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An integer programming approach to support the US Air Force's air mobility network

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Abstract

The United States Air Force's air mobility command is responsible for creating a schedule and executing that schedule for a large-scale air mobility network that encompasses aircraft with prioritized missions. Aerial ports (airports) can process or park a maximum number of aircraft, called the maximum on ground (MOG). As the schedule changes due to disruptions, such as equipment failure or weather, the MOG constraint can cause the new schedule to be infeasible. Traditionally, re-planning the channel route schedule to adhere to MOG constraints has been a manual process that usually stops after the first feasible set of changes is found, due to the challenges of large amounts of data and urgency for a re-plan. We extend Bertsimas and Stock's integer program formulation for the commercial airline Multi-Airport Ground-Holding Problem to the air mobility network. Our integer programming formulation recommends delays to certain aircraft on the ground to minimize the effects of system-wide disruptions while taking account mission priorities of the aircraft.

Keywords: Airlift; Military applications; Scheduling; Integer programming

1. Introduction

The United States military logistics system is an integral part in providing flexible and responsive transportation to project and sustain forces in times of war. Also important is the ability of the system to provide support for peacetime operations, and it must continuously adapt to a wide range of missions and geographical locations in a dynamic environment.

Ensuring smooth execution of the military logistics system is a challenging task. It is a large, complex system that interfaces with many organizations. Furthermore, the current state of the world does not allow for the long lead time that existed during the Cold War for planning and scheduling of military logistics operations. To ensure high efficiency of the military logistics operations, interfacing organizations must be able to understand and analyze the effects that their decisions have on the system in a real-time environment.

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The military logistics system operates on the framework of the Defense Transportation System. The United States Transportation Command (USTRANSCOM) operates the system and is responsible for being "the single manager for defense transportation during peace and war" [1]. Through three transportation component commands that report directly to USTRANSCOM and partnerships in the commercial sector, USTRANSCOM has the transportation resources necessary to perform its mission. The air mobility command (AMC) is the component command with the mission to "provide airlift, air refueling, special air mission, and aeromedical evacuation for US forces" [1].

AMC has the ability to move material and personnel long distances in a matter of hours. This movement occurs over the AMC network, which is the aircraft, aircrew, and aerial ports (i.e., airports) that support AMC missions. This network is a complex system that includes 1000 Department of Defense aircraft, more than 100,000 personnel, 16 permanent locations within the US, over 100 aerial ports and international airports around the world, and partnerships with 25 commercial airlines [2,3].

A key mission area of AMC are channel route missions. These missions provide airlift on a regular basis for sustaining, rather than deploying, military forces by transporting materiel and military personnel around the world. Deployment refers to the initial military build-up for a contingency or war. Channel route missions are not allocated dedicated aircraft but must share aircraft with other mission areas, such as exercises, deployment of forces in a contingency, and special assignment airlift missions. Channel route missions are not always executed as scheduled because the other mission areas are less predictable and have a higher priority for use of the aircraft that are scheduled to be used in channel route missions. Further complicating the execution of channel route missions are disruptions such as unscheduled aircraft maintenance, weather, and unpredictable loading requirements for material and personnel.

Once a new schedule is found to overcome disruptions, the maximum on ground (MOG) constraints can cause the new schedule to be infeasible. MOG refers to the maximum number of aircraft that can simultaneously be processed (e.g., fueling, maintenance, or unloading cargo) or parked at an aerial port. Each type of MOG is referenced with a different name, such as fueling MOG, working MOG, or parking MOG. Recently implemented human-computer interface software automates some functions of finding MOG solutions and gives AMC operators the ability to visualize problems caused by the MOG constraints. However, operators do not have a tool to solve system-wide problems caused by MOG constraints. The work presented in this paper would add "intelligence" to this software or other elements of AMC information systems [4].

Our model can help improve the execution of channel route missions. Because of the high operating costs of sustaining flight operations, small improvements in the execution of channel route missions can lead to significant efficiencies in aircraft usage and improvement in the ability of AMC to respond to changes in a dynamic environment. Bertsimas and Stock [5] developed an optimization-based network model to help solve the multi-airport ground-holding problem. This problem considers delaying commercial aircraft on the ground to reduce airspace congestion at airports. This paper extends the model of Bertsimas and Stock to consider delaying AMC aircraft to help quickly re-plan the channel route schedule.

The idea motivating this research is to help AMC find a better trade-off between delivering channel route cargo on time and executing missions of higher priority when faced with an infeasible schedule caused by MOG constraints. There are two challenges to overcome to find the better trade-off. The first challenge is large amounts of data, making it very time consuming to manually find a solution. This leads to the second challenge, which is an urgency to find a solution. Decisions must be made in real-time and delays in decision making can cause lost opportunities.

The remainder of this paper is structured as follows: we describe the AMC structure and its missions, the channel route planning and execution processes, our integer programming model that resolves real-time ground congestion, and the computational results of our model. Throughout the paper, the focus is on channel route missions, but our method can help improve re-planning of all mission areas. In future papers, we will consider additional optimization models that can be combined into a system-wide family of models.

2. Description of the AMC network and missions

Channel route missions fly in the AMC network. The physical components of the AMC network are aerial ports, cargo, and aircraft. Aerial ports can be thought of as nodes in the AMC network. The aircraft have different priorities that depend on its mission area. While the channel route mission area has the lowest priority, it has a significant responsibility of transporting material and military personnel to support military activities throughout the world.

Aerial ports are military locations that have the infrastructure to process cargo, Department of Defense aircraft, and commercial aircraft contracted to support AMC. Aerial ports contain runways, parking and servicing ramps for aircraft, maintenance hangars, fuel storage, and cargo processing equipment and facilities. Some aerial ports are the home base locations for one or more Department of Defense aircraft types. Each aerial port is designated a unique international civil aviation organization code that is useful in identifying the aerial port. Operators within AMC identify aerial ports that are located within the lower 48 states as Continental United States (CONUS) and identify all other aerial ports as offshore.

Aircraft movement into and out of aerial ports can be restricted by associated operating hours, bird air strike hours and in some cases, quiet hours. Operating hours are when personnel are on duty at an aerial port. Bird air strike hours restrict aircraft landing and takeoff during certain times of wildlife migration to ensure safety. Some aerial ports, especially those located near large population centers, might place restrictions on the types of aircraft that can take off and land during certain times of the day [6].

An aerial port where cargo originates is defined as an aerial port of embarkation. The destination aerial port of the cargo is defined as the aerial port of debarkation. Cargo can be flown directly from its origin to its destination or it can have multiple stops along the way. Cargo is any material used to support the troops. It can be anything from aircraft parts to spray paint.

Department of Defense owned aircraft, also called “organic” aircraft, and associated personnel are organized by Air Force wings. Within the wings are squadrons that have a single type of aircraft. A squadron is permanently stationed at an aerial port that it may share with other squadrons. The squadrons are responsible for maintaining the aircraft and training aircrews. Squadrons have contract and trainer aircraft. Thirty days prior to the execution month, the wings report to AMC the number of aircraft and associated aircrew that will be available for contract. These are the maximum resources that AMC can use from the squadrons. The remaining aircraft in the squadron are the squadron’s trainers, which are used for local training missions [6].

The Air Force contracts civilian aircraft through commercial airlines. Because AMC considers using commercial aircraft to be much more expensive than using organic aircraft, commercial aircraft are only used when absolutely necessary. In our model, we treat commercial and organic aircraft the same, because we strategically delay aircraft that are already assigned missions.

When scheduling aircraft, AMC must consider hazardous material and diplomatic clearances. To enter the airspace of foreign countries that do not have a blanket clearance for US aircraft, diplomatic clearances are required. To obtain diplomatic clearances, aircraft must meet lead-time, operational, route, cargo and other requirements that will vary from country to country. Lead-time, usually around two weeks, refers to the advance notice that some countries require of a diplomatic clearance request. Short-notice requests must be justified and might not be approved. Operational requirements include the type of aircraft and the window of time for entry into and exit out of the country. Route considerations include whether the flight will be landing at a specific aerial port or simply flying over the country and the geographical entry and exit points. Cargo requirements usually limit the types of hazardous material that can be flown into a country but could include other restrictions.

Because AMC has limited aircraft resources, it needs a system to help allocate its aircraft resources to AMC airlift missions. For peacetime missions, AMC uses the Joint Chiefs of Staff (JCS) airlift priority system to assign JCS airlift priority codes to AMC airlift missions. Customers submit a JCS priority code for their cargo when requesting transportation from the USTRANSCOM. In general, the first priority is given to cargo of Special Assignment Airlift Missions, which regularly have empty flight legs, because customers might only purchase the aircraft one-way. Second priority is given to cargo of contingency missions. Contingency missions are different from channel route missions by deploying troops and material for a war effort. Contingency missions are very dynamic and are currently planned using ad hoc methods. Third priority goes to exercise missions that are used to train for wartime. Cargo transported by channel route missions receives fourth priority. The only mission area that usually has lower priority than channel route missions are joint service missions, which have a low occurrence.

Because channel route missions are of the lowest JCS priority, it makes them susceptible to changes on short notice during the execution phase. Channel route missions can be made more efficient by solving problems caused by MOG constraints. Because methods to solve problems caused by MOG constraints are less researched than methods to solve problems in the commercial airline industry, we look to the area of air traffic flow management. We construct our model to overcome MOG constraints in real-time using a clever variable transformation method first introduced in the context of delaying ground holds of commercial flights [5].

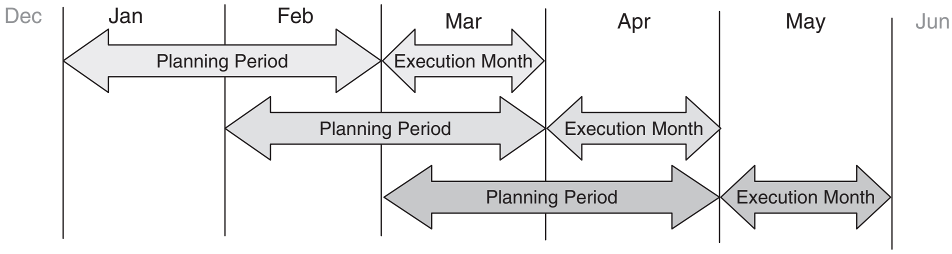

Fig. 1. Visualization of channel route planning periods and execution months.

3. AMC channel route planning and execution

The previous section described the AMC network. In this section, we explain the current decision process for planning and executing a channel route schedule. Responsibility for different parts of the process is divided among the many organizations of AMC. Because channel route missions share aircraft resources with other mission areas, the process is intertwined with the planning and execution of all mission areas. In the next section, we formulate a model to recover the channel route schedule when MOG limits are exceeded at aerial ports, which is applicable to all mission areas.

Planning and execution of channel route missions occurs over a three month period. The first two months comprise the planning period, and the third month is the execution month. During the planning period, the *organic scheduler* creates an initial cut of the channel route schedule using organic aircraft. The CONUS *cargo bookie*; who schedules cargo being loaded in the CONUS, and *barrelmaster*, who allocates aircraft among the different mission areas, will review the initial cut and give feedback to the organic scheduler who makes appropriate changes before it is published on the global decision support system (GDSS) (explained in Section 3.2). Once published, other organizations make inputs by coordinating with the organic scheduler to make incremental changes to the channel route schedule. Finally, the missions are executed during the execution month, with individual missions entering the execution phase twenty-four hours before the mission begins and remaining in the execution phase until the mission ends. The execution month uses the schedule created in the planning period, but requires reactionary solutions to problems that arise in missions in the execution phase. Fig. 1 shows the overlapping nature of planning periods and execution months.

During the execution month, the CONUS cargo bookie, barrelmaster, and organic scheduler continue to make updates to the schedule and a variety of organizations still have inputs. In addition, the CONUS cargo bookie finds solutions to disturbances in the schedule that occur when excess cargo arrives at its CONUS origination aerial port, while the *offshore cargo bookie*, who is not involved during the planning period, finds solutions to excess cargo that arrives at aerial ports outside the CONUS. Once missions enter the execution phase, *the floor* becomes responsible for the channel route missions, but often seeks advice from the organic scheduler and barrelmaster. The CONUS and offshore cargo bookies continue to coordinate with the floor to find solutions to cargo flow problems that might be implemented beyond the execution phase.

3.1. Strategic planning and execution objectives

AMC has three high level objectives for channel route missions—readiness, customer service and net operating result [6]. The ability to perform as expected in a wartime situation is considered the readiness of a military unit. Readiness is achieved through peacetime training and practice of job skills. The exercises mission area helps military units learn to work together and AMC requires pilots to fly a minimum number of hours to achieve currency and proficiency of its pilots' skills. Customer service is AMCs mission of supporting its customers' ability to perform their own mission. AMC does not intend to make a profit. Rather it ensures that its operating costs equal the funding for its flying hours combined with reimbursement for transporting cargo for its customers. This objective is the Net Operating Result. Schedulers plan channel route missions in a timeframe that allows them to focus on AMCs high level objectives [6], but as the time frame shifts from days in the planning stage to minutes in the execution phase, focus shifts from meeting high level objectives to reactionary decision making and an urgency to meet the short term mission goals.

3.2. Channel route planning and execution tools

The GDSS is AMC's overarching database that supports the TACCs command and control of aircraft. GDSS stores information such as the routes, departure and arrival times of specific aircraft, the priority of missions, and the status of diplomatic clearances and hazardous materials. Aircraft squadrons access the information on GDSS to show the missions they are assigned to fly. The data in GDSS can be accessed and updated using different user interface software such as the integrated management tool (IMT), consolidated air mobility planning system (CAMPS), and global air transportation execution system (GATES). The IMT consolidates the command and control data of GDSS with weather and logistical information to support flight managers during the execution of flight missions. CAMPS is an interface used by the organic scheduler to assign aircraft resources to missions and is used during the execution month to make updates to the channel route schedule. The GATES tracks AMCs cargo and passenger information at aerial ports and is used as a resource manager to ensure AMCs customer's cargo is being transported.

Besides the GDSS database and the user interface software, AMC personnel rely on a manual process during the execution of missions. AMC's decision making and problem solving processes are outlined as official policy. AMC has created a series of forms that present procedures adhering to the policies in a step-by-step format that cover specific types of disruptions in the schedule. The checklist forms help guide personnel on the floor to either resolve disruptions or to inform a supervisor of disruptions. A disruption that cannot be easily resolved using the software tools and checklists requires innovation, experience, job training, and intuition.

3.3. The planning period

The organic scheduler is responsible for scheduling all channel route missions during the planning period that begins sixty days before the execution month. The organic scheduler initiates the planning period by beginning development on the initial cut. Currently, the organic scheduler creates the initial cut of the channel route schedule without the aid of a decision support tool by modifying the previous month's schedule to account for "known special circumstances" [6]. Once the initial cut has been created, it is sent to the barrelmaster and CONUS cargo bookie. The barrelmaster is responsible for allocating aircraft among all the mission areas and will determine how many aircraft the organic scheduler receives in support of the channel route schedule. The CONUS cargo bookie ensures that the initial cut of the channel route schedule is capable of transporting all validated cargo. If the amount of organic aircraft capacity does not meet the needs of the channel route schedule, then the organic scheduler coordinates with the commercial scheduler to use fixed-buy commercial aircraft. The organic scheduler updates the initial cut using the feedback from the barrelmaster and CONUS cargo bookie and post the resulting channel route schedule on GDSS. Once the schedule is posted on GDSS, it becomes visible to other AMC organizations and Air Force wings, which coordinate with the organic scheduler to make incremental changes to the channel route schedule. Nielsen et al. [6] describe the current process (see Fig. 2) and develop an optimization model to help the organic scheduler create the initial cut of the channel route schedule during the planning period. The tool simultaneously considers all inputs to help create the initial cut.

3.4. The execution month

Once the channel route schedule has been visible on GDSS for thirty days, it enters the execution month. The organic scheduler can still make updates to the schedule, but the floor becomes responsible for the execution of individual channel route missions beginning 24 h this is to ensure justification on previous line before the mission begins and ending once the mission is completed. Because different missions start and end at different times, the execution phase is a window that slides through the execution month as individual missions are executed. The twenty-four hour time frame is arbitrary, but is adequate for detailed mission planning and lets the floor prepare for future missions. Once missions enter the execution phase (T-24 h), the organic scheduler cannot make changes to the missions in the execution phase although the floor might coordinate changes with the organic scheduler who developed the schedule.

The execution of channel route missions is a dynamic and intense process that uses ad hoc methods and informal flows of information. The process is a mix of monitoring missions and reactionary replanning. Many organizations are responsible for monitoring and solving problems arising in the execution of missions that could not be foreseen in the planning period and that might overlap the organizations' responsibilities.

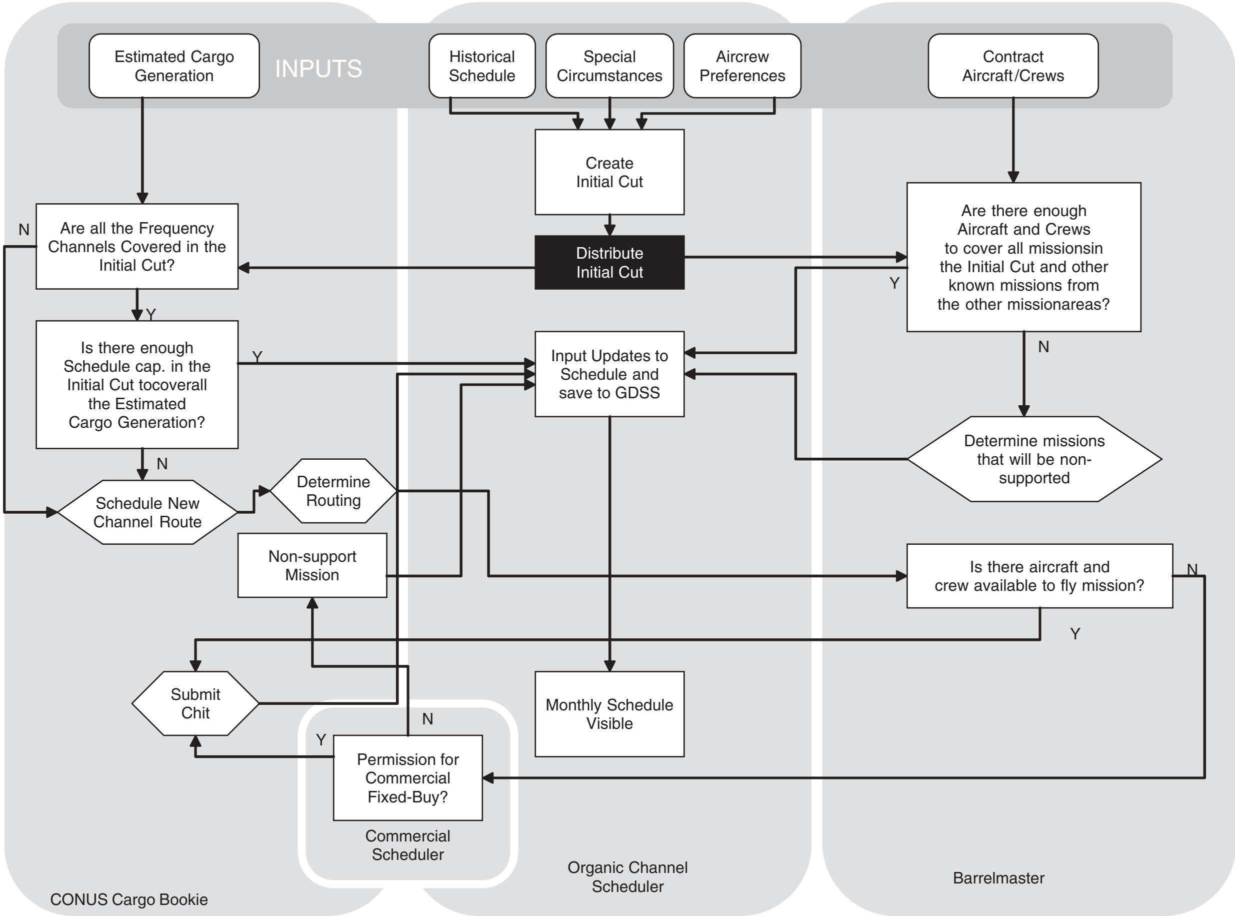

Fig. 2. The current channel route planning process [6].

During the execution month, especially the execution phase, reactionary changes are made to the channel route schedule. The floor, the CONUS and offshore cargo bookies, air evacuation (AE) mission planners, who oversee the evacuation of injured and deceased troops, the barrelmaster, and the commercial scheduler coordinate with the organic scheduler to make updates to the channel route schedule. Updates are required when the channel route schedule is disrupted. Common sources of disruption include the following:

- higher mission priorities,
- aircraft crew needs,
- aircraft maintenance,
- diplomatic clearances,
- unplanned aerial evacuations
- MOG limits,
- weather, and
- operating hours.

For example, consider a disruption that causes cargo to lose its airlift, leaving an excess of cargo at an aerial port. The CONUS and offshore cargo bookies find solutions to get the airlift needed for the excess cargo at CONUS and Outside CONUS (OCONUS) Aerial Ports of Embarkation (APOEs), respectively. Because channel route missions usually begin at CONUS APOEs, the CONUS cargo bookie has few options and most likely has to wait until the next scheduled aircraft arrives at the APOE. However, the offshore cargo bookie can take a more active role in finding solutions at OCONUS APOEs, such as rerouting aircraft and finding opportunities to use spare capacity from the other mission areas. While the cargo disruptions occur in the execution phase, the CONUS and offshore cargo bookies might re-plan the channel route schedule beyond the execution phase.

The execution phase within the execution month combines monitoring and problem solving in real-time. The floor is the focal point for the execution phase and the organic scheduler no longer make changes to the missions. The floor is organized into the command and control center; maintenance cell, which coordinates maintenance of grounded aircraft; Aerial Port Control Center (APCC), which represents the CONUS and offshore cargo bookies; and AE cell. The command and control center is responsible for executing all missions, while the other divisions are representatives of outside organizations that support the command and control center. If disruptions do not arise in the channel route schedule, then the missions are executed as planned by the organic scheduler and there would be no need for the floor. However, this is unrealistic, and the schedule needs continual updating during the execution phase as disruptions occur.

The current MOG levels at an aerial port are dynamic due to the number of personnel on shift at the aerial port, the threat level to security, the number of aircraft currently at the aerial port, and the status of the aircraft and infrastructure. Therefore, the *MOG master*, a position on the floor, ensures that the aircraft missions will not exceed the MOG level at the aerial ports. To accomplish this task, the MOG master uses customized Excel macros that warn the MOG master of potential violations of MOG levels. The Excel macros do not suggest how to rectify MOG problems. Before we present our formulation, we discuss areas of research relating to both mobility planning and air traffic flow management.

3.5. Literature review

Existing software tools developed for AMC planners and schedulers involve some components that employ operations research methods. Planning tools used within AMC have included the airlift deployment analysis system (ADANS), a database decision support system used to schedule and analyze airlift missions and to distribute the schedule to flying units across the globe. During the first Gulf War in the early 1990s, supporting the wartime planning functions was the priority for ADANS development. Included in ADANS is a two-step heuristic for generating airlift missions (see [7–9] for details of the algorithms and their implementation). A description of the complete development of the ADANS system and its use during the war is provided by Hilliard et al. [10]. The bulk of the ADANS work focuses on the creation of missions and their schedules, as well as cargo assignments. When cargo requirements change in real-time, however, one component in ADANS uses an insertion heuristic to determine how to best handle the new requirements while minimizing disruption to the original schedule (see [11]). Components of ADANS were built into the follow-on decision support system known as the CAMPS.

Optimization models have also been developed for long-range planning and analysis of the airlift system. A series of efforts from the Naval Postgraduate School and the RAND Corporation led to the NPS/RAND Mobility Optimizer. Baker et al. [12] describe the use of linear programming models and cascade heuristics to analyze the composition of the strategic mobility network, and Rosenthal et al. [13] describe its predecessor, known as Thruput II. For an overview of models used for strategic airlift planning, see McKinzie and Barnes [14].

Recent work on planning methods for AMC has included a number of papers using Tabu search. Barnes et al. [15] describe the use of group theoretic Tabu search for planning and scheduling of tanker aircraft to support aerial refueling operations. Crino et al. [16] apply Tabu search to the problem of determining routes and schedule of aircraft within a given theater of operations. Heuristic approaches are also used in the *Barrel Allocator*, a component of CAMPS that assigns aircraft to the five AMC mission areas given fixed schedules and known priorities of the missions (see [17]). Nielsen et al. [6] describe network design formulations for creating monthly schedules for channel route missions. These formulations are solved using the strategy of composite variable formulations first introduced for commercial air cargo distribution problems by Armacost et al. [18]. Brigantic and Mahan [19] provide a thorough compendium of models used in practice for Defense Transportation System planning as well as models in research and development.

The problem we address in this paper involves assigning delays to aircraft to overcome congestion limits (i.e., MOG limits) at each aerial port. Work in the area of commercial air traffic flow management applies here, specifically work on methods to assign ground-holds to commercial airlines in light of congestion at airports. Select examples include Richetta and Odoni (see both [20,21]), Vranas et al. [22], and Bertsimas and Stock [5], which provide alternative formulations for the multi-airport ground holding problem. Andretta et al. [23] compare the computational aspects of the Vranas and Bertsimas models, along with one of their own, concluding that the Bertsimas/Stock formulation outperforms the others. Andreatta et al. [24] also present similar holding models, consisting of heuristics and integer programming formulations, applied to a system of "free flight," in which airlines choose their routes, departure times, and air speeds. Additional extensions to the ground holding problem include stochastic variants (see [25]) and models that incorporate the airlines' banking structures of flight arrivals and departures (see [26]).

Developing models that resolve MOG congestion issues in real-time represents a new area of study for AMC. The goal of the next section is to employ the decision variable definition strategy from Bertsimas and Stock [5] to develop a highly tractable model that will serve as the basis for a future decision support tool. This tool would be used by the floor to resolve congestion issues across all mission areas.

4. MOG compliance formulation

The MOG compliance formula (MCF) suggests how to delay aircraft on the ground to avoid a violation of MOG constraints. The MCF can be used by the offshore cargo bookie, who finds solutions to transport cargo on disrupted aircraft routes outside the United States, to identify MOG violations quickly that are caused by his/her decisions. The MOG master, who monitors MOG levels at all aerial ports, can use MCF to quickly find solutions to MOG violations.

MCF is based on the variable definition approach developed by Bertsimas and Stock [5]. While the model developed by Bertsimas and Stock strategically delays aircraft on the ground to avoid congestion when leaving from or arriving to airports, AMC wants to ensure that at any given time aerial port MOG limits are not violated. To accomplish this goal, MCF delays certain aircraft in the AMC network to minimize a weighted penalty of delays among all aircraft. The penalty could include cost, but is based upon AMC network attributes and system-wide objectives.

MCF represents ground arcs as the time an aircraft is landed at an aerial port and implies flight arcs as the time aircraft are airborne between a ground arc ending and the next ground arc beginning. The time aircraft spend flying on the flight arcs remain constant, although the departure and arrival times can change as aircraft are delayed, causing the ground arcs to become longer. Every ground and flight arc is aircraft specific.

Conventional formulation strategies for this type of scheduling problem would use variables that represent a flight route, begin time, and end time. Bertsimas and Stock [5] introduced a variable transformation approach which is unique from its predecessors in that its binary decision variables do not explicitly represent where an aircraft will be at a particular moment. Rather, they indicate if an aircraft has arrived/departed or not arrived/not departed an airport at a certain time. Constraints are used to ensure that once a flight has arrived at its arrival airport at a certain time period that all decision variables with subsequent time periods relating to the arrival of the same flight have also arrived. By defining variables as "arriving by time period t" rather than "arriving at time period t", Bertsimas and Stock formulated their problem with a stronger LP relaxation than others in literature [5]. As an example, suppose an aircraft is scheduled to arrive at the aerial port during time period 4. In Fig. 3, the aircraft arrives late during period 6 and then departs during period 8. The arrival decision variables equal 1 for periods 6 and later, while the departure decision variables equal 1 for periods 8 and later. The difference of the two indicate when the aircraft is actually on the ground.

We define MCF by first introducing the notation used for sets and data, then the decision variables, and finally the integer programming formulation:

Sets:

- E set of all aerial ports $e \in E$;
- G set of all ground arcs $g \in G$;
- G^e set of ground arcs $g \in G^e$ associated with aerial port $e \in E$;
- H set of all flight arcs $h \in H$;
- T_g^a set of time periods that determine when ground arc $g \in G$ can begin (aircraft arrival time);
- T_g^d set of time periods that determine when ground arc $g \in G$ can end (aircraft departure time). T_g^d includes d_g and the remaining elements are consecutive time periods beyond d_g. There is a difference of o_g time periods between corresponding elements of T_g^a and T_g^d.

Data:

- h_g the flight arc directly after ground arc $g \in G$;
- d_g scheduled departure time period of the aircraft associated with ground arc $g \in G$;

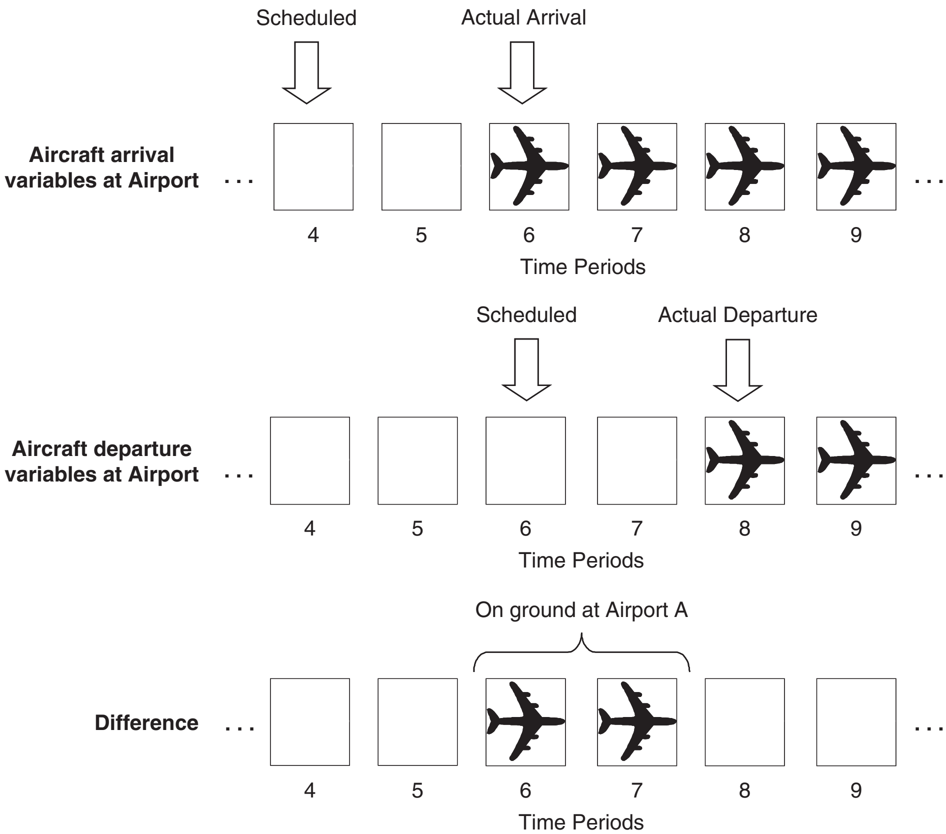

Fig. 3. Example of variable definition for an airplane arriving to and departing from an airport. The first row represents arrival variables for each time period, the second row represents the departure variables for each time period, and the third row shows the difference of the two. An empty box corresponds to decision variable with value equal to zero, and an airplane corresponds to a decision variable with value equal to one.

o_g number of time periods spent on the ground for the aircraft associated with ground arc $g \in G$;

l_g number of time periods between ground arc $g \in G$ and the next consecutive ground arc $g' \in G$ for the aircraft associated with ground arc $g \in G$. In other words, it is the flight time of the aircraft associated with flight arc $h_g \in H$;

$M_e(t)$ the MOG limit of aerial port $e \in E$ at time period $t \in T^e$. This represents the most limiting MOG at aerial port $e \in E$ of all MOGs (e.g., parking MOG and working MOG);

m_g the contribution of the aircraft associated with ground arc $g \in G$ towards the MOG limit;

c_g the marginal penalty of delaying the aircraft associated with ground arc $g \in G$.

Decision variables:

$$w^a_{g,t} = \begin{cases} 1 & \text{if the aircraft associated with ground arc } g \in G \text{ arrives by time period } t \in T^a_g, \\ 0 & \text{otherwise;} \end{cases}$$

$$w^d_{g,t} = \begin{cases} 1 & \text{if the aircraft associated with ground arc } g \in G \text{ departs by time period } t \in T^d_g, \\ 0 & \text{otherwise.} \end{cases}$$

$$\mathrm{MCF} = \min \sum_{g \in G} \left[c_g \sum_{t \in T^d_g} (t - d_g)(w^d_{g,t} - w^d_{g,t-1}) \right] \tag{9}$$

$$\text{s.t.} \quad \sum_{g \in G^e : t \in T_g^a, t \notin T_g^d} m_g w_{g,t}^a + \sum_{g \in G^e : t \in T_g^a, t \in T_g^d} m_g (w_{g,t}^a - w_{g,t}^d)$$

$$+ \sum_{g \in G^e : t \notin T_g^a, t \in T_g^d} m_g (1 - w_{g,t}^d) \leqslant M_e(t) \quad \forall e \in E, \tag{10}$$

$$w_{g,t+o_g}^d - w_{g,t}^a \leqslant 0 \quad g \in G, t \in T_g^a, \tag{11}$$

$$w_{g',t+l_g}^a - w_{g,t}^d = 0 \quad \forall g, g' \in G, t \in T_g^d, \tag{12}$$

$$w_{g,t}^a - w_{g,t-1}^a \geqslant 0 \quad \forall g \in G, t \in T_g^a, \tag{13}$$

$$w_{g,t}^d - w_{g,t-1}^d \geqslant 0 \quad \forall g \in G, t \in T_g^d, \tag{14}$$

$$w_{g,t}^a \in \{0, 1\} \quad \forall g \in G, t \in T_g^a, \tag{15}$$

$$w_{g,t}^d \in \{0, 1\} \quad \forall g \in G, t \in T_g^d. \tag{16}$$

The objective function (9) minimizes the penalty due to ground delays. Note that $c_g \cdot d_g$ is constant. Constraints (10) ensure that the MOG limitations are met at each aerial port for every time period that pertains to the aerial port. Constraints (11) are connecting constraints within ground arcs. They ensure that ground arcs require no less time than the corresponding ground time presented in the data. Constraints (12) are connecting constraints within flight arcs. They ensure that flight arcs require exactly the same number of time periods as the corresponding flight time presented in the data. Constraints (13) and (14) are connecting constraints of time. For instance, if an arc has arrived at its arrival aerial port by time period t, then the arc has also arrived at its arrival aerial port by time period $t+1$, $t+2$, and so on. Finally, constraints (15) and (16) ensure that the decision variables are binary.

The decisions of the planner are based on the current requirements of the system, motivating a need to subjectively decide the penalty of delaying individual aircraft, represented by c_g in the MCF. The MCF delay penalties are applied to ground arcs in the model for each time period that the ground arcs are delayed but are based on the information of subsequent flight arcs. We use parameters β, γ, ε, and ω to weight key AMC network attributes. The planner desires to minimize disruption to the original schedule when delaying aircraft, and subjective weighting can be used to minimize the severity of the disruptions. We describe each AMC network attribute needed for the MCF penalty equations and briefly explain the importance of each AMC network attribute in minimizing disruptions.

A mission priority of an aircraft indicates the importance of the aircraft being on schedule relative to other aircraft, which is defined as:

$$PRTY_g = \begin{cases} 1 & \text{if the highest priority of flight arc } h_g \in H \text{ and all flight arcs after} \\ & \quad \text{flight arc } h_g \in H \text{ in the route of the associated aircraft has} \\ & \quad \text{first priority of all aircraft missions,} \\ 2 & \text{if the highest priority of flight arc } h_g \in H \text{ and all flight arcs after} \\ & \quad \text{flight arc } h_g \in H \text{ in the route of the associated aircraft has} \\ & \quad \text{second priority of all aircraft missions,} \\ \vdots & \\ 23 & \text{if the highest priority of flight arc } h_g \in H \text{ and all flight arcs after} \\ & \quad \text{flight arc } h_g \in H \text{ in the route of the associated aircraft has} \\ & \quad \text{twenty-third highest priority of all aircraft missions.} \end{cases}$$

Aircraft requiring diplomatic clearances (DIPS) may require significant lead time to coordinate changes, so we define the following:

$$DIPS_g = \begin{cases} 1 & \text{if the flight arc } h_g \in H \text{ requires DIPS or is before another flight,} \\ & \quad \text{arc requiring DIPS in the route of the associated aircraft} \\ 0 & \text{otherwise.} \end{cases}$$

The more time available for making changes to an aircraft schedule, the easier it is to make these changes. This encompasses the idea that a schedule has "momentum," such as aircrews preparing for missions and maintenance personnel returning to work. The parameter $TIME_g$ is calculated as the lead time available between the model's beginning time period and the originally scheduled departure time period of an aircraft of a ground arc that is delayed, such that:

$$TIME_g = \begin{cases} 0 & \text{if the associated aircraft of ground arc } g \in G \text{ originally departs the} \\ & \quad \text{associated aerial port 0 time periods beyond a specified beginning} \\ & \quad \text{time period,} \\ 1 & \text{if the associated aircraft of ground arc } g \in G \text{ originally departs the} \\ & \quad \text{associated aerial port 1 time period beyond a specified beginning} \\ & \quad \text{time period,} \\ \vdots & \\ t & \text{if the associated aircraft of ground arc } g \in G \text{ originally departs the} \\ & \quad \text{associated aerial port t time periods beyond a specified beginning} \\ & \quad \text{time period.} \end{cases}$$

An aircraft that is transporting hazardous material requires lead time for changes to be made to its schedule. For example, ground handling crews need to be aware of hazardous material, so they will be prepared with the proper equipment. We define this as

$$HAZ_g = \begin{cases} 1 & \text{if the flight arc } h_g \in H \text{ is or is before another flight arc transporting} \\ & \quad \text{HAZMAT in the route of the associated aircraft,} \\ 0 & \text{otherwise.} \end{cases}$$

So we create a total delay penalty for each ground arc in the network by taking a weighted function of these network attributes:

$$c_g = \beta * DIPS_g + \varepsilon/PRTY_g + \omega/(TIME_g + 1) + \gamma * HAZ_g. \tag{17}$$

The parameters β, γ, ε, and ω are determined from the operator's experience and current understanding of the system. By adjusting these parameters, the planner can create solutions with the desired characteristics. Because c_g contributes to the objective function of an integer programming model, β, γ, ε, and ω can be of any value. However, it is pragmatic to restrict the values to some range of nonnegative numbers that include zero. Including zero allows attributes to be "turned off." In the next section, we base our results on a range of 0–100. The MCF could be used to create a solution space by quickly finding multiple solutions. This solution space can be visually presented so that the decision maker can pick the solution that best fulfills the current requirements of the system.

5. MCF results

In this section we describe the data used, investigate the computational results of the MCF, and present a case study that helps demonstrate the potential of the MCF.

Table 1
The effects of varying ω and maximum delay in time periods on MCF model attributes ($\beta = 1$, $\gamma = 1$, and $\varepsilon = 1$)

Attributes	Maximum delay in time periods										
	3	6	7	8	9	10	11	12	24	30	72
Preprocessing time in seconds	3.86	3.83	3.95	3.83	4.05	4.08	4.10	4.02	4.67	4.88	10.02
Rows	3175	5538	6325	7112	7899	8686	9473	10 260	19 704	24 426	57 480
Columns	1712	2996	3424	3852	4280	4708	5136	5564	10 700	13 268	31 244
Case 1 ($\omega = 0.01$)											
Obj function value	infeas	infeas	infeas	infeas	90.09	90.09	90.09	90.09	90.09	90.09	90.09
MCF solve time in seconds	0.361	0.172	0.259	0.305	1.297	2.906	2.468	2.875	3.719	11.781	32.031
Case 2 ($\omega = 100$)											
Obj function value	infeas	infeas	infeas	infeas	2703.59	2698.72	2698.72	2698.72	2698.72	2698.72	2698.72
MCF solve time in seconds	0.081	0.096	0.106	0.114	0.407	0.312	0.344	0.766	0.969	1.172	2.813

5.1. Data description

We use actual data from AMC operations to include routing for all aircraft. Our data set was derived from a randomly selected 6-h time period in March, 2003. Flight legs that began during this 6-h time period are included in the data set. We use the actual schedule to derive flight and ground arcs. Because aerial ports are not under AMCs direct control, it is difficult to centrally collect MOG limit data and data that indicates the time limits placed on aircraft flying into the aerial ports, such as closed times and bird air strike hours. We synthesized most of the data that pertained to the aerial ports, but it matches our understanding of AMC operations and the expertise of AMC operators. MOG limits are conservatively based on the observed number of aircraft flying in or out of aerial ports over a two month time span. The resulting data set includes 261 flight legs, 191 unique aircraft, and 136 unique aerial ports located throughout the world. Generating this data is a manual time-consuming step. We utilize this single scenario to analyze various objectives.

Before MCF is run, data is processed using heuristics coded in Java. This preprocessing converts the AMC data into a time-space network of arcs and nodes. Once in this network format, the data can be easily converted into the format required for MCF. This also allows the data to be easily passed between MCF and other optimization models. The preprocessing determines into which time periods an aircraft can be delayed based upon time limitations of aerial ports.

5.2. Computational results

Here we examine the computational attributes of the MCF by increasing the number of time periods for the maximum delay, represented by the absolute difference between the largest and the smallest numbers in the sets T_g^a or T_g^d. Conceptually, the maximum delay is the number of time periods that an aircraft can be delayed on the ground beyond its originally scheduled departure or arrival time.

The computations were made using a Pentium IV 2.66 GHz Dell Computer with 512 MB of RAM and the computer code was programmed in Java, which solved the MCF by calling XPress-MP 2003 software. A typical solution requires only 2.8 s to solve, where $\omega = 0.01$, $\beta = 1$, $\gamma = 1$, $\varepsilon = 1$, and the maximum delay is 6 time periods, with each time period representing 2 h in the schedule. Only minimal additional data preprocessing time (< 1 s) is required when one changes these values. It is realistic to imagine that, through repeated runs of MCF and varying the parameters, a solution space could be created in a few minutes and input into a visual tool for the decision maker to understand tradeoffs and select the appropriate solution.

Table 1 presents the results of changing the number of maximum delay time periods and changing the parameter ω, which weights the AMC attribute of the number of time periods a mission is scheduled beyond a designated time period (defined in Eq. (17)). Each time period is equivalent to two hours and the variables β, γ, and ε are held constant with a value of 1.

The extremes of $\omega = 0.01$ and $\omega = 100$ represent the tradeoff between immediate changes, giving operators little time to prepare for changes, and the schedule changing later, allowing operators much time to prepare for changes. An operator might start with $\omega = 0.01$, only to discover that one of the changed flights will interfere with the sleep time of

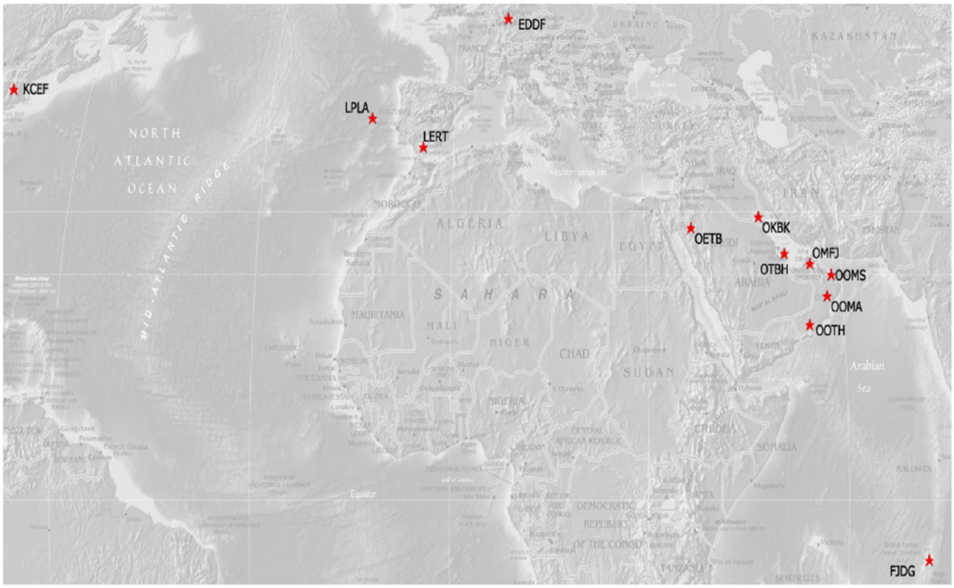

Fig. 4. Aerial ports of interest in scenario analysis.

a pilot, so the operator chooses the solution with $\omega = 100$. From the operator's perspective, MCF is a tool that aides in the decision making process, not to present the "right" answer.

Solution times change when altering either the number of maximum delay time periods or ω. The MCF is infeasible up to eight maximum delay time periods because there is not enough operational flexibility to avoid violating the MOG limits. For case 1 ($\omega = 0.01$), the objective function value is constant for maximum delay time periods $\geqslant 9$. For case 2 ($\omega = 100$), the value of the objective function is slightly higher when the value of maximum delay time periods is 8, then is reduced and constant for maximum delay time $\geqslant 9$. Thus, for case 2, in which less immediate changes are desired, the MCF suggests delaying individual aircraft for more than 9 time periods.

The quick solution time of MCF allows operators to explore beyond the first feasible solution, despite overwhelming data and a need for urgency. An operator is in the best position to understand the tradeoffs between the operational attributes and could use the solutions of MCF to find better tradeoffs.

5.3. Scenario analysis

In this section, we describe how the results of the MCF are useful for the operator, how MCF solutions compare with the existing schedule, and how we can visualize the changes suggested by MCF. We assume that MOG limits at each aerial port remain constant. In reality, MOG limits are dynamic, depending on unique circumstances such as the number of maintenance personnel available, equipment available, and local requirements. Some of the aerial ports in our case study have initial MOG values that exceed their MOG limits, so we assume that the first ground arc of each aerial port can exceed its MOG limit. Of course, MCF can avoid this if the MOG limit data is available and had been used to create the schedule of the first ground arc. When an aircraft reaches its final destination in the case study, it is no longer counted towards a MOG value. This allows MCF to find a feasible solution, even though the final time periods might have MOG values that exceed their corresponding MOG limits. A rolling horizon can be used to continuously update the schedule which can take account changes to the MOG limits.

As shown in Fig. 4, we limit our attention to 12 of the 136 aerial ports. The aerial ports are at the following locations:

- LERT: Rota, Spain;
- LPLA: Lajes Acores, Portugal;
- KCEF: Westover Air Force Base, Massachusetts;

Table 2
MOG levels at aerial ports for the first 6 time periods ($\beta = 1$, $\gamma = 1$, $\omega = 1$, and $\varepsilon = 0.01$)

ICAO code	MOG limit	Data source for MOG level	Time period						
			0	1	2	3	4	5	6
LERT	8	Baseline	9	1	0	0	0	0	0
		Solution 1	8	1	1	0	0	0	0
LPLA	8	Baseline	0	0	0	0	1	0	0
		Solution 1	0	0	0	0	0	1	0
KCEF	8	Baseline	12	12	10	4	4	0	0
		Solution 1	8	8	5	8	4	4	4
OOMA	8	Baseline	9	0	0	0	0	0	0
		Solution 1	7	2	0	0	0	0	0
EDDF	20	Baseline	30	24	6	3	0	0	0
		Solution 1	18	18	18	12	6	6	6
OOTH	8	Baseline	0	2	2	0	0	0	0
		Solution 1	0	2	0	2	0	0	0
OOMS	8	Baseline	0	2	0	2	2	0	0
		Solution 1	0	2	0	2	0	2	0
OKBK	8	Baseline	14	16	4	0	0	0	0
		Solution 1	8	8	8	8	6	6	0
OETB	8	Baseline	6	1	2	0	0	0	0
		Solution 1	8	1	2	0	0	0	0
FJDG	8	Baseline	4	4	4	0	0	0	0
		Solution 1	4	4	4	0	0	0	0
OMFJ	8	Baseline	2	0	0	0	0	0	0
		Solution 1	1	1	0	0	0	0	0
OTBH	8	Baseline	2	2	5	0	0	0	0
		Solution 1	2	2	0	3	0	2	0

- OOMA: Masirah, Oman;
- EDDF: Frankfurt, Germany;
- OOTH: Thumrait, Oman;
- OOMS: Seeb International Airport, Oman;
- OKBK: Kuwait International Airport, Kuwait;
- OETB: Tabuk, Saudi Arabia;
- FJDG: Diego Garcia, British Indian Ocean Territory;
- OMFJ: Fujairah, United Arab Emirates;
- OTBH: Al Udeid Air Base, Qatar.

In Table 2 we display the MOG limits for each location and the actual MOG levels by period for the original data (e.g., "Baseline") and the MCF solution data over 12 h (e.g., "Solution 1"). Different aircraft types have different contributions to the MOG level. For instance a larger aircraft requires more parking space and security resources than a smaller aircraft. Note that LERT, KCEF, OOMA, EDDF, and OKBK all have time periods where the MOG limit is exceeded in the baseline data. In Solution 1, we see that MOG limits are met at all locations and during all time periods. This is accomplished by delaying the departure of flights from preceding locations.

We next present a way to visualize, by location, the effect MCF has on MOG Levels. In Fig. 5, the MOG limit is exceeded at OKBK during time periods 0 and 1. By delaying aircraft on the ground at other locations, Solution 1 does not exceed the MOG limit of OKBK and the MOG values are higher in subsequent time periods. In Fig. 6, a similar situation occurs at EDDF. One difference is that the MOG values for Solution 1 are less than the MOG limits during time periods 0 and 1 because the MOG contribution of a large, inbound aircraft would cause MOG to exceed its limit. Overall, Solution 1 delays 32 of 191 total aircraft on the ground.

As we have noted, the subjective control parameters influence the characteristics of MCF solutions. By looking closely at six of the 32 delayed aircraft, we can explore the effects of changes in subjective control parameters on the

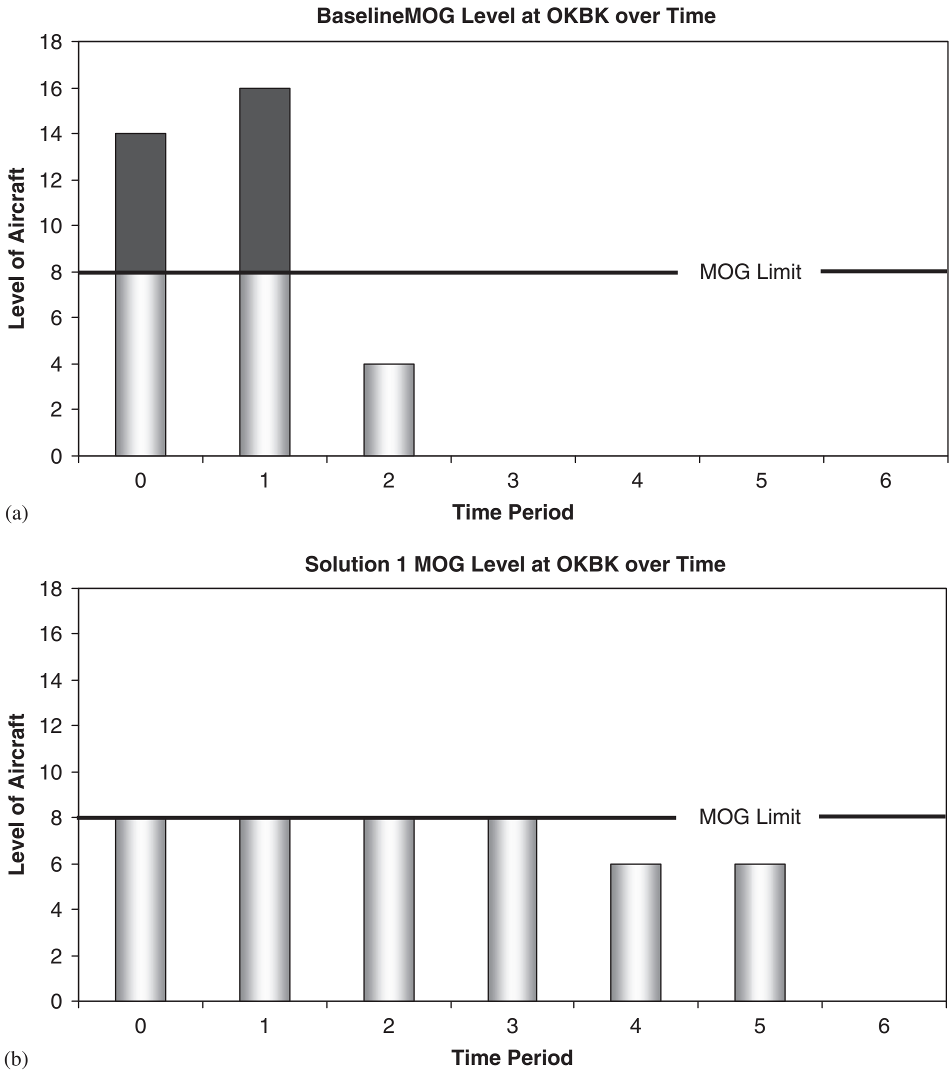

Fig. 5. Graph of MOG levels at OKBK, before (a) and after (b) running MCF.

MCF solution. To demonstrate the possible effects, we change the value of the subjective control parameter for the priority of the aircraft's mission, ε, from a value of 0.01 (Solution 1) to a value of 100 (Solution 2). Table 3 presents the solution characteristics of MCF for $\varepsilon = 0.01$ and $\varepsilon = 100$. Note that the only differences were found in the departure and arrival times of these six aircraft. The first column is the aircraft listed by individual tail numbers. Under each tail number is the aircraft type and the aircraft's contribution to the MOG level. The next two columns are the ICAO codes for the origin and destination aerial ports of each flight leg, and the last two columns present the attributes of the arcs. As an example, consider aircraft 40060B, which requires diplomatic clearances (DIPS) on its single flight arc with first priority. In the baseline schedule, aircraft 40060B is scheduled to depart LERT at time period 0 and then fly to aerial port KCEF to arrive at time period 4. In Solution 1, when $\varepsilon = 100$, the aircraft is delayed an additional time period and scheduled to depart LERT at time period 1.

In Solution 2, when $\varepsilon = 100$, more weight is placed on the priority of aircraft and relatively less weight on DIPS. Aircraft requiring DIPS (i.e., aircraft 40060B, 50102A, and 90002B) are delayed beyond their Solution 1 schedules and aircraft not requiring DIPS (i.e., aircraft 10880E, 56712T, 80808T, and ZH874T) have fewer delays. In other words, aircraft requiring DIPS have additional delays when $\varepsilon = 100$ to allow for fewer delays in significantly more flight arcs of other aircraft.

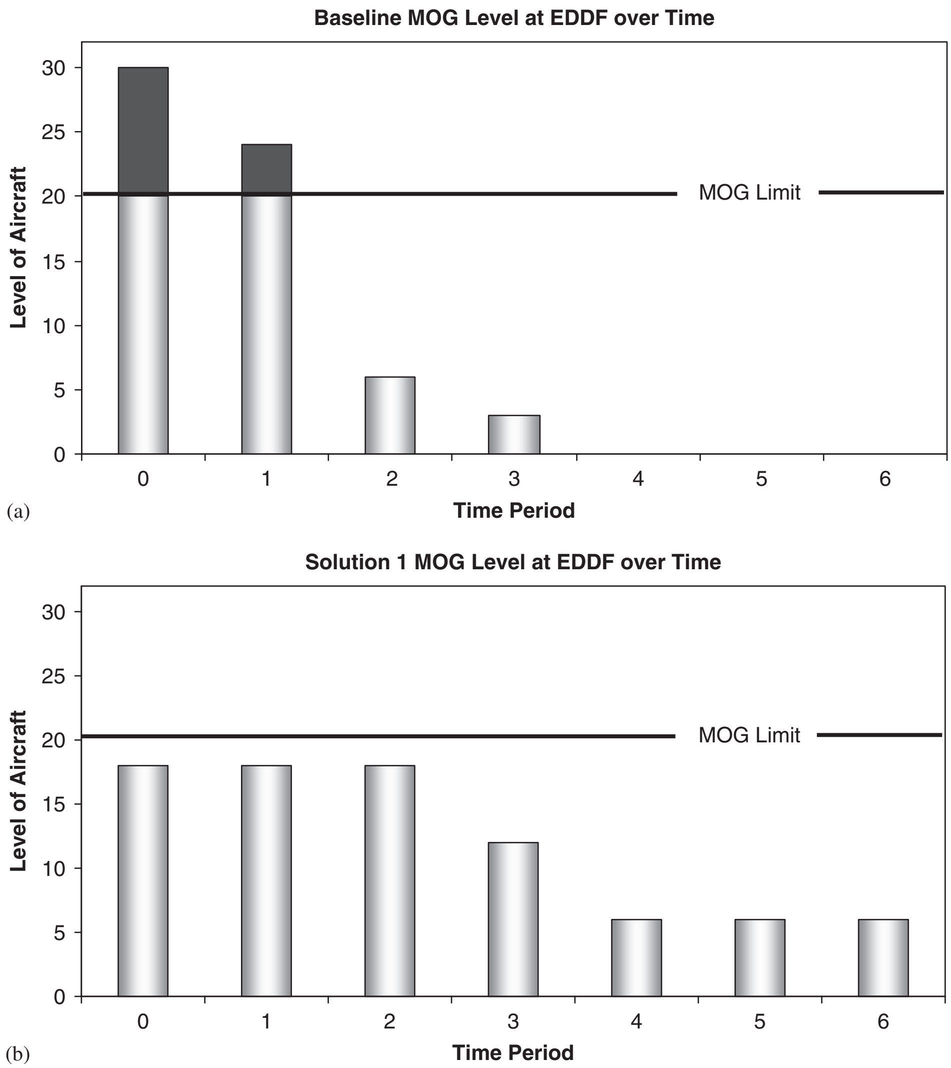

Fig. 6. Graph of MOG levels at EDDF, before (a) and after (b) running MCF.

Operators might know that the diplomatic clearances required for a particular day allow for operational flexibility. In this case, the operator could "spin" a dial on a GUI from a moderate value of ε to a low value of ε. On the other hand, the operator might have just been informed that a certain country is restricting aircraft into its air space, so the operator would turn the ε dial to high. We envision that all three solutions based on the different values of ε could be presented visually to the operator, who could then easily understand the tradeoffs. This type of visual representation has been explored in developing the Human Interaction with Software Agents Port Viewer [4] and researched by Dasgupta [27] in his master's thesis.

6. Conclusion

The MOG Compliance Formulation (MCF), which uses a variable transformation strategy introduced in Bertsimas and Stock's work on scheduling ground holds for air traffic flow management, can be used to quickly find solutions to problems caused by MOG constraints at the system-wide level of the AMC network. Through this clever variable definition, MCF has fast run times. From a planner's perspective, the MCF can also be used to conduct "what if" analysis by changing the weighting of different AMC network attributes.

Table 3
Difference in characteristics of two MCF solutions ($\beta = 1$, $\gamma = 1$, and $\omega = 1$)

Aircraft	Depart ICAO code	Arrive ICAO code	Baseline data		Solution 1 ($\varepsilon = 0.01$)		Solution 2 ($\varepsilon = 100$)		Priority	DIPS
			Depart time period	Arrive time period	Depart time period	Arrive time period	Depart time period	Arrive time period		
10800E	LERT	LERT	0	2	1	3	0	2	Aircraft Ground Arc	
C-9 (MOG + 1)	LERT	LPLA	2	3	3	4	2	3	Second	No
	LPLA	LPLA	3	4	4	5	3	4	Aircraft Ground Arc	
	LPLA	LERT	4	5	5	6	4	5	Second	No
40060B	LERT	LERT	0	0	0	0	1	1	Aircraft Ground Arc	
C-5 (MOG + 4)	LERT	KCEF	0	4	0	4	1	5	First	Yes
50102A	OOMA	OOMA	0	0	0	0	1	1	Aircraft Ground Arc	
C-17 (MOG + 3)	OOMA	EDDF	0	5	0	5	1	6	First	Yes
56712T	OOMA	OOMA	0	1	1	2	0	1	Aircraft Ground Arc	
C-130 (MOG + 2)	OOMA	OOTH	1	2	2	3	1	2	First	No
	OOTH	OOTH	2	3	3	4	2	3	Aircraft Ground Arc	
	OOTH	OOMS	3	4	4	5	3	4	First	No
	OOMS	OOMS	4	5	5	6	4	5	Aircraft Ground Arc	
	OOMS	OOMA	5	6	6	7	5	6	First	No
80808T	OKBK	OKBK	0	2	4	6	1	3	Aircraft Ground Arc	
C-130 (MOG + 2)	OKBK	OETB	2	4	6	8	3	5	First	No
90002B	OKBK	OKBK	0	2	1	3	4	6	Aircraft Ground Arc	
C-5 (MOG + 4)	OKBK	FJDG	2	6	3	7	6	10	First	Yes
ZH874T	OMFJ	OMFJ	0	0	2	2	0	0	Aircraft Ground Arc	
C-130 (MOG + 2)	OMFJ	OKBK	0	1	2	3	0	1	First	No
	OKBK	OKBK	1	2	3	4	1	2	Aircraft Ground Arc	
	OKBK	OTBH	2	3	4	5	2	3	First	No
	OTBH	OTBH	3	4	5	6	3	4	Aircraft Ground Arc	
	OTBH	OMFJ	4	5	6	7	4	5	First	No

The implementation of the methods presented in this paper is currently being explored. MCF would add additional "intelligence" to the Human Interaction with Software Agents Port Viewer, which graphically displays aircraft schedules being affected by MOG constraints, or other elements of AMC Information Technology systems. Because of the high operating costs of sustaining flight operations, small improvements in the execution of aircraft missions in the AMC network can lead to significant efficiencies in aircraft usage and improvement in the ability of AMC to respond to changes in a dynamic environment.

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