A FLEET ASSIGNMENT MODEL FOR OPTIMIZING MILITARY AIRLIFT

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ABSTRACT

Developed in this paper is a mathematical model for optimizing the airlift capability of the US Air Force (USAF) in a large-scale deployment operation. Given a number of airbases from which a number of cargos of various sizes and weights are to be airlifted to a number of destinations using a specific fleet of military aircrafts subject to equipment airlift capability and aircrew availability constraints, the model assigns the most appropriate fleet type and determines the number of aircrafts required for each flight segment in such a way to minimize the overall cost of the airlift operation.

Keywords: Military logistics, Fleet assignment, Airlift optimization, Integer programming

INTRODUCTION

In military terms, *Force projection* refers to a large-scale deployment of military equipment from a set of bases to a set of destinations, with the objective of executing such deployment using a given set of transportation assets with limited capacities and capabilities as efficiently as possible. Since force projection is concerned with the transportation of military equipment and personnel over long distances in a short amount of time, it often takes the form of an airlift operation.

The airlift assets used to transport military cargos are typically procured and operated by the USAF or by commercial airline companies under contract to the military. While a variety of airlift assets can be used by the military, this study assumes that the airlift operation is carried out by a USAF fleet consisting of a mix of three types of commonly used cargo planes: the C-5M, the C-17A, and the C-130J. These aircrafts have different payload and volume capacities, cruising speeds, flight ranges, and flight costs. Payload is the carrying capacity of an aircraft usually measured in terms of weight. An aircraft volume capacity is measured in pallet position equivalents (PPE). For our purposes, we assume that when the distance of the flight route is longer than the aircraft maximum range or when such a range is shortened due to the aircraft cruising speed and/or cargo weight, aerial refueling from a tanker aircraft, such as the McDonnell-Douglas KC-10 or the Boeing KC-135, is available and successful.

The hourly flight costs used in this study are the reimbursement rates for fixed wing aircrafts published by the Department of Defense (DOD reimbursement rates, 2017). These rates are used by DOD to reimburse organizations providing airlift services to the department. Table 1, below, provides a summary of the three aircraft types' payload, PPE, speed, range, flight cost, and crew data.

Table 1. Aircraft Types and Characteristics

Aircraft Type	Payload (lbs.)	PPE	Speed (Mach)	Range (nm)	Flight Cost ($/hr.)	Crew
C-5M	270,000	36	0.77	2,650	26,394	7
C-17A	170,000	18	0.74	2,400	12,357	3
C-130J	44,000	8	0.58	1,700	6,150	3

LITERATURE REVIEW

Planning a military airlift is a complex task that involves fleet selection, aircraft routing, cargo loading, and scheduling decisions. Owing to problem complexity, the fleet selection problem has been traditionally addressed by mathematical modeling.

As early as the late 1950s, operations researchers started using mathematical programming to address a number of difficult problems faced by the commercial airline industry. One of the earliest applications of this approach was proposed by Ferguson and Dantzig (1956) who describe a linear programming model for assigning aircrafts to routes under uncertain demand. Subsequently, a variety of optimization methods has been successfully applied in the commercial airline industry to solve such problems as flight scheduling, fleet assignment, aircraft routing, crew scheduling, and revenue management; see, for an overview, Teodorovic (1988).

However, civilian airline problems differ from military airlift problems in a variety of ways. Military airlift requirements are, for example, driven by an infrequent and highly variable demand, while commercial airlines face less variable demand over time. Another differencing characteristic is that commercial airlines can decide the markets to serve and the flights frequencies, while military airlift planners do not have this type of control, and need to operate within an existing transportation network infrastructure (Baker et al., 2002).

While a rich body of work on the operations of commercial airlines exists, only a smaller amount of this literature addresses military airlift and mobility problems. Rappoport et al. (1994) propose a transportation problem formulation which can be used as a preprocessor of a heuristic algorithm for the allocation of airlift resources for the movement of cargo and passengers. A joint effort between researchers from the Naval Postgraduate School and the RAND Corporation, led to the development of the NPS/RAND Mobility Optimizer, a model that routes cargo through a specified transportation network under physical and policy constraints (Baker et al., 2002). For an overview of models supporting the planning of military airlift operations, see McKinzie and Barnes (2004).

More recently, Maywald et al. (2017) propose a single-airbase two-step fuel consumption minimization heuristic for the cargo aircraft selection problem. The first step enumerates the set of aircraft alternatives for a given airlift requirement, while the second step attempts to efficiently allocate the specified payload to each aircraft in each alternative.

Military airlift operations are capital, fuel, and labor intensive. The fleet size and the number of aircrafts of different types available at departure airbases, as well as the weight and volume of cargos have an impact on the allocation of aircrafts to routes. Clearly, the cost and success of force projection depend on the ability to operate flights through a transportation network as efficiently as possible. This paper addresses the fleet assignment problem to support military airlift operations. The basic fleet assignment trade-off is that if too small a plane is assigned to a given route, potential cargos will be left behind, while if too large a plane is assigned to the route, the airlift operation will suffer the higher expense of having a larger plane transporting a lesser load than its payload capacity. The goal is to have the right plane in the right airbase at the right time, but many operational constraints make this difficult to accomplish.

The optimization model developed in this paper is a binary integer program that decides the number of aircraft types to assign to routes so as to minimize operating and penalty costs, subject to a variety of operational constraints, the most important of which are the available number of aircrafts of each type, and the available crew capable of flying such aircrafts at the departure airbases. The model deals with a single-planning period of a multiple-base airlift operation, which is assumed to have a unique, non-repetitive, schedule cycle and does not consider the specific requirements and restrictions pertaining to jointly transporting cargos and passengers (troops) on the same flights. For the purpose of this paper, we treat troop's transportation as cargos defined by their respective routes, weights, and volumes.

PROBLEM STATEMENT AND MODEL OVERVIEW

The basic fleet assignment problem consists of determining the number of aircrafts of each type to assign to each route consistent with aircraft and crew availabilities and deciding how much cargo cannot be delivered in the prescribed planning period due to shortage of allocated transportation assets to meet demand on the various routes, or cost considerations. The goal is to move equipment and personnel in a timely fashion from a number of origin airbases to destination airbases using a fleet of aircrafts with differing airlift capabilities, flight ranges, cruising speeds and flight costs. For our purposes, the movement requirements is specified through a detailed list of cargo IDs, each of which specifying the associated cargo's departure and destination bases, weight, and volume.

The primary decision variables in the fleet assignment problem specify the type of aircraft assigned to airlift a particular cargo, and the number of planes for each aircraft type required to airlift all assigned cargos over a given route. Another set of decision variables is included to account for cargos that, due to capacity limitations or cost considerations, are not assigned to any flight and thus will not be delivered to their respective destinations within the planning period.

The objective of the fleet assignment problem is to minimize the sum of the loading and unloading costs of all airlifted cargos plus flight costs of all planes assigned to flying the various routes and penalties for non-delivered cargos to destinations. The flight cost of a particular aircraft over a given route is determined by the time the aircraft takes to fly the given route at typical cruising speed multiplied by the DOD reimbursable rate given in Table 1 above. Table 2, below, provides an example of aircraft flight times and costs for a 3,449 nautical mile (nm) route between Dover AFB, DE (KDOV) and Ramstein Airbase, Germany (ETAR).

Table 2. Aircraft Flight Times and Costs for a Sample Route

Aircraft Type	C-5M	C-17A	C-130J
Flight Time (hrs:min)	7:48	8:07	10:22
Flight Cost ($)	205,873	100,298	63,755

The model's constraints can be grouped into three broad categories: airbase-related constraints, aircraft-related constraints, and cargo-related constraints.

Airbases have their own fleet which is not shared with other departure airbases during the planning period. Also, each airbase has a sufficient amount of fuel for fueling departing flights, but a limited number of rested crew available to operate such flights.

Aircraft-related constraints enforce aircraft payload and volume capacities of each aircraft type, as well as crews and planes availability. The following are specific aircraft-related constraints:

1. An aircraft delivers only one destination at a time. Thus, cargos having different destinations need to fly on separate aircrafts.

2. An aircraft can only carry cargos that are compatible with its capabilities in terms of volume and weight payloads.

3. The number of sorties of each aircraft is limited by the available number of rested crews capable of flying such aircrafts at the departure airbases.

4. Each type of aircraft has its own set of crews, and crews are not interchangeable between aircraft types.

Cargo-related constraints govern demand and routes requirements. Each cargo is identified by an ID and has a known weight, volume, delivery route, and cost of its loading and unloading to and from a specific type of aircraft. Cargo loading/unloading costs are generally based on the volume-weight of the cargo and the type of aircraft used. We assume for our purpose, in accordance with SH&E, the International Air Transport Consultancy, report (2006), that for a given volume-weight shipment, the cost of cargo loading/unloading decreases as the aircraft size reduces. The following are specific cargo-related constraints:

1. Each cargo's route must be a direct delivery route with specific origin and destination airbases, thus no transshipment of cargo via an intermediate airbase is allowed.

2. Each cargo is configured in such a way to be fully contained and airlifted by one or more of the types of aircrafts available at the departure airbase.

3. Each cargo must be loaded on a unique aircraft, and cannot be split between multiple aircrafts.

4. Cargos that are not delivered to their respective destination airbases within the planning period will suffer a non-delivery penalty. This monetary penalty reflects the importance of the timely deployment of the cargo at destination.

PROBLEM FORMULATION

Sets

Airbase-Related Set

$B =$ set of all airbases

Route-Related Sets

$R =$ set of all routes

$R_b =$ subset of routes whose origin is airbase b

Cargo-Related Sets

$I =$ set of all cargos

$I_k =$ subset of cargos that can be carried by type k aircraft

$I_r =$ subset of cargos requiring transportation over route r

$I_{kr} = I_k \cap I_r =$ subset of cargos requiring transportation over route r that can be carried by type k aircraft

Aircraft-Related Sets

$K =$ set of all aircraft types

$K_i =$ subset of aircraft types that can carry cargo i

Data

Airbase-Related Data

$N_{kb} =$ number of type k aircrafts available at airbase b

$M_{kb} =$ number of rested aircrews available at airbase b capable of flying type k aircraft

Aircraft-Related Data

$W_k =$ payload capacity of type k aircraft

$P_k =$ PPE capacity of type k aircraft

$c_{kr} =$ flight cost of type k aircraft over route r

$m_k =$ number of aircrews required to fly type k aircraft

Cargo-Related Data

$w_i =$ weight (in lbs) of cargo i

$w_{ik} =$ proportion of type k aircraft payload capacity required for carrying the weight of cargo i, $w_{ik} = \frac{w_i}{W_k}$

$p_i =$ total pallet position equivalents (PPE) of cargo i

$p_{ik} =$ proportion of type k aircraft PPE capacity required for containing the PPE of cargo i, $p_{ik} = \frac{p_i}{P_k}$

$l_{ik} =$ loading/unloading cost of cargo i onto and from type k aircraft

$e_i =$ nondelivery penalty of cargo i

Decision Variables

$x_{kr} =$ number of type k aircrafts assigned to route r

$$y_{ik} = \begin{cases} 1, \text{ if cargo } i \text{ is assigned to type } k \text{ aircraft;} \\ 0, \text{ otherwise.} \end{cases}$$

$$z_i = \begin{cases} 1, \text{ if cargo } i \text{ is not assigned to any flight (not delivered);} \\ 0, \text{ otherwise.} \end{cases}$$

Fleet Assignment Model

$$\text{Min} \sum_{i \in I} \sum_{k \in K} l_{ik} y_{ik} + \sum_{k \in K} \sum_{r \in R} c_{kr} x_{kr} + \sum_{i \in I} e_i z_i \qquad (1)$$

Subject to:

$$\sum_{i \in I_{kr}} w_i y_{ik} \le W_k x_{kr}, \qquad \forall\, k \in K,\ r \in R; \qquad (2)$$

$$\sum_{i \in I_{kr}} p_i y_{ik} \le P_k x_{kr}, \qquad \forall\, k \in K,\ r \in R; \qquad (3)$$

$$\sum_{i \in I_k} w_{ik} y_{ik} \le 1, \qquad \forall\, k \in K; \qquad (4)$$

$$\sum_{i \in I_k} p_{ik} y_{ik} \le 1, \qquad \forall\, k \in K; \qquad (5)$$

$$\sum_{k \in K_i} y_{ik} + z_i = 1, \qquad \forall\, i \in I; \qquad (6)$$

$$x_{kr} \le N_{kb}, \qquad \forall\, k \in K,\ r \in R_b,\ b \in B; \qquad (7)$$

$$m_k x_{kr} \le M_{kb}, \qquad \forall\, k \in K,\ r \in R_b,\ b \in B; \qquad (8)$$

$$y_{ik}, z_i = \{0,1\},\ x_{kr} \ge 0 \text{ and integer}, \quad \forall\, i \in I, k \in K, r \in R. \qquad (9)$$

The objective function (1) minimizes the sum of loading and unloading costs of all airlifted cargos, plus flight costs for all aircrafts used in the airlift operation plus any penalties for undelivered cargos. Constraints (2) determine, based on airlifted cargo weights, the number of type *k* aircrafts needed to fly each route *r*. Constraints (3) determine, based on airlifted cargo volumes, the number of type *k* aircrafts required to fly each route *r*. Constraints (4) ensure that the payload limitations are met for each type of aircraft. Constraints (5) ensure that the PPE capacities are met for each type of aircraft. Equations (6) are demand satisfaction constraints. They reflect the logical condition that each cargo is either airlifted to its corresponding destination or, if it is not, be considered not delivered. Constraints (7) ensure that aircraft availability limitations are met for each type of aircraft at each airbase. Constraints (8) ensure that aircrews' availability limitations are met for each flight originating from each airbase. Constraints (9) ensure binary and integrality conditions on the decision variables.

CONCLUSION

Ensuring the smooth execution of a strategic military airlift operation is a challenging task. It is a large, complex system of multiple airbases, and airlift assets that interfaces with many organizations. The United States Transportation Command (USTRANSCOM) is responsible for managing the transportation resources necessary to perform such a task. The model developed in this paper provides an organization such as USTRANSCOM with a decision-support tool for improving their strategic airlift capability. The model assigns cargos, which need to be shipped through a specific transportation network, to a given fleet of aircrafts. Subject to physical and policy constraints, the model assigns the most appropriate fleet type and determines the number of aircrafts required for each flight segment in such a way to minimize the overall cost of the airlift operation. The implementation and computational experiment of this model are currently being explored and results of this experiment will be reported at a later date.

References gladly provided upon request