraft usually include fuel costs, crew costs, maintenance, depreciation, and insurance. DOC estimates are also dependent on the payload, route distance, empty weight, landing weight, and take-off gross weight. While AMC does not have the same operating cost structure, the problem formulation here started using total fleet operating cost as the objective function. Because cost-estimating relationships exist for commercial aircraft, the AMC formulation uses these estimators, even if they may not directly match the costs for AMC operations. The trip DOC of each nominally loaded (based on typical loaded operations) aircraft type, for each route, appears in Table 2.

Table 2. Aircraft Operating Costs of Flight for Each Route

Aircraft Type	Route 1 Cost	Route 2 Cost	Route 3 Cost
Aircraft 1 (C-5)	\$130,503	\$54,752	\$81,671
Aircraft 2 (C-17)	\$107,299	\$43,858	\$66,098
Aircraft 3 (747F)	\$141,124	\$62,691	\$90,358

Figure 2 shows a typical mission profile used for the aircraft sizing and operating missions. To compute the fuel weight necessary for flying the route distance, the fuel required for each mission segment is computed and aggregated. The fuel weight fractions for the different mission segments such as warm-up and take-off, climb, landing and taxi, and reserves are based on empirical data presented in Raymer's textbook (2006). To compute the fuel weight fractions for the cruise and loiter mission segments, the Breguet range and endurance equations are used. The descent segment uses a no-range credit assumption. The reserve fuel fraction is assumed to be 6%, which also accounts for a small amount of trapped and unusable fuel.

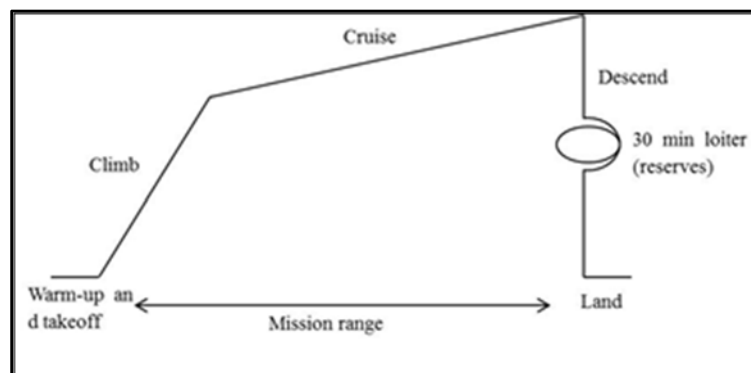


Figure 2. Mission Flight Profile

The payload-range curves for the existing aircraft fleet, depicted in Figure 3, indicate the maximum payload carrying capacity of the aircraft as a function of the distance flown by the aircraft. The payload-range curves for the existing fleet are constructed by using piecewise linear interpolation between specified points from charts presented in Baker, Morton, Rosenthal, and Williams (2002).

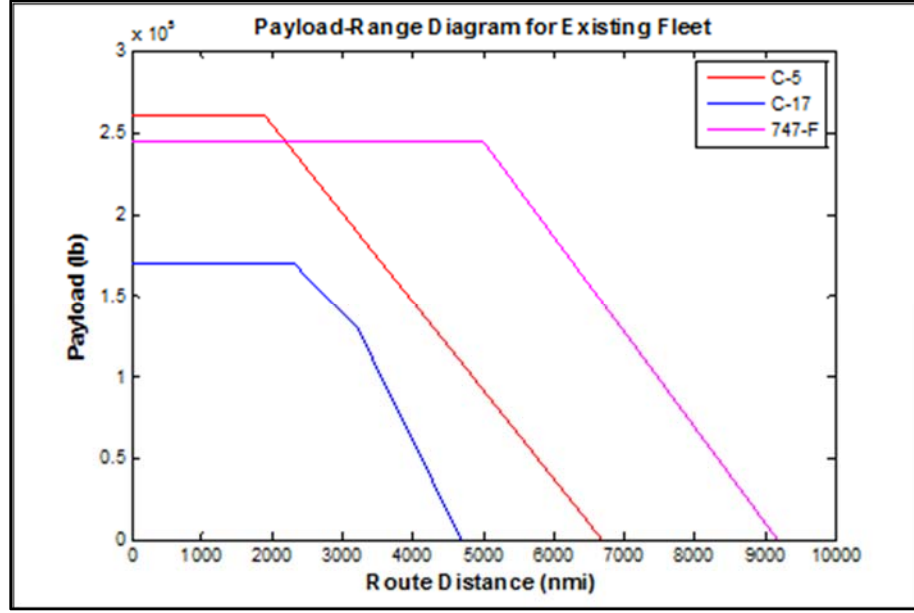


Figure 3. Payload Range Curves for Existing Fleet

Traditional Aircraft Allocation Problem

Using the information provided on the aircraft flight costs (including fuel costs), the objective for the allocation problem seeks to minimize fleet-level DOC by allocating the available fleet to the three routes. Cost coefficients from Table 2 are used in the formulation of the following mathematical programming problem. Mathematical programs have two important aspects of formulation; the *objective function* that reflects the metric being minimized/maximized and *constraints* that reflect resource constraints to the problem. The *decision variables* are the variables of interest that can be manipulated to optimize the objective. The allocation problem statement is as follows:

$$\text{minimize} \quad \text{Fleet DOC} = \sum_{i=1}^3 \left\{ \sum_{A \in C-5, C-17, 747-F} [C_{Ai} x_{Ai}] \right\} \quad (1)$$

$$\text{subject to} \quad \sum_{i=1}^3 x_{Ai} \leq B_{Ai} \quad A = C-5, C-17, 747-F \quad (\text{trip limits/aircraft count}) \quad (2)$$

$$\sum_{A \in C-5, C-17, B-747} Cap_{Ai} x_{Ai} \geq C_i \quad (\text{capacity}) \quad (3)$$

$$x_{Ai} \in \text{int}, \quad x_{Ai} \geq 0 \quad (4)$$

In the case of the traditional aircraft allocation problem, the objective function in Equation 1 seeks to minimize the fleet DOC. The decision variable is given by x_{Ai} (with subscripts for aircraft type and route) and is an integer, making the allocation problem an integer programming problem. The total fleet DOC is the sum of costs associated with the number of round trips an aircraft of type A flies on route i . The constraints expressed in Equations 2 and 3 are the aircraft trip limit and cargo capacity limits on each route (i). The trip limit constraints account for the number of aircraft available; the limiting values for

number of trips operated by a given aircraft type in one year are based upon information from the GATES data.

AMC Fleet Allocation Including Design of New Aircraft

Here, we extend the AMC aircraft allocation problem, to consider the potential addition of a new, yet-to-be-designed aircraft, and its impact on fleet-wide operating costs and fuel consumption. The optimization problem now needs to consider the aircraft costs of the new aircraft as a function of the variables describing the new aircraft. The monolithic optimization problem simultaneously considers the aircraft design and allocation of the fleet's aircraft to meet demand obligations and is given by the following equations.

Minimize

$$\text{Fleet DOC} = \sum_{i=1}^3 \left\{ \left[\sum_{\substack{A \in C-5, \\ C-17, 747-F}} C_{Ai} x_{Ai} \right] + C_{Xi} \left(Pallet_x, (AR)_x, (W/S)_x, (T/W)_x \right) \right\} \quad (5)$$

$$\text{Subject to } \sum_{i=1}^3 x_{Ai} \leq B_{Ai} \quad A = C-5, C-17, 747-F, X \quad (\text{trip limits/aircraft count}) \quad (6)$$

$$\sum_{\substack{A \in C-5, C-17, \\ 747-F, X}} Cap_{Ai} x_{Ai} \geq C_i \quad (\text{capacity}) \quad (7)$$

$$S_{TO} \left(Pallet_x, (AR)_x, (W/S)_x, (T/W)_x \right) \leq D \quad (\text{aircraft take-off distance}) \quad (8)$$

$$6 \leq Pallet_x \leq 36 \quad (9)$$

$$6.0 \leq (AR)_x \leq 9.5 \quad (10)$$

$$65 \leq (W/S)_x \leq 161 \quad (11)$$

$$0.18 \leq (T/W)_x \leq 0.35 \quad (12)$$

$$x_{Ai}, Pallet_x \in \text{int}, x_{Ai} \geq 0 \quad (13)$$

Equation 5 is the objective function that seeks to minimize the fleet's DOC. This equation can be modified for different studies as alternate objectives, such as directly minimizing fuel consumption, and so forth, are considered. Equation 6 preserves the aircraft trip limits for a typical year from values calculated from existing flight data; this represents utilization rate. Equation 7 ensures sufficient pallet capacity for cargo traveling on route i . Equations 8–13 limit the aircraft design based on minimum take-off distance to ensure that the new aircraft can operate at bases in the network. The continuous design variables describing the new aircraft area were limited to remain near the range of values associated with current cargo aircraft. As in the “traditional allocation” problem, the number of trips of each aircraft type, x_{Ai} , are integers. The coupling of the fleet allocation (integer programming) with the aircraft design (non-linear programming) makes the resource allocation problem a mixed-integer, non-linear (MINLP) problem. MINLP problems are sometimes impossible to solve for even moderate-sized problems. However, we adopt a Multidisciplinary Design Optimization (MDO; inspired subspace decomposition approach from prior literature; Mane et al., 2007) that breaks the monolithic MINLP problem of



Equations 5–13 into a coordinated sequence of more tractable problems, as depicted in Figure 4.

Volumetric load factor is a measure introduced as the ratio of the number of pallets carried to the maximum pallet capacity of the aircraft type. As the density of cargo varies by missions, the average weight of a pallet is calculated from the route data and used as the pallet weight for the entire route. The volumetric load factor of the new aircraft is assumed to be the average of the volumetric load factor of the existing aircraft types on that route.

$$\text{Load factor}_{xi} = \frac{\sum_{\substack{A = \text{C-5,} \\ \text{C-17, B-747}}} \text{Load factor}_{Ai}}{\# \text{ of aircraft type operated on route } i} \quad (14)$$

The volumetric load factor formulation, together with average weight of the pallet calculated implicitly, assumes that the new aircraft would be operationally utilized in a similar manner to existing aircraft. The GATES dataset is limited to the AMC operations involving palletized cargo. The design of the new aircraft is strongly influenced by the operational characteristics of the existing AMC fleet and the AMC route network as described in the GATES dataset. However, existing aircraft in the AMC fleet are expected to have the capability to transport outsized cargo and military vehicles in addition to palletized cargo. For instance, the C-5 is capable of carrying two Abrams main battle tanks, an Abrams tank plus two Bradley armored fighting vehicles, 10 LAV light armored vehicles, six Apache attack helicopters, or 36 standard pallets, type 463L (Bolkcom, 2007). The volumetric load factor limitation for the new aircraft based on AMC operations listed in the GATES dataset is a simple and indirect way of ensuring that the new aircraft design meets outsized cargo requirements.

Method and Approach

The consideration of the simultaneous design of a yet-to-be-introduced aircraft and operations of the new aircraft, presents significant computational challenges. We adapt a previously used decomposition strategy, with aviation applications including commercial airlines, fractional management companies, and air taxi services (Mane & Crossley, 2006, 2012; Mane et al., 2007).

Subspace Decomposition Approach

The decomposition strategy, as shown in Figure 4, decomposes the MINLP problem into smaller optimization problems—each sub problem follows the natural boundaries of disciplines involved in formulating the original problem. Prior research (Mane et al., 2007) has applied this decomposition approach to the case of a commercial air transportation problem where the objective is to design a yet-to-be-introduced aircraft that minimizes fleet-level operating cost while meeting passenger demand travel obligations. Here, we adapt the same decomposition approach, adapted to the AMC airlift scenario. The top-level problem, shown in Figure 4, coordinates the aircraft sizing and fleet allocation subproblems.



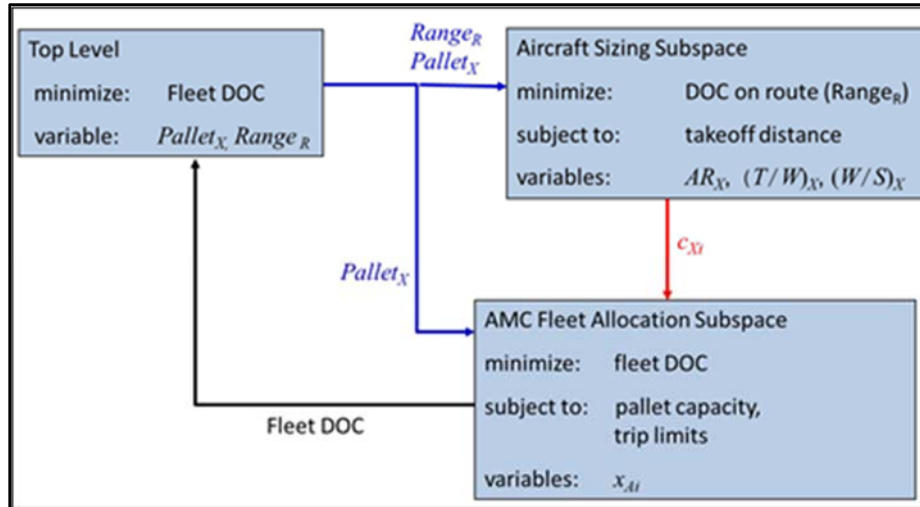


Figure 4. Subspace Decomposition of MINLP Problem

Top-Level Optimization

The top-level problem seeks to minimize the fleet-level DOC using pallet capacity (an integer) and design range (continuous) of the new, yet-to-be-introduced aircraft type X as the decision variables; the optimization problem, at this stage, is addressed using a simple enumeration scheme. A quasi-enumeration approach of varying pallet capacity in increments of one and design range in increments of 200 nmi reduces computational time, albeit with the possibility of reduced resolution of the design space. However, the quasi-enumeration approach maps out correct trends for the objective function topology in the solution space. Heuristic algorithms such as Simulated Annealing (SA), Genetic Algorithms (GA), and so forth, may be needed to solve the small MINLP top-level optimization problem for studies involving more computationally intensive and larger sized top-level problem formulations. These top-level decision variables are essentially “design requirements” for the new cargo aircraft design.

Aircraft Sizing Subspace

The pallet capacity and design range of the yet-to-be-introduced aircraft from the top-level problem then become inputs to the aircraft sizing problem. Here, the aircraft sizing problem seeks to minimize the direct operating cost of the new yet-to-be-introduced aircraft, subject to constraints on minimum take-off distance. Operating cost is the aircraft objective here because it matches the top-level objective for minimum fleet cost.

The aircraft design variables are aspect ratio $(AR)_X$, thrust-to-weight ratio $(T/W)_X$, and wing loading $(W/S)_X$. There are many other design variables, but these three have significant impact on the size, weight, and performance of the aircraft. The objective function can be altered to minimize alternative objectives such as fuel burn, and be subject to additional constraints as required. The aircraft sizing problem is a nonlinear programming problem (NLP) and described by Equations 15–20.

$$\text{Minimize} \quad f = (DOC_{range})_X \quad (15)$$

Subject to

$$S_{To}(Pallet_X, (AR)_X, (W/S)_X, (T/W)_X) \leq D \quad (\text{aircraft take-off distance}) \quad (16)$$



$$6 \leq Pallet_x \leq 36 \quad (17)$$

$$6.0 \leq (AR)_x \leq 9.5 \quad (18)$$

$$65 \leq (W/S)_x \leq 161 \quad (19)$$

$$0.18 \leq (T/W)_x \leq 0.35 \quad (20)$$

After finding the aircraft that leads to the lowest operating cost for the aircraft design range, the aircraft performance is predicted for the routes in the cargo network. The allocation subproblem then uses the cost coefficients for the new aircraft, C_{X1} , C_{X2} , C_{X3} , together with the top-level design variables, design range, and pallet capacity, as inputs.

Determination of Number of New Aircraft

The number of new aircraft to be introduced to the existing fleet is unknown *a priori*, because the capacity of the new aircraft is described by the top-level design variable, $Pallet_x$. However, the AMC strategic fleet is expected to be capable of servicing the maximum possible demand scenario by requirement. AMC force structure programmers use the metric million-ton-miles per day (MTM/D) when funding out-year aircraft purchases, and many civilian agencies are accustomed to visualizing fleet capability in terms of MTM/D (Air Mobility Command, 2010). The *Mobility Capabilities and Requirement Study (MCRS) 2016* (Jackson, 2009) illustrates three different scenarios that the capacity of the strategic fleet must always meet. The peak for MCRS Case 1, which represents the highest level of modeled strategic airlift demand, required 32.7 MTM/D. MTM/D values for each type of aircraft are calculated using empirical data. A C-5 carries 0.1209 MTM/D. The newer C-17 carries 0.1245 MTM/D (Kopp, 2004). The Boeing 747-F carries 0.1705, but is not included in calculating strategic airlift fleet MTM/D, because AMC does not operate the Civil Reserve Air Fleet (CRAF). Hence, the 747-F does not affect the number of new aircraft X required to meet the peak demand. MTM/D of the new aircraft X is calculated using Equation 21. The resulting value is then used to compute the number of new aircraft X required.

$$MTM/D = \frac{\text{Block speed} \times \text{Average payload} \times \text{UTE rate} \times \text{Productivity Factor}}{1,000,000} \quad (21)$$

The utilization rate (UTE rate) of the new aircraft is assumed to be 12 hr/day, and a productivity factor of 4.8 is assumed for the new aircraft, which is within the typical range of the strategic airlift fleet average value.

AMC Fleet Allocation Subspace

The cost of operating the yet-to-be-introduced aircraft type X on individual routes, C_{Xi} , and with pallet capacity $Pallet_x$ are constants in the aircraft allocation problem. Here, the objective is to minimize the fleet-level direct operating costs using characteristics of the existing and yet-to-be-introduced aircraft (cost coefficients for each route, pallet capacity). Constraints are set such that the number of trips per aircraft does not exceed the trip limit for each aircraft type, and the combined capacity of all aircraft provided meets the demand on each route. The allocation subproblem equations are described by Equations 22–25. As described previously, this approach assumes an aircraft round trip assumption, which removes the need for a node balance constraint; this means the capacity enforced by Equation 24 will be sufficient to carry the largest demand between the two bases connected by route i . The local decision variables in the allocation problem, x_{Ai} —the numbers of trips made by aircraft type A on route i —are integers, making the allocation problem an integer



programming (IP) problem. The Generic Algebraic Modeling System (GAMS) software package, accessed through a MATLAB interface, was used to solve the allocation problem, using the CPLEX solver option (Ferris, 1998.)

$$\text{Minimize} \quad \text{Fleet DOC} = \sum_{i=1}^3 \left\{ \sum_{\substack{A \in C-5, \\ C-17, 747-F, X}} [C_{Ai} x_{Ai}] \right\} \quad (22)$$

$$\text{Subject to} \quad \sum_{i=1}^3 x_{Ai} \leq B_{Ai} \quad A = C-5, C-17, 747-F, X \quad (\text{trip limits/aircraft count}) \quad (23)$$

$$\sum_{\substack{A=C-5, C-17, \\ B=747, X}} Cap_{Ai} x_{Ai} \geq C_i \quad (\text{capacity}) \quad (24)$$

$$x_{Ai} \in \text{int}, \quad x_{Ai} \geq 0 \quad (25)$$

Solution for Cases

Example Problem Solutions

The MDO decomposition method reduces the computational cost by separating discipline-specific analysis of problems. As described previously, the route network for the three-route example uses data from GATES for demand and to set trip limits. The objective was to minimize fleet DOC for a representative year of operating the fleet. The actual size of the strategic airlift fleet dedicated to cargo transport was obtained from GATES dataset by identification of unique tail numbers, resulting in fleet composition of 92 C-5s, 145 C-17s, and 69 747-Fs. Because this three-route problem is much smaller than the full network reconstructed from the GATES dataset, the number of aircraft and the fleet-level MTM/D value for the three-route problem were reduced proportionally to the pallet demand from the entire GATES dataset pallet demand. The reduced fleet consists of four C-5 aircraft, five C-17 aircraft, and three 747-Fs. Each aircraft type is limited to a trip limit value calculated from the GATES dataset by extracting the number of trips made by each type of aircraft per year. The C-17 has a limit of 53 trips per year per aircraft, the C-17 has a limit of 103 trips per year per aircraft, and the 747-F is limited to 69 trips per year per aircraft. Because the utilization rate of an aircraft depends highly on the aircraft's age, the newly designed aircraft's trip limit is assumed to be 110% of the highest trip limit in the existing fleet, or 113 trips per year per aircraft. These trip limits ensure that the allocation does not exceed the number of available aircraft. Figure 5 shows the results of the partial enumeration employed for the top-level problem, and Table 3 summarizes the solution obtained for the example three-route network.



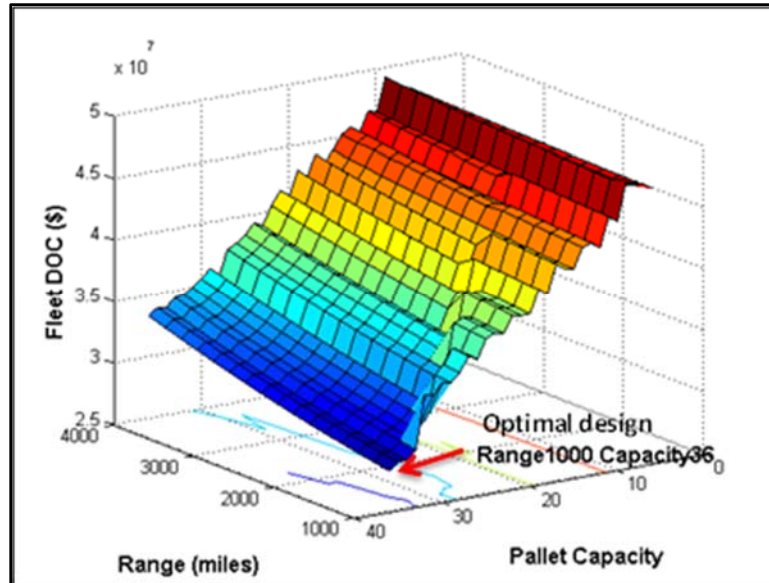


Figure 5. DOC Variation for the Top-Level Design Space for the Three-Route Problem

Table 3. Solution for the Example Problem

Variable, Constraint, Objective	Baseline Allocation	Allocation & Design Solution
$x_{C-5,1}$ (trips by C-5s on Route 1)	126	0
$x_{C-5,2}$ (trips by C-5s on Route 2)	0	167
$x_{C-5,3}$ (trips by C-5s on Route 3)	86	0
$x_{C-17,1}$ (trips by C-17s on Route 1)	1	0
$x_{C-17,2}$ (trips by C-17s on Route 2)	236	1
$x_{C-17,3}$ (trips by C-17s on Route 3)	1	1
$x_{747-F,1}$ (trips by Boeing 747-F on Route 1)	0	0
$x_{747-F,2}$ (trips by Boeing 747-F on Route 2)	117	0
$x_{747-F,3}$ (trips by Boeing 747-F on Route 3)	90	0
x_{X1} (trips by aircraft X on Route 1)	-	133

x_{x2} (trips by aircraft X on Route 2)	-	49
x_{x3} (trips by aircraft X on Route 3)	-	157
Number of new aircraft X introduced	-	3
$Range_x$, nautical miles	-	1,000
$Pallet_x$	-	36
$(W/S)_x$, lb/ft ²	-	104.2
$(T/W)_x$	-	0.208
AR_x	-	6.00
Total pallet capacity on Route 1	4,554	4,788
Total pallet capacity on Route 2	7,641	7,794
Total pallet capacity on Route 3	5,724	5,670
Fleet DOC for one year	\$ 49,458,132	\$ 28,304,998
DOC saving from baseline	-	42.77 %
Fleet fuel cost for one year	\$ 21,716,142	\$ 11,597,685
Fuel cost saving from baseline	-	46.59 %

The baseline scenario describes the current fleet operation without the introduction of the new aircraft type X. The results obtained for this allocation problem provide a baseline to measure the effectiveness of introduction of the yet-to-be-designed aircraft in the fleet mix. The allocation problem from the baseline scenario results in a \$49,458,132 fleet DOC per year. For these two solutions, the fleet-level fuel consumption is also available. With the newly introduced type X aircraft, the fleet uses almost 47% less fuel. However, this approach clearly customizes the new aircraft to the route network and demand structure. As a result, the new aircraft X is a short-range aircraft with a very large volume; this enables fewer flights of this smaller aircraft to meet demand. Figure 6 emphasizes this result by including the new aircraft's payload-range performance along with the existing aircraft.



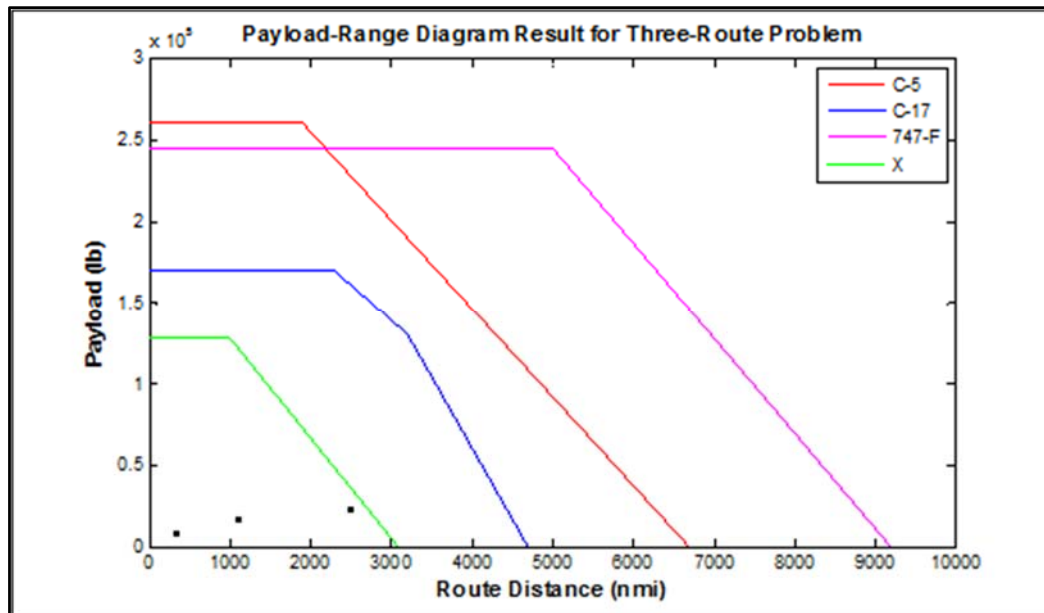


Figure 6. Payload Range Curves for Existing Aircraft and Optimal Aircraft Sizing Solution for Three-Route Problem

AMC Expanded Network Solution

Symmetric Demand Network

The three-route problem provides a simplistic example of AMC operations to illustrate the approach and demonstrate the ability to generate solutions. Increasing the size of the network to investigate the ability to solve larger and more complex network system problems using decomposition is appropriate. Our current formulation assumes a round trip assumption, where each aircraft flies from an origin base to a destination base and then returns to the same origin; this is a reasonable assumption under symmetric demand conditions, which was appropriate for previous commercial passenger airline work. However, many of the routes in the AMC network do not have symmetric demand, because most cargos are transported one way. To study the effects of asymmetric demand and effectively address this issue, we developed a metric that calculates the asymmetry between origin destination pairs (O-D pairs).

$$\text{Demand asymmetry} = \frac{|Demand_{O,D} - Demand_{D,O}|}{\max(Demand_{O,D}, Demand_{D,O})} \times 100 \quad (26)$$

This approach would be zero if the demand was symmetric. With demand asymmetry calculated on each route, the routes with a demand asymmetry greater than 25% are filtered from the route network before implementing the decomposition approach to simultaneously design the new cargo aircraft while also allocating the fleet to meet demand. Of the 701 routes in the full network reported in GATES, 111 routes have a demand asymmetry of less than 25%. This set of filtered routes represents 16% of total routes and 28% of the pallets, and has an average of 11% demand asymmetry

As the size of the route network and demand increased from the three-route problem, the numbers of aircraft available for use in the problem also increased in proportion to the demand increase. The existing fleet in this symmetric demand problem comprises 27 C-5s, 42 C-17s, and 20 747-Fs. The MTM/D value is also increased in proportion to demand decrease to have more aircraft type X introduced to the fleet. Table 4

summarizes the solution obtained for the symmetric demand route network (although without the per-route detail, given the size of the problem), and Figure 7 presents the partial enumeration scheme to solve the top-level problem.

Table 4. Solution for the Symmetric Demand Problem

Variable, Constraint, Objective	Baseline Allocation	Allocation & Design Solution
x_{C-5} (trips by C-5)	1,431	1,431
x_{C-17} (trips by C-17)	3,074	344
x_{747-F} (trips by 747-F)	1,378	1,380
x_x (trips by aircraft X)	-	1,469
Number of aircraft X introduced	-	13
$Range_x$, nautical miles	-	2,200
$Pallet_x$	-	35
$(W/S)_x$, lb/ft ²	-	113.6
$(T/W)_x$	-	0.227
AR_x	-	6.15
Fleet DOC for one year	\$595,393,013	\$469,500,435
DOC saving from baseline	-	21.14 %
Fleet fuel cost for one year	\$297,067,262	\$231,347,251
Fuel cost saving from baseline	-	22.12 %



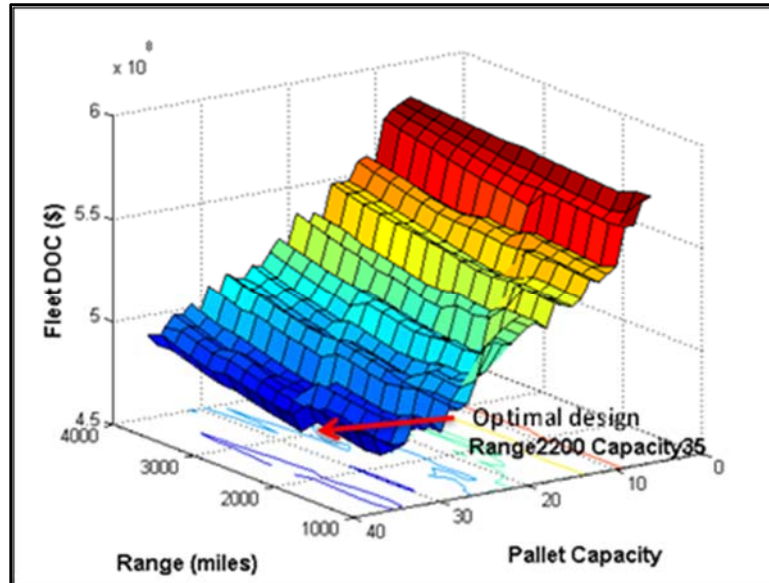


Figure 7. DOC Variation for the Top-Level Design Space for the Symmetric Demand Problem

With the dataset at hand, the allocation of the problem with the introduction of aircraft type X was investigated. The resulting optimal design variable at the top level suggests an aircraft design capacity of 35 pallets and a design range of 2,200 nautical miles. The aircraft sizing subproblem result suggests aircraft type X design with the wing loading of 113.6 lb/ft², aspect ratio of 6.15, and thrust-to-weight ratio of 0.227. The allocation subproblem introduces 13 aircraft type X in the fleet and provides DOC savings of 21.14% and fuel cost savings of 22.12% compared to the allocation of the fleet without the new aircraft for this symmetric demand scenario. These results also indicate a comparatively short-range aircraft with a high pallet capacity. As apparent from Figure 8, this solution also requires some of the existing aircraft to perform longer range routes, while the fleet cost and fuel savings result by using the newer aircraft on shorter routes.

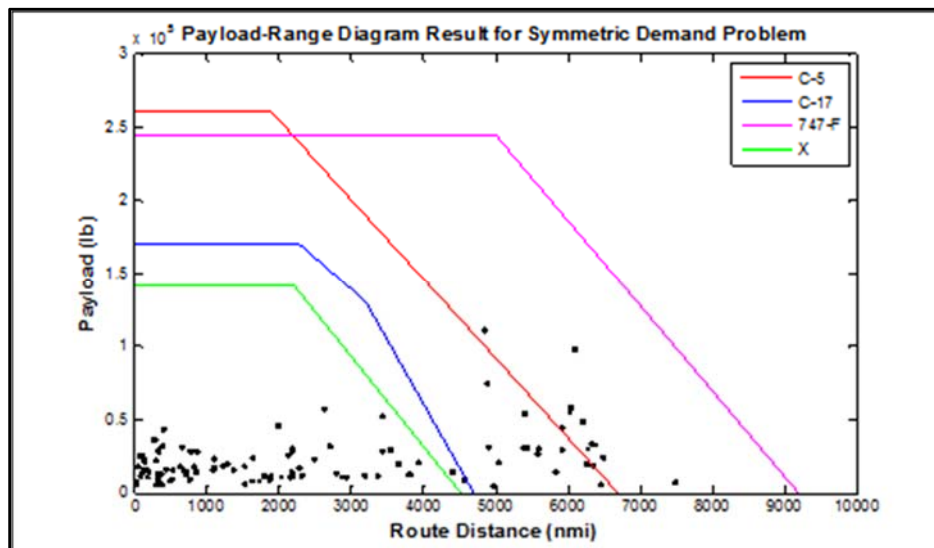


Figure 8. Payload-Range Curves for Existing Aircraft and Optimal Aircraft Sizing Solution for Symmetric Demand Problem

Full Network

Having presented applicability of the decomposition strategy to the symmetric demand problem, the full AMC network problem was attempted. Routes and pallet demand from the entire GATES dataset were considered in this full network problem. The fully considered AMC service network has a 66% demand asymmetry (based on Equation 11). Thus, the round trip assumption may not be reflective of actual operations, but the constraints will ensure there is sufficient capacity in both directions on a route, even if one direction has a substantially lower demand. With this potentially limiting assumption, addressing this problem demonstrates that the approach can scale to larger problems, in terms of routes served. In the full network problem, the round trip assumption implies every trip has symmetric demand resulting in a total of 209,787 pallets delivered between 701 routes. Table 5 summarizes the solution obtained for the full network problem, and Figure 9 illustrates the partial enumeration to find the top-level variables.

Table 5. Solution for the Full Network Problem

Variable, Constraint, Objective	Baseline Allocation	Allocation & Design Solution
x_{C-5} (trips by C-5)	4,876	4,876
x_{C-17} (trips by C-17)	6,320	303
x_{747-F} (trips by 747-F)	4,753	2,112
x_x (trips by aircraft X)	-	5,537
Number of aircraft X introduced	-	49
$Range_x$, nautical miles	-	2,400
$Pallet_x$	-	36
$(W/S)_x$, lb/ft ²	-	114.4
$(T/W)_x$	-	0.228
AR_x	-	6.23
Fleet DOC for one year	\$1,743,525,560	\$1,370,781,919
DOC saving from baseline	-	21.38 %
Fleet fuel cost for one year	\$888,509,686	\$693,047,455
Fuel cost saving from baseline	-	22.00 %



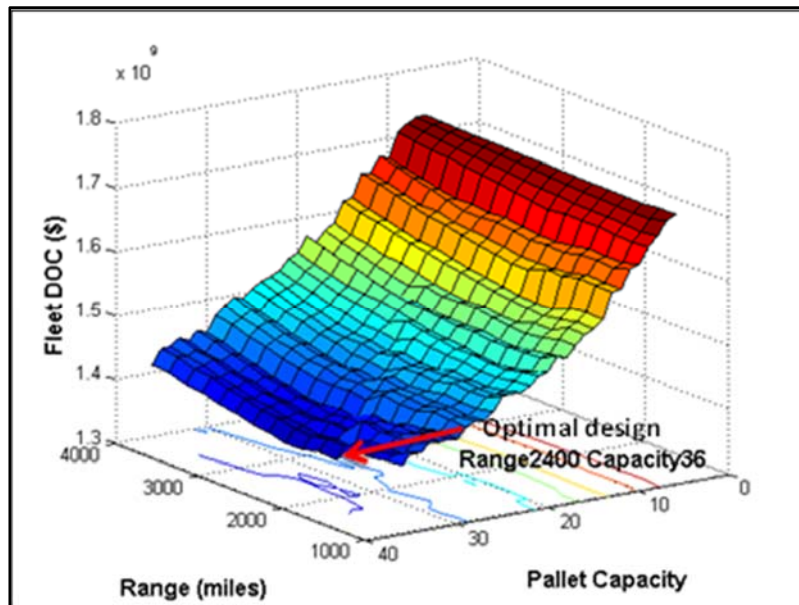


Figure 9. DOC Variation for the Top-Level Design Space for the Full Network Problem

The results suggest the introduction of 49 aircraft type X to the existing fleet with a maximum pallet capacity of 36, using the design pallet weight of 4,003 pounds to set the volume of the fuselage and design range at MTOW of 2,400 nautical miles. The new aircraft again mainly service the shorter routes in the route network as evidenced in Figure 10. The wing loading of aircraft X is 114.4 lb/ft², the aspect ratio is 6.23, and the thrust-to-weight ratio of aircraft X is 0.228, which is a slight increase compared to the solution from the symmetric demand scenario due to a slight increase in fuselage size and design range.

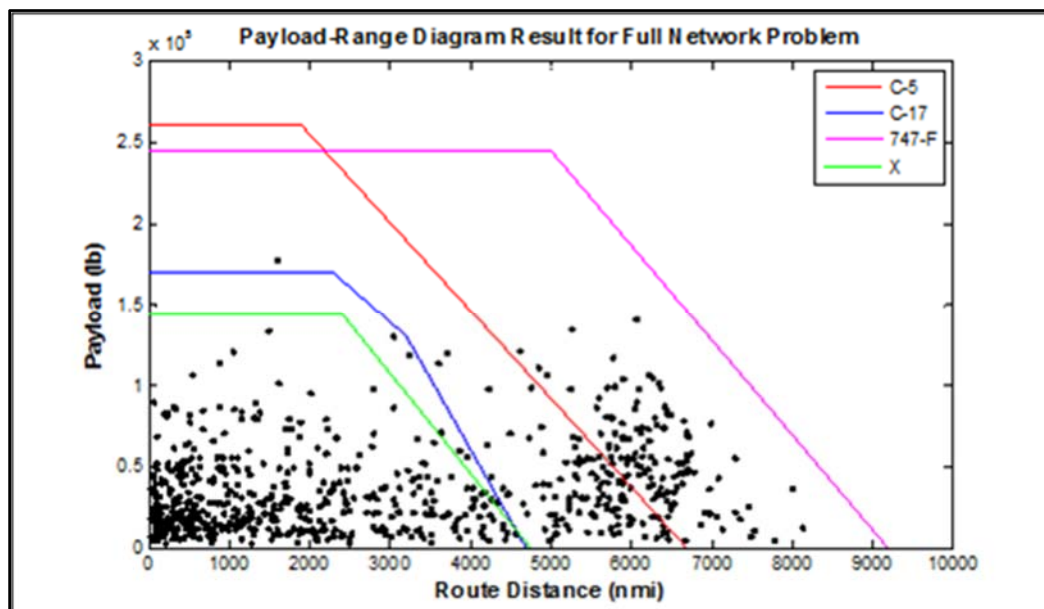


Figure 10. Payload Range Curves for Existing Aircraft and Optimal Aircraft Sizing Solution for Full Network Problem

Future Work and Conclusions

The studies presented here assume simplified demand scenarios to demonstrate the viability and applicability of the decomposition approach in solving problems that represent AMC operations, and as a tool to better inform acquisition decisions. AMC operations typically involve highly uncertain cargo demand operations—a contrasting difference to airline problems that are fairly constant. The uncertainties in cargo demands and shipping priorities manifest as uncertainties in the load factor and quantity of cargo flow between O-D pairs.

The uncertainties in load factor and total cargo can be modeled using a Monte Carlo sampling technique. This model addresses the uncertainty in both demand and load factor, within a probabilistic framework. Through addressing uncertainty via a Monte Carlo sampling technique, the subspace decomposition method can determine a yet-to-be-introduced aircraft design that is tailored to minimize fleet-level cost (fuel/direct operating) under prescribed uncertainty. Future work will reflect a more representative mixture of the AMC fleet from the GATES dataset with uncertainty in the operational characteristics of the fleet and route network.

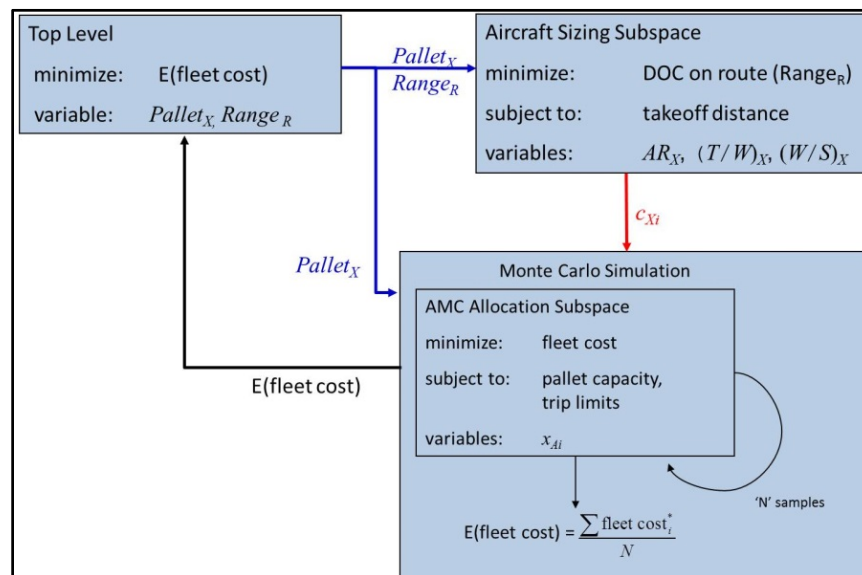


Figure 11. Subspace Decomposition of MINLP Problem With Uncertainty

The round trip assumption, although valid for studies with a symmetric demand route network, appears to be a weak abstraction for the entire network, as mentioned earlier. Future work will consider “scheduling-like” formulations for the resource allocation problem by implementing node balance constraints. The addition of node balance constraints would increase the computational complexity and possibly the computational burden, as individual aircraft tail numbers need to be tracked in the model. However, this formulation allows modeling of varying directional pallet demand between origin destination pairs. An acquisition support issue is the selection of the top-level design variables that represent some of the requirements for a new platform. Payload capacity, design cruise velocity, and range are common aircraft design variables and are logical choices for these top- or system-level variables. Future investigations will consider other platform requirement variables as necessary. The resulting values for these requirement variables can inform acquisition decisions about what new platform requirements will lead to a more successful fleet.

The studies presented here also use direct operating cost as the objective function. This follows from the previous work for commercial airline-related investigations, but here this allows for the chartered 747-F aircraft to be modeled as part of the problem. If a formulation sought to minimize fuel consumed by AMC, it is possible that one solution would lead to carrying all cargo on the chartered 747-F aircraft. As demonstrated previously, fleet-level fuel values are readily available and minimizing DOC has a strong relationship to minimizing fuel consumption.

From the results, all of the newly designed aircraft should be smaller aircraft than the existing aircraft in the strategic fleet. This diversifies the size of the aircraft, and tries to exploit the fact that existing large-size aircraft generally carry only a small fraction of their maximum weight (and in some cases volume) capacity. The smaller aircraft will be used predominantly on routes that are short and will carry a comparatively large number of pallets per flight. In comparison, the scenario in which the new aircraft design and allocation relaxes the load factor imposed on weight suggests an even smaller aircraft that is designed to carry only a small number of palletized cargos weighing approximately 4,000 lbs each. Results suggest that this platform will be even more efficient as many of the routes are short and day-to-day base cargo. The fuel saving in all cases are directly related to the DOC saving as fuel cost is a driving factor in DOC.

The research presented in this paper demonstrates an approach to concurrently design a yet-to-be-introduced aircraft and its fleet-level operations in the context of military airlift operations. The decomposition approach presented in this paper makes the resulting MINLP problem tractable. The solution space of the top-level optimization problem provides a landscape that could help acquisition practitioners make informed acquisition decisions and design choices about the new platform. The design combination of the top-level problem corresponds to different levels of fleet-level direct operating costs, and consequently, different operations (allocation of fleet over service network.)

Although the studies presented here focus on the concurrent design of aircraft to improve fleet-level operational performance metrics, the problem formulation and solution methodology have features that can be extended to other systems of interest and/or the design of multiple yet-to-be-designed systems.

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