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Alleviating Airspace Restrictions through Strategic Control

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This paper presents a linear integer programming model for assigning pre-departure delays to flights under airspace capacity restrictions. The model is applied to control air traffic arriving at Chicago O'Hare International Airport over its eastern arrival fixes. Even in the absence of any convective weather, the FAA places miles-in-trail (MIT) restrictions at these fixes due to high traffic demand. The delay reduction by applying the optimization model was approximately 56% compared to what is done in practice, i.e., passing back the MIT restrictions to adjacent Centers. It is illustrated that the optimal departure delays of flights obtained from the optimization model can be used to back-calculate the necessary MIT restrictions at the Center boundaries. Furthermore, a sensitivity analysis estimates the effect of varying traffic demand and capacity on delays.

I. Introduction

STRATEGIC decisions in air traffic flow management (TFM) mitigate congestion in the airspace and at airports. Congestion occurs when demand exceeds capacity at one or more resources in the National Airspace System (NAS) such as airports and en route sectors. Typical TFM strategic decisions include ground delay, reroute, and airborne holding, among which, ground delay is most prevalent[1]. Ground delays are those that are assigned to an aircraft prior to its departure. Typically, ground delays are assigned in the face of airport capacity reduction due to adverse weather conditions, which affect the maximum rate at which flights can land at or depart from an airport. Since 2006, the FAA has launched a new TFM initiative known as the Airspace Flow Program (AFP), where ground delays are assigned to mitigate airspace congestion[1].

The problem of strategic decision-making in TFM can be solved through linear or non-linear optimization techniques. However, due to the highly complex nature of the problem, which evolves from the large number of variables, uncertainty in predicting capacity and demand in the NAS, and a lack of efficient algorithms to tackle such problems, applying optimization methods in real-life TFM decision-making remains elusive. Past research efforts have shown that applying optimization methods to many TFM problems can have a potentially significant effect on increasing efficiency in the NAS.[2,3] Most research has either focused on a small problem, which is computationally tractable, or apply approximations and heuristics to obtain solutions to more complex problems reasonably fast.

In this paper, a linear integer programming (IP) model is proposed that can determine flight delays and miles-in-trail restrictions in the face of demand-capacity imbalance at an airport's Terminal Radar Approach Control (TRACON). Although the model is based on existing IPs[5-9], it has far fewer variables and constraints, which makes it computationally tractable for large-scale problems such as the one considered in this study. It is demonstrated this this model can be applied to alleviate congestion at the Chicago TRACON.

The problem statement is presented in Section 2 followed by a literature review in Section 3. The binary integer programming model that was adapted for this study is presented in Section 4. The experimental setup is described in Section 5 followed by the results in Section 6. Finally, the concluding remarks are presented in Section 7.

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II. Problem Statement

Figure 1 shows the flight tracks on a good weather day for aircraft arriving at ORD from various origin airports. For reference, the Future Air Traffic Management Concepts Evaluation Tool (FACET[4]) was used to generate and display the flight tracks from Enhanced Traffic Management System (ETMS) data. Due to the heavy volume of traffic scheduled for ORD, the Chicago TRACON (C90) typically implements 10 miles-in-trail (MIT) restrictions at the two east arrival fixes, Pullman (PMM) and Knox (OXI). Due to the limited airspace available in Chicago Center (ZAU) to meet these 10-MIT restrictions, the restrictions are subsequently passed back to the two Centers adjacent to ZAU to the east, which are Cleveland Center (ZOB) and Indianapolis Center (ZID). The passed-back restrictions for the northern-most flow that arrives over PMM remains at 10-MIT; however, since three streams merge over the southern OXI fix, each stream typically receives 30-MIT. The rationale for applying 30 MIT is that, on average, if three traffic streams are spaced by 30-MIT restrictions, on average the combined stream will be spaced by 10-MIT. Finally, due to the limited available airspace in ZOB to properly space the northern-most flow that passes over PMM, the restrictions on this flow are typically passed back to New York Center (ZNY) and Boston Center (ZBW) as 20-MIT restrictions.

Since the sectors in ZNY are small and highly aligned with the major traffic flows, there is little room for flights to deviate laterally from their flight plans to absorb the delays imposed on them while en route. As a result, ZNY is often forced to pass the restrictions back to the New York TRACON, which are then translated to departure delays of flights. Flights departing from Boston International Airport (BOS) face similar restrictions.

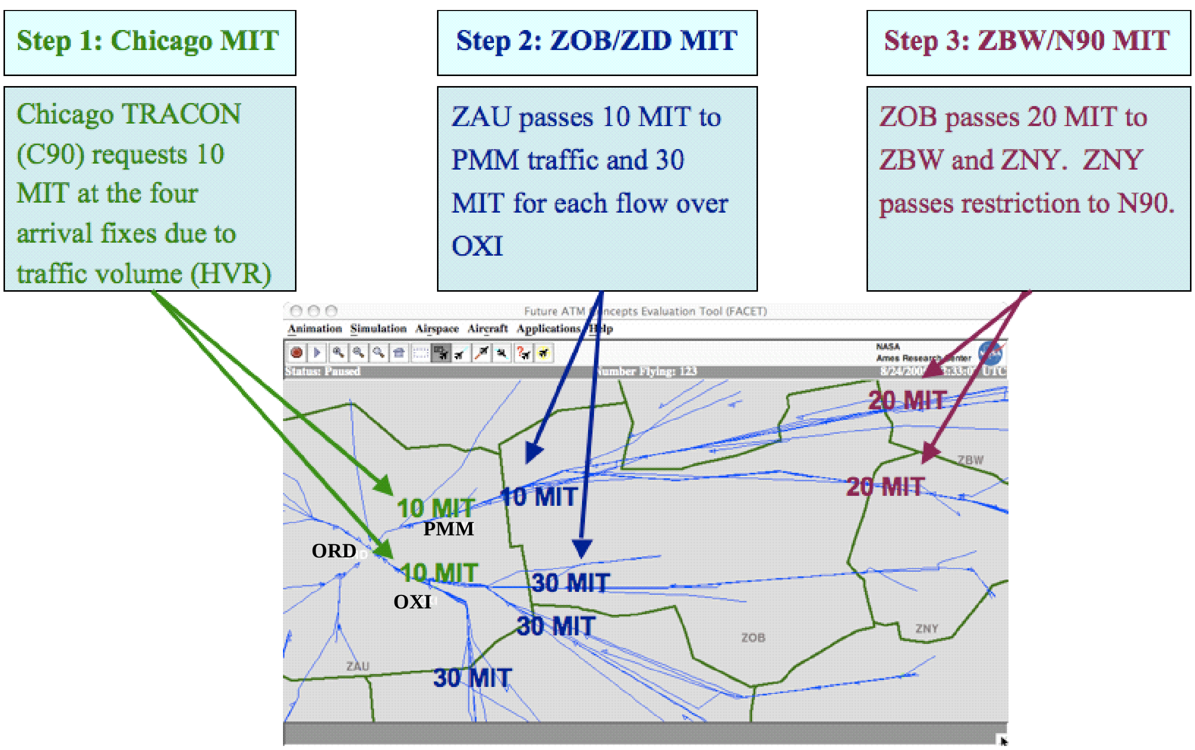

Figure 1: Airspace restrictions passed back from ORD TRACON to adjacent Centers

The linear IP model presented in Section 4 of this paper is applied to decide on ground delays of flights that are required to meet the 10-MIT restrictions over the arrival fixes – PMM and OXI. In parallel, for the sake of comparison, a "first-scheduled-first-served" algorithm was applied to assign delays to flights when the MIT restrictions are passed on to nearby centers – ZOB, ZID, ZNY, and ZID. The algorithm is analogous to the Ration-by-Schedule (RBS) algorithm, which is commonly used to allocate landing slots to aircraft during Ground Delay Programs[3]. It is shown that by applying the optimization model, overall delays can be reduced by approximately

56% compared to those obtained by passing the MIT restrictions to control flights originating from the nearby centers. The size of the problem, i.e., the number of decision variables and constraints, is small enough to keep the solution time of the IP within 5 minutes. Further, a sensitivity analysis was performed to estimate the effect of varying traffic demand and capacity on delays.

III. Literature Review

Applying optimization methods toward TFM strategic decisions has enticed researchers since late 1980's. There exists a moderate amount of research literature on this topic. This section discusses only those that are most relevant to the current problem being addressed in this paper.

Ref. 5 developed a deterministic optimization model that addresses en-route as well as airport capacity constraints. The model, which treats the NAS as a multiple origin-destination network, was formulated as a multi-commodity network flow problem where decisions on scheduling as well as routing air traffic through the network can be made. The decision variables are related to the volume of traffic on various links of the network. A deterministic model for deciding ground and airborne holding of individual flights under airport and airspace capacity constraints was formulated as a binary IP by Ref. 6. Ref. 7 formulated a binary IP to solve a similar problem. Along with solving for an optimum set of ground and airborne delays, their model can also be extended to decide on rerouting individual aircraft. More recently, Ref. 8 proposed an optimization model, formulated as an IP, that considers controller workload, safety, and equity among airlines, along with TFM strategic delay decisions.

Ref. 7, although computationally most efficient compared to other models, becomes computationally intractable for large scale TFM problems that address capacity constraints at many airports and sectors in the NAS. Ref. 9 discusses the limitations of this model when applied to scheduling flights over Central East Pacific oceanic airspace. The number of variables and constraints in their formulation were approximately 1.7 million and 19 million respectively. In order to achieve practical run times, Ref. 9 proposed a heuristic, which is based on partitioning flights into subsets according to their schedules.

Although the Ref. 7 model allows airborne holding, such actions are rarely needed in a deterministic setting. TFM actions such as airborne holding and dynamic rerouting become necessary mainly in the event of unforeseen weather evolution. In other words, flights released under imperfect information on airspace capacity may become subject to airborne holding if weather blocks their filed routes. There is sparse literature on stochastic optimization models[10,11] that account for uncertainty in airspace capacity while deciding ground delays of aircraft. Such models also decide on contingency plans (i.e., airborne holding and dynamic rerouting) in the event of unpredicted weather movement.

The problem being addressed in this paper, as described in Section 2, is unrelated to any capacity drop due to weather, which is typically associated with uncertain forecasts. The objective here is to assign delays to aircraft so that the deterministic MIT restrictions over the arrival fixes, PMM and OXI, are not violated. Therefore, it is safe to assume that a deterministic optimization model can be applied to decide on such TFM decisions. As mentioned above, under a deterministic setting, airborne holding is rarely needed. Therefore the optimization model presented in Section 4 only decides on ground delay assignment to individual flights, and assumes there is no airborne holding. As shown later, this assumption leads to tremendous reduction in the number of decision variables, and hence makes the IP computationally tractable.

In a parallel track of research that was initiated in the 1990's, a sizeable body of work has focused on developing time-based metering algorithms, concepts, and decision-support tools for generating sequence and schedule information to reduce delays for arrival aircraft destined for capacity constrained airports[12,13]. The modeling approach adopted in this study is believed to be complimentary to this line of research. The primary differences between the methods employed in this study and the time-based metering studies are the explicit inclusion of en-route sector and departure airport capacities, as well as the location at which flight controls are applied, which is discussed more in the following section. Furthermore, integer programming models can be applied to assign arrival times to individual aircraft while minimizing a global objective function such as total delay.

IV. 0-1 (Binary) IP Formulation

In this section, a deterministic optimization model, formulated as a binary IP, is presented. The model is applied to determine ground delays of flights subject to airspace capacity restrictions. The model parameters are defined as follows:

F : set of flights whose ground delays are to be determined,

J : set of sectors,
K : set of airports from where flights originate,
Q : set of arrival fixes,
N_f : number of resources (i.e., departure airport, sectors and an arrival fix) in flight f 's trajectory,
$P(f,i)$: i^{th} resource along flight f 's trajectory,
$l_{f,j}$: amount of time flight f is required to spend in sector j ,
d_f : scheduled departure time of flight f ,
T : number of discrete time intervals that constitute the planning horizon,
G : maximum amount of ground delay that can be assigned to any flight,
$S_j(t)$: sector capacity (i.e., maximum number of aircraft allowed to be present within a sector at any time),
$D_k(t)$: departure capacity of an airport $k \in K$,
and
$M_q(t)$: Capacity of arrival fix q derived from the MIT restriction applied at that fix.

The binary decision variables, $x_{f,t}$, are defined as follows:

$$x_{f,t} = \begin{cases} 1, \text{ if flight } f \text{ departs by time period t} \\ 0, \text{ otherwise} \end{cases}.$$

With this definition of $x_{f,t}$ the objective function of this model minimizes the total ground delay with respect to the unconstrained schedule, and is expressed as:

$$\min \sum_{f \in F} \sum_{t=d_f}^{d_f+G} (t-d_f).(x_{f,t} - x_{f,t-1}) \tag{1}$$

The set of constraints are defined as follows:

$$\sum_{f:P(f,1)=k} (x_{f,t} - x_{f,t-1}) \le D_k(t) \tag{2}$$

$$\sum_{\{(f,j'):P(f,i)=j,P(f,i+1)=j',i<N_f\}} (x_{f,t-\sum_{m=1}^{i-1} l_{f,P(f,m)}} - x_{f,t-\sum_{m=1}^{i} l_{f,P(f,m)}} \le S_j(t), \quad \forall j \in J, t \in \{1,..,T\} \tag{3}$$

$$\sum_{f:P(f,N_f)=q} (x_{f,t-\sum_{m=1}^{N_f} l_{f,P(f,m)}} - x_{f,t-1-\sum_{m=1}^{N_f} l_{f,P(f,m)}} \le M_q(t), \quad q \in Q, t \in \{1,..,T\} \tag{4}$$

$$x_{f,t} - x_{f,t-1} \ge 0 \quad \forall f \in F, t \in \{d_f,..,d_f+G\} \tag{5}$$

$$x_{f,d_f+G} = 1 \tag{6}$$

The constraint set (2) ensures that the number of flights departing an airport during a given time period does not exceed the airport's departure capacity. Similarly, constraint set (4) imposes arrival-fix capacity constraints derived from MIT restrictions. Constraint set (3) ensures that the number of flights present in a sector at any instant is limited by the sector capacity. Constraint set (5) implies that the decision variables are non-decreasing, while constraint set (6) limits the maximum amount of ground delay that can be assigned to any aircraft to an amount G.

The optimization model presented above decides when to release aircraft so that the airspace capacity constraints are not violated. The set of flights being controlled are only those that are scheduled to arrive at an airport, flying over a pre-specified arrival fix. The main constraints in the airspace are the sector capacity and MIT restrictions imposed at the arrival fixes. The maximum permitted ground delay is imposed due to two main reasons: (1) in order to limit the size of formulation (i.e., number of decision variables and constraints), and (2) to ensure that no flight faces an excessive amount of delay. In other words, the parameter G also imposes some degree of equity in the delay distribution. Setting G to a very high value can cause excessive computing time, while setting it to a low value can result in infeasible solution of the IP.

The size of the formulation of the IP depends on the number of aircraft being controlled, $|F|$, the number of discrete time intervals that constitute the planning horizon, T, the number of en route sectors, $|J|$, the number of origin airports, $|K|$, and the number of arrival fixes, $|Q|$. The number of decision variables in the above IP formulation is given by $|F|.G$. The number of constraints is given by $T.(|K|+|J|+|Q|)+|F|.G$.

V. Experimental Setup

The deterministic optimization model presented in Section 4 was applied to control 93 flights scheduled to arrive at ORD, passing over either of the eastern arrival fixes – PMM and OXI, during the 10:00 – 13:00 Coordinated Universal Time (UTC) period on August 24, 2005. This particular day was chosen because it was a good-weather day. Figure 2 shows the 51 airports from where flights originated and the en route centers and sectors that were involved in the study. The traffic flying to ORD from the west was assumed to be free of any airspace restrictions and hence was not controlled. The remainder of flights in ZNY, ZOB, ZBW, and ZAU Center were considered uncontrolled in this problem. The time-varying airport arrival, and airport departure rates associated with these flights was calculated and subtracted from the nominal airport arrival and departure rates to establish reduced capacities for these resources.

The sector capacities used in the optimization model were derived from the monitor alert parameters (MAP) and the traffic load due to flights that were not controlled (i.e., no delays assigned to them) in this study. The uncontrolled flights are those that use the same airspace during the 3-hour planning horizon as the controlled flights, but are flying to airports other than ORD. To obtain the capacity of a sector that may be allocated to the controlled flights, the MAP value of the sector is reduced by the traffic load due to "uncontrolled" flights. Therefore, the time varying traffic volume of the uncontrolled flights induces the change in sector capacities that remains to be allocated to the controlled flights.

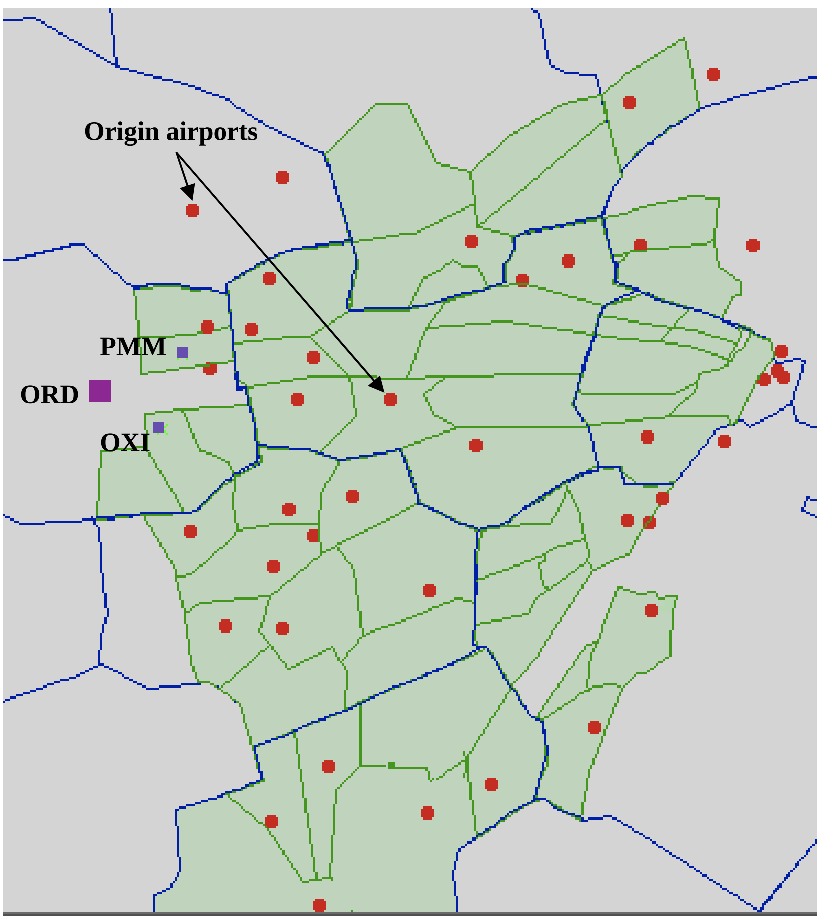

Figure 2: Airports and sectors considered in the study

As mentioned previously, FACET[3] was used to obtain operational flight and airspace data for the optimization model, and to simulate the impact of the ensuing traffic flow restrictions. FACET can operate in a playback, simulation, live, and hybrid mode using the FAA's Enhanced Traffic Management System (ETMS)[14] or Aircraft Situation Display to Industry (ASDI)[15] data along with wind and weather data from NOAA on a laptop computer.

To facilitate this study, an Application Programming Interface (API) was developed for FACET that leverages many of the core capabilities designed in the development of the Configurable Airspace Research and Analysis Tool – Scriptable (CARAT#)[16] system. A graphical depiction of a Java-based client that utilizes the FACET API, and was used in generating the results for this study is depicted in Figure 3. Starting at the box labeled "[1] Start Simulation," the FACET application is instantiated, and a simulation is started with a user-specified input file containing a list of active and scheduled flights. For the purpose of this study, the list of scheduled and active flights was obtained from an ASDI data file, and the simulation planning horizon was set to three hours. After starting the simulation, the software represented by the box labeled "[2] Log airspace/airport occupancy/usage statistics" was used to create a Java hash table of "Aircraft" objects that was used to record the entry time and usage time for all airports and sectors along the flight path of each scheduled and active flight in the simulation.

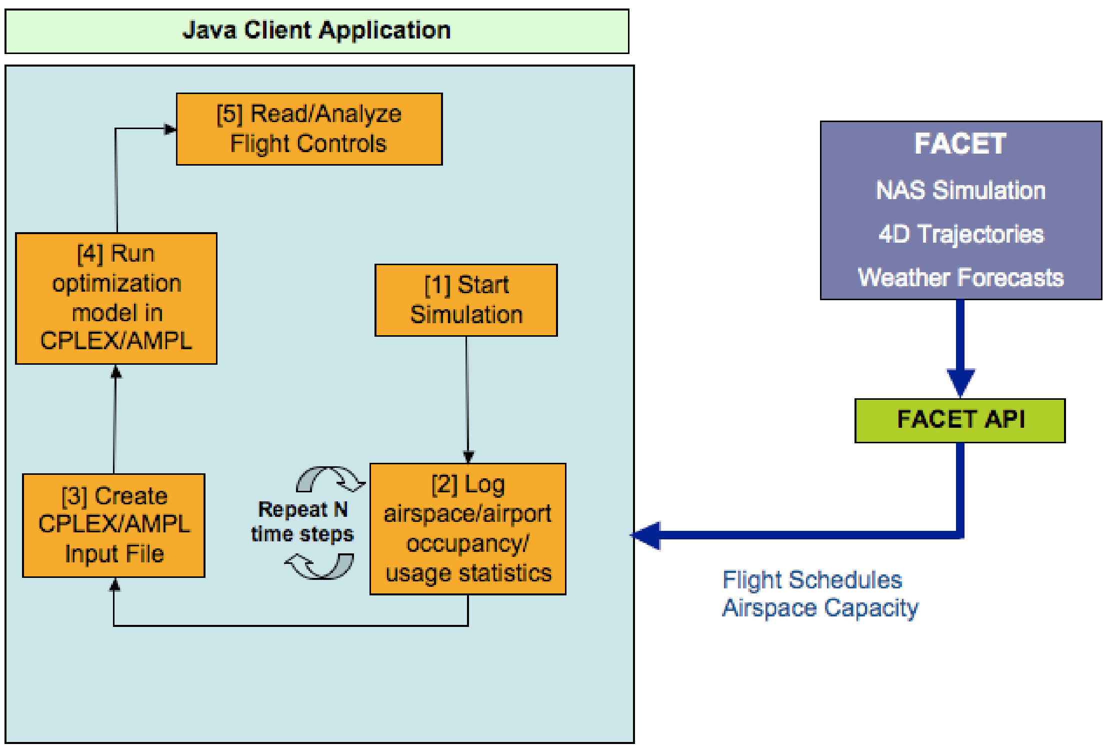

Figure 3: Java-based client interaction with the FACET Application Programming Interface

Following the simulation, the box labeled, "[3] Create CPLEX/AMPL Input File," formats the forecasted aircraft and airspace demand data using A Modeling Language for Mathematical Programming (AMPL)[17] to provide the inputs to the previously defined binary integer programming model. After casting the binary integer programming model in the AMPL format, which is done only once, both the AMPL formatted input file and model file are passed into ILOG's AMPL/CPLEX optimization software in order to assign the optimal departure delays to the set of flights included in this study. This optimization occurs in the section of the code labeled "[4] Run optimization model in CPLEX/AMPL" in Figure 2, and version 10.0 of AMPL/CPLEX was installed on a Redhat Linux- based laptop computer with a 3.0 GHz Pentium 4 processor and 1GB of RAM to support these calculations. The results presented in the Results section are the output from this stage of the modeling process, indicated by the box labeled, "[5] Read/Analyze Flight Controls."

The performance of the deterministic optimization model, presented in Section 4, was compared to two other approaches to achieving the 10 MIT restriction over PMM and OXI. The first one resembles the current day operations where 20 MIT restrictions are imposed at Center boundaries between ZOB, ZNY and ZBW. An algorithm, which functions analogous to the RBS algorithm, was applied to assign flight crossing times over these Center boundaries. The algorithm prioritizes flights based on their schedules when assigning Center boundary crossing. For a given flight the departure delay was calculated from the difference between its scheduled and assigned Center boundary crossing times. In the second approach, MIT restrictions were passed back only to Chicago's first tier centers, ZOB and ZID. RBS was then applied to assign flight crossing times, which translates to departure times, and hence departure delays.

VI. Results

Figure 4 illustrates three approaches to achieving 10 MIT for the ORD arrival flows that pass over the PMM and OXI fixes. The right-most example in this figure represents the restrictions imposed under current-day operations, as previously discussed. The middle example represents a refinement over current-day operations in which restrictions are not automatically passed back to ZNY and ZBW. The left-most example represents a scenario in which no restrictions are passed back.

In terms of total delay, the approach used to manage ORD arrival flows under current-day operations was the most restrictive and resulted in 785 minutes of delay. As mentioned before, an algorithm analogous to the RBS algorithm was used to schedule flights in order to meet the MIT restrictions at the locations of the six magenta rectangles in Figure 4. When restrictions were only passed back to Chicago's first-tier Centers (ZOB and ZID), the results improved to 735 minutes, which represents a 5% delay reduction. Finally, when a deterministic optimization model was applied to assign departure delays to aircraft subject to the MIT restrictions placed at the airport arrival fixes, and en-route sector capacity constraints were considered, the total delay reduced to 343 minutes (i.e., savings amounting to 56%).

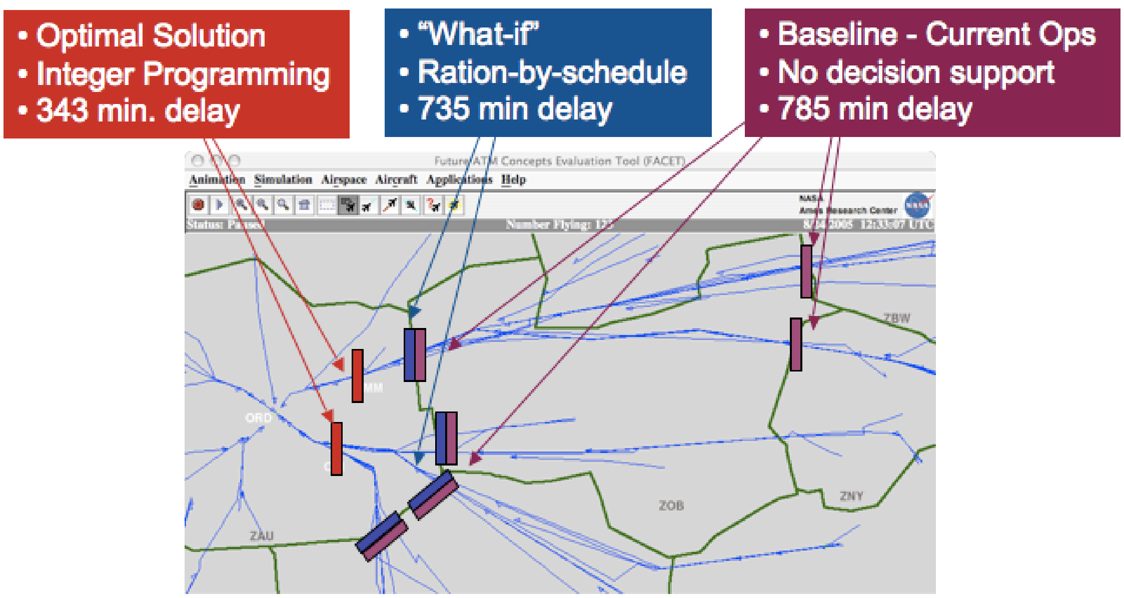

Figure 4: Three approaches to applying MIT restrictions at the eastern arrival fixes

Figure 5 shows the cumulative delays obtained from the three scheduling approaches. In the RBS-based schedules, flights that are scheduled to arrive later in the planning interval face significantly higher delay than those arriving early. This result is intuitive, as the RBS algorithm prioritizes flights based on their schedules. Although a similar trend is observed in the cumulative delays obtained from the deterministic optimization model, the slope of the corresponding curve in the figure is lower than the other two, which means that the incremental delays faced by flights arriving later in the day are lower in this case.

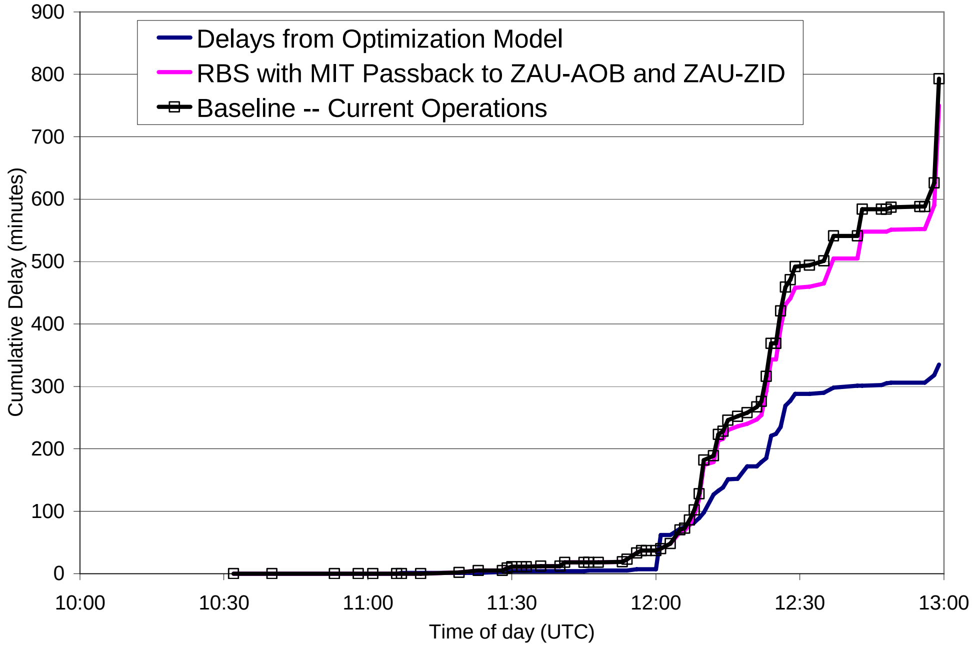

Figure 5: Cumulative Flight Delays

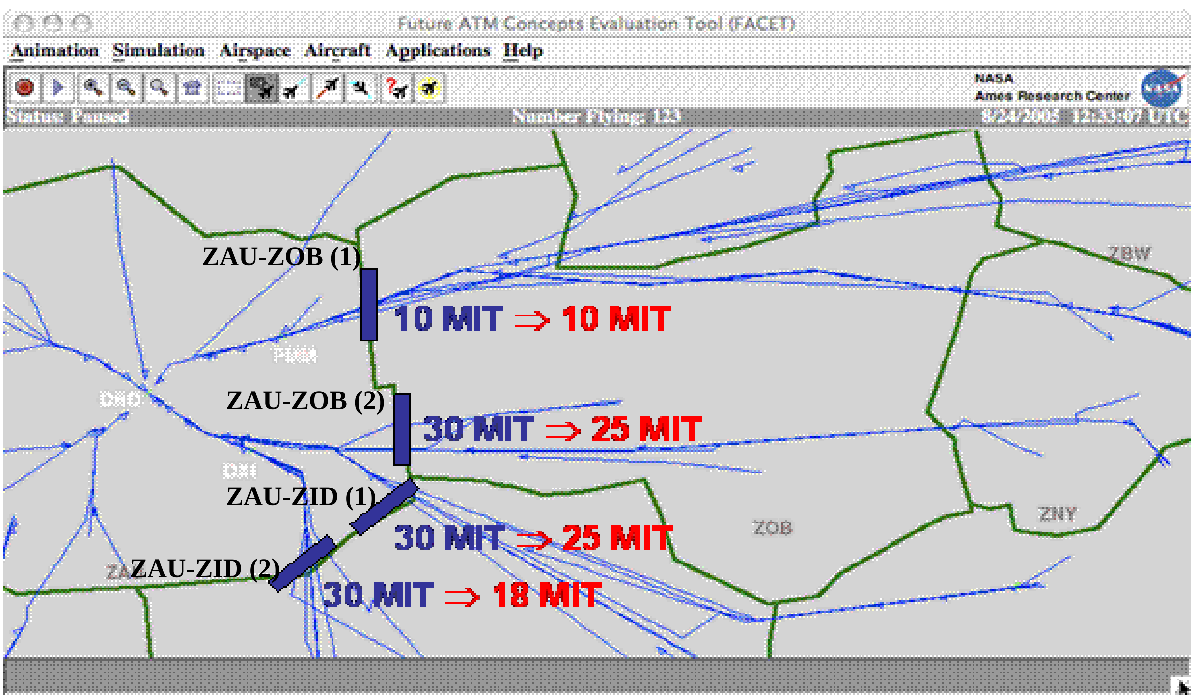

Figure 6: Improved pass-back MIT restrictions at center boundaries ZAU-ZOB and ZAU-ZID

The deterministic optimization model generates aircraft crossing times over various resources such as arrival fixes, and Center boundaries. As discussed in Section 2, this is not aligned with the present-day procedure where MIT restrictions are placed, and air traffic controllers are responsible for ensuring those restrictions are met. The optimal departure delays of flights were used to compute the flight crossing times at the Center boundaries – ZAU-ZOB and ZAU-ZID. Based on these values and average aircraft speed, which was assumed to be 300 nmi/hour, the minimum spacing required between any two consecutive flights was calculated. The MIT required between two flights was set to the minimum, i.e., 10 nmi, if the trailing flight had no delay. Figure 6 shows the MIT restrictions, computed from the average minimum spacing between two consecutive flights, at various center boundary crossing points. As indicated in the figure, there are two major flows for each center boundary. Based on these results, flights arriving to ORD from the south, and flying over OXI, face reduced MIT restrictions. Figure 7 shows the average MIT restrictions in 15-minute time intervals. The MIT restrictions are time-varying, and it reflects the need to adjust these restrictions across time of day in response to varying demand levels. It can be concluded that with these new MIT restrictions applied at the boundaries between ZAU, ZOB, and ZID Centers, overall delays of flights arriving from east of ORD can be reduced by approximately 56%. Given the simplistic nature of such a change in the TFM strategy, the gains are significant.

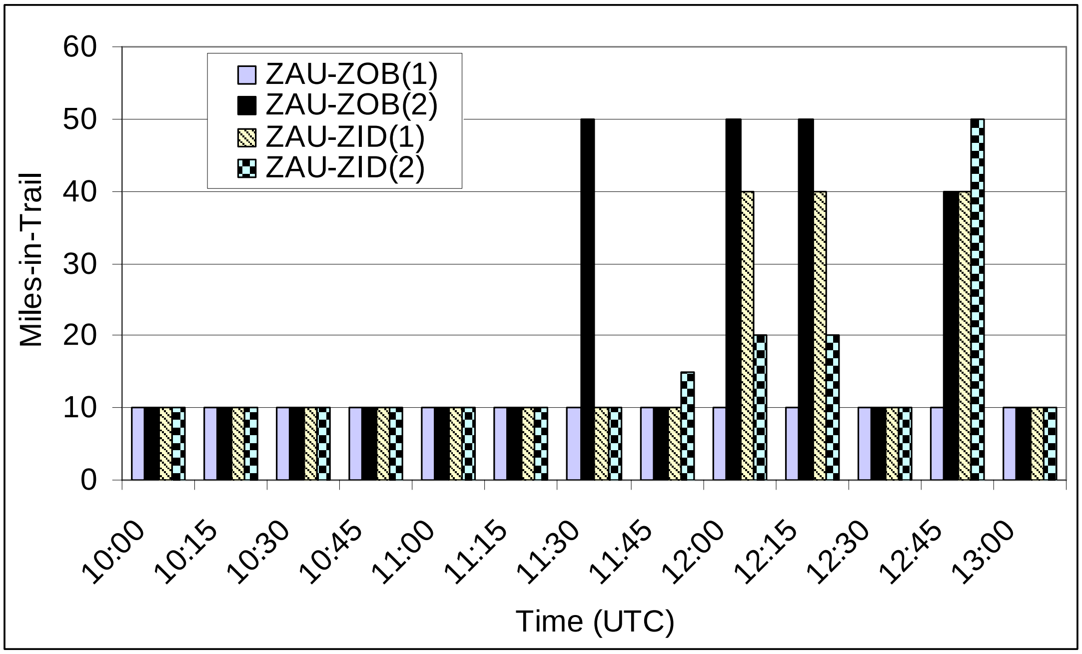

Figure 7: Time-Varying MIT restrictions at center boundaries ZAU-ZOB and ZAU-ZID based on the IP model

Table 1 presents total delay obtained from the deterministic optimization model applied to four different 3-hour planning horizons. Also presented are the delays obtained from the current-day operations and from the RBS algorithm applied to scheduled flights at the Center boundaries ZAU-ZOB and ZAU-ZID. The delay savings from optimizing flight departure times varies between 46-81%.

Table 1: Delay Variation with Planning Period

Time Interval	Total Delay from Deterministic Optimization Model (minutes)	Total Delay from RBS Applied at Center Boundaries – ZAU-ZOB and ZAU-ZID (minutes)	Total Delay from Current-Day Operations (MIT Restrictions Passed Back to ZNY and ZBW) (minutes)
10:00-13:00 UTC	343	735	785
13:00-16:00 UTC	297	755	757
16:00-19:00 UTC	84	438	460
19:00-22:00 UTC	224	403	415

The deterministic optimization model presented in Section 4 was applied to test the sensitivity of the results under varying demand and capacity, the results of which are presented in Table 2. Clearly, if the traffic volume increases 3-times, as is predicted in the Next-Generation Air Transportation (NextGen) time-frame[18], without any increases in en-route or surface capacity, the problem becomes infeasible. The infeasibility results from a constraint in the binary integer program model used in this example that limited the maximum ground delay of a flight to 200 minutes or less. In other words, demand increase in the NAS must occur in parallel with technological changes and capacity enhancements. From the table it is evident that the ORD arrival fix capacities pose more severe constraints than en-route sector capacities. For example, under the scenario in which en-route sector capacities remain at the present-day level while the airport arrival fix capacities double, there is a feasible solution (total delay of 13,000 approx.) compared to an infeasible solution when airport fix capacities remain at today's level. If capacities of all resources increase proportionally to the forecasted demand growth, the average delay remains the same as the current level.

Table 2: Sensitivity Analysis using the linear IP model

Traffic Demand	En route Sector Capacity	Chicago Arrival Fix Capacity	Delay (min.)	Average Delay (min.)
1X	1X	1X	343	4
3X	1X	1X	Infeasible	-
3X	2X	1X	18,606	73
3X	1X	2X	13,022	51
3X	2X	2X	4,718	19
3X	3X	2X	4,718	19
3X	3X	3X	1,008	4

VII. Conclusion

A deterministic optimization model, formulated as a linear integer programming model, to make ground delay decisions in the face of airspace capacity restrictions was presented in this paper. The model was applied to control air traffic arriving at Chicago O'Hare International Airport over its eastern arrival fixes, PMM and OXI. Due to heavy traffic volume even on a good-weather day, the FAA places a 10-MIT restriction at these fixes. The deterministic optimization model was applied to assign ground delays to ORD-bound flights originating from various airports in the eastern United States. It was shown that the delay savings by applying the optimization model varied between 46-81% compared to what is done in today's operations. It was also shown that the optimal departure delays obtained from the optimization model can be used to back-calculate the necessary amount of MIT restrictions at the center boundaries. The optimization model was then used to test the sensitivity of delays under varying demand and capacity. From the results, it can be concluded that the capacities of the arrival fixes, PMM and OXI, posed more severe constraints than the en-route sector capacities. If the demand increases 3 times while the capacities of NAS resources are doubled, the overall delay increases by about 14 times. On the other hand, if the capacity increase is proportional to demand growth, the average delay remains at the current level.

Acknowledgments

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