

# Benefits from Collaborative Flow Planning of Alternative Route Options

Rafal Kicingier\* and Jimmy Krozel†  
*Metron Aviation, Inc., Dulles, VA, 20166*

Jeffrey Henderson‡ and Husni Idris§  
*Engility Corporation, Billerica, MA, 01821*

and

Pierrick Burgain\*\*  
*Georgia Institute of Technology, Atlanta, GA, 30332*

Collaboration between the service providers and users of the national airspace system is currently limited to strategic traffic flow management planning. Extending the collaboration to mitigating localized flow constraints is expected to result in benefits including increasing the available solutions and incorporating user preferences in these solutions. This paper presents preliminary analytical results for the benefits from collaborative planning of alternative route options available to the users when imposing a flow plan. It describes a collaboration scheme and models supporting a fast-time simulation of this collaboration. The simulation is used to demonstrate and quantify how flow planning collaboration can improve the utilization of airspace resources through the negotiation of alternative routes. Simple scenarios are used to investigate the impact of various user and service provider collaboration behaviors such as the type of user preferences and the criteria the service provider uses for accepting and rejecting user preferences on the obtained benefits. Insights are gained on the tradeoff between the increased flexibility through additional route options and the increased complexity of the flow plan.

## Nomenclature

$\alpha$	=	Minimum topological separation rule
$\beta$	=	Maximum additional path cost
$\gamma$	=	Topological path separation threshold
$\chi$	=	Total number of alternative paths
$\lambda$	=	Threshold for the number of flights required to define a flow
$\delta_1, \delta_2$	=	Weights for AOC route ranking cost function
$\mu$	=	Maximum number of alternative paths per flow which can be accepted in the flow plan
$\omega$	=	Flow plan complexity threshold
$A$	=	Arc index
$\mathbf{A}(p)$	=	Set of arcs defining path $p$
$c(p)$	=	Total cost of path $p$
$CF_{AOC}(p)$	=	AOC cost function for path $p$
$d(p)$	=	Total delay along path $p$
$F$	=	Flow index

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\* Senior Analyst, 45300 Catalina Court, Suite 101, AIAA Member.

† Senior Engineer, 45300 Catalina Court, Suite 101, AIAA Associate Fellow.

‡ Senior Research Engineer, 300 Concord Road, Suite 400, AIAA Member

§ Principal Research Engineer, 300 Concord Road, Suite 400, AIAA Member.

\*\* Ph.D. Candidate, School of Aerospace Engineering, 270 Ferst Drive, AIAA Student Member.

$fpcomp$	=	Flow plan complexity function
$fuelcost$	=	Cost of fuel
$Fuel(p)$	=	Fuel burn for path $p$
$I_{AOCimpact}(p)$	=	AOC schedule impact cost index for path $p$
$I_{fuel}(p)$	=	AOC fuel burn cost index for path $p$
$P$	=	Path index
$\mathbf{P}(f)$	=	Set of paths assigned to flow $f$
$topodist$	=	Topological distance between two paths

## I. Introduction

Traffic flow management strives to maintain a balance between the demand for airspace and the available system capacity in an equitable and efficient manner. The air traffic service provider strategically resolves projected flow constraints well in advance of expected demand so that the safety of operations is not compromised. This is achieved through the implementation of various traffic management initiatives, which include ground stops, ground delay programs, airspace flow programs, reroutes, and miles-in-trail restrictions. Currently, traffic management initiatives are developed and implemented by the Air Traffic Control System Command Center and Traffic Management Units located at Air Route Traffic Control Centers (referred to as centers), which together we refer to as the air traffic service provider.

The traffic management initiatives implemented by the air traffic service provider have potentially large impacts on user operations in the National Airspace System. However, the air traffic service provider cannot make optimal traffic flow management decisions without collaboration from users, such as commercial and business airlines and general aviation users<sup>1</sup>. In order to facilitate user input and increase the efficiency of the National Airspace System, a collaborative decision-making paradigm has been implemented<sup>2</sup>. It is a joint government/industry initiative aimed at improving air traffic flow management through increased information exchange, cooperative procedures, and enhanced automated decision support tools<sup>3</sup>. To date, collaborative decision-making has been largely focused on national-level traffic management initiatives (i.e., ground delay programs and airspace flow programs); its benefits have not been extended to local traffic situations in which users coordinate directly with the Traffic Management Unit at the local center<sup>4</sup>.

Several approaches have been proposed to address traffic flow management collaboration at the local level. The concept of Distributed Air/Ground Traffic Management<sup>5</sup> included initial ideas for increasing users' involvement in traffic flow management decision-making beyond current collaborative decision-making practices. System Enhancements for Versatile Electronic Negotiation defined collaborative mechanisms that allow users to submit prioritized lists of multiple reroute options for their flights. These user preferences are then taken into consideration by traffic managers when they assigns reroutes and delays to flights subject to traffic flow constraints<sup>6</sup>. Another recently proposed Credits Concept<sup>7-9</sup> provides users with credit points to specify priorities for their flights. The Collaborative Traffic Flow Management concept<sup>10,11</sup> instantiates ideas included in the concept of Distributed Air/Ground Traffic Management<sup>5</sup> and extends collaboration to local constraint situations. It dynamically allocates some of the responsibility for selecting and implementing traffic flow management plans from the service provider to the users, using a three-tier system centered at constrained airspace resources. Collaborative Traffic Flow Management proposes to expand the scope of user preferences and to define new collaboration schemes at the constraint identification, impact assessment, flow planning, and flight implementation phases.

Complementary to our previous studies which focused on collaboration mechanisms for the impact assessment and flight implementation phases<sup>12,13</sup>, this paper analyzes the benefits of collaboration during the flow planning phase of Collaborative Traffic Flow Management. In particular, we use fast-time simulation to demonstrate and quantify how flow planning collaboration can improve utilization of airspace resources through negotiation of reroute alternatives. We study the impact of and benefits gained from modifying the scope of user-service provider collaboration during the flow planning phase. This encompasses user preferences for the number, location, and relative importance of alternative routes as well as preferences for the ranking of flows which are included in the flow plan. We also use simple scenarios to study criteria the service provider can use for accepting or rejecting user preferences.

This paper is organized as follows. Section II reviews the collaboration framework for flow planning and discusses roles and responsibilities for users and the service provider in flow planning activities. Section III introduces the algorithms supporting flow plan collaboration, including a network model for representing aircraft flows, an alternative path generation algorithm, and an algorithm for accepting/rejecting flow plan preferences

submitted by users. Section IV provides results obtained in fast-time simulations aimed at evaluating the benefits of flow plan collaboration. The paper concludes in Section V.

## II. Flow Plan Collaboration

Flow planning includes Traffic Flow Management (TFM) planning for a flow-level solution to mitigate the impact of constrained airspace resources, for example, due to hazardous weather<sup>14</sup>. A flow plan includes the following<sup>11</sup>:

- Resources available for use (airports, sectors, fixes, and route segments),
- A flow network through them,
- Assignment of traffic flows to network elements, where a traffic flow is a collection of flights sharing particular characteristics, and
- Acceptable flow rates for resource usage.

The flow plan is then implemented by allocating flights to resources as specified by the flow plan. In previous Collaborative Traffic Flow Management (CTFM) studies<sup>13,15,16</sup>, collaborative mechanisms involved user preferences (i.e., flight ranking, route ranking, and location where delay should be absorbed) specified at the level of individual aircraft during the implementation of a flow plan. In this study, we investigate and simulate collaborative flow planning in which users define their preferences (flow paths and flow priorities) at the level of network flows.

Flow plan collaboration is defined as follows. In response to an identified demand-capacity imbalance, CTFM Impact Assessment algorithms define a three-tier system around a constrained resource. For example, Figure 1 shows that a flow constraint is predicted at the ZOB79 sector. Given this constraint, a three-tier system consisting of an inner tier, middle tier, and outer tier is defined<sup>11</sup>. When flights affected by the constraint are in the outer tier, the air traffic service provider (ATSP) is not engaged in any flow planning activities to address the constraint. Only a default (or nominal) flow plan exists, and airline operation centers (AOCs) must plan their flights according to this default plan. The AOCs can engage in generating flow plan preferences while the flights are in the outer tier, and they communicate these preferences to the ATSP for consideration in the middle tier.

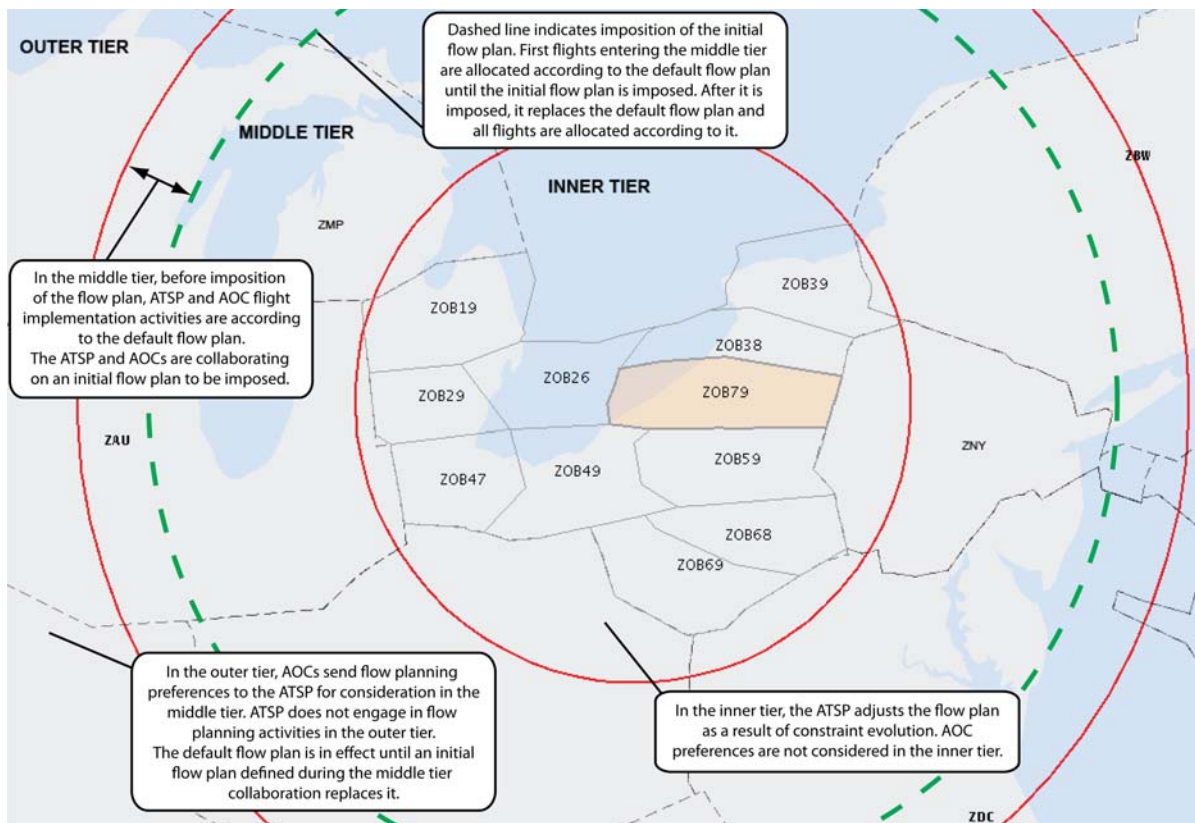


Figure 1: Flow plan collaboration activities and their impact on flight routes and delay decisions.

When preemptive actions of the AOCs in the outer tier do not resolve the constraint, the ATSP defines an initial flow plan, and forwards it to the AOCs for their input. The AOCs can either agree to the initial flow plan or can send alternative flow plan suggestions to the ATSP. The ATSP evaluates AOCs' proposals and develops a revised flow plan which represents a compromise between ATSP objectives and AOC preferences. The ATSP evaluates AOC proposals and develops a revised flow plan which represents a compromise between ATSP objectives and AOC preferences. This revised flow plan is selected by the ATSP for implementation and flight trajectories must abide by it. At this stage, the middle-tier flow plan is determined and gives participating AOCs the flexibility to choose among multiple routes by setting route options rather than imposing specific reroutes on flights<sup>14</sup>.

Field observations at the AOCs and air traffic control (ATC) facilities<sup>4</sup> showed that existing flow planning collaboration may be inefficient for a number of reasons. Due to high workload, the ATSP may not consider all potential flow planning solutions and may compromise with a less efficient plan. While it is straightforward to increase solution space by, for example, increasing the number of alternative routes, this increase must be consistent with ATSP and AOC behavior.

Field observations and interviews with AOC and ATC personnel provided the following valuable insights which were incorporated into the present research:

- ATSP behavior in current operations is experience-based and relies on the traffic flow manager to select a flow plan that has worked under similar circumstances in the past. This generally results in large regions of under-utilized airspace with few routes and low traffic density. AOCs would like the flow plan to consider these airspace regions, thereby reducing delays.
- ATSP often applies delays to some flows, such as high traffic flows from large hubs, but not lower traffic flows from small and medium hubs. Typically it is easier for the traffic managers to reroute or restrict traffic from a smaller number of large airports with a large contribution to a constraint than to deal with a larger number of airports with smaller contributions. At other times, limited airspace resources are exclusively given to major airports at the expense of huge delays at secondary airports. These differences in ATSP behavior result from a traffic flow manager biases based on their previous experience and historically used flow plan solutions which worked in similar situations.
- AOCs consider a larger number of alternative routes for their flows as this gives them greater flexibility. Considering additional flows as well as a larger number of alternative routes for each flow can increase the solution space, thereby improving equitable allocation of scarce resources and higher utilization of under-utilized resources. However, high ATSP workload often prevents the ATSP from considering all potential flow planning solutions. Hence, maintaining ATSP workload within a threshold is a key constraint on the complexity of flow planning solution considered.
- AOCs are mostly concerned with their own flights and typically do not consider the NAS-wide impact of a flow plan. Hence, they look for flows containing their flights and seek to minimize the travel time, distance, fuel burn, and potential schedule disruptions resulting from the ATSP flow plan.

Given these observations, the flow plan collaboration scheme described in this paper defines the following AOC preferences:

- Priorities for flows expressed in terms of their relative ranking
- The number and location of alternative routes for each flow and their relative ranking

At the current stage of model development, these preferences are limited to a fixed set of flows defined by the ATSP. An AOC determines the ranking of flows included in the set in the following way. First, it identifies the subset of flows which include its flights. This subset is then ordered by the total number of flights included in the flow. The flows containing the largest number of flights are ranked first (most important for this AOC) and the flows containing the smallest number of flights are ranked last (least important). The AOC then uses the set of ranked flows to generate its alternative route preferences using the Alternative Path Generation Algorithm and the network model described in Section III. The alternative paths obtained in this way for each AOC's flows are subsequently ranked using an alternative route ranking algorithm which considers two major factors:

- The fuel burn cost along the alternative flow path, and
- The impact on AOC schedule.

The resulting flow and alternative route rankings are subsequently communicated to the ATSP for the consideration in the middle-tier flow plan. The ATSP could use a number of criteria to accept or reject AOC flow plan preferences, with flow equity and flow planning workload being prime candidates. In the current implementation of the AOC flow plan preferences algorithm, only flow ranking and alternative route preferences are considered and hence our initial version of the algorithm for accepting or rejecting AOC preferences includes only flow planning workload factor.

The ATSP obtains flow plan preferences from all participating AOCs and iteratively considers their flow plan preferences starting from highest ranked flows and their highest ranked alternative routes. The AOCs' preferences are granted provided that the workload of the resulting flow plan does not exceed its acceptable workload threshold.

The algorithms supporting this model of the flow plan collaboration process are described next.

### III. Algorithms

The flow plan collaboration framework described in the previous section has been implemented in the CTFM simulation environment described in our previous studies<sup>12,13,15</sup>. The following sections describe the models and algorithms included in the framework.

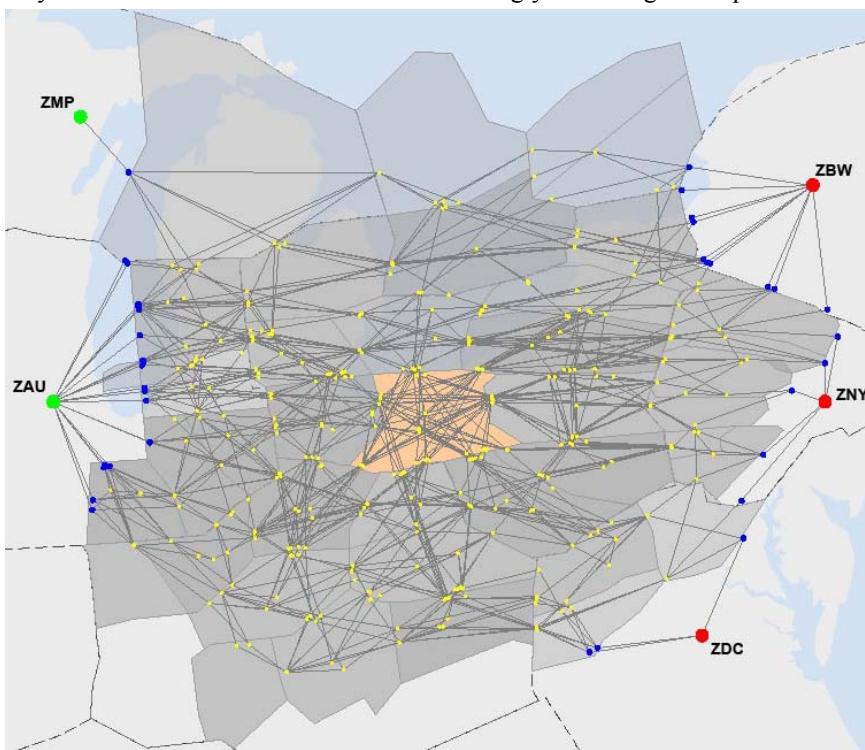
#### A. Network Model

Flow plan collaboration algorithms use an underlying network model to represent flows of aircraft and their routes through an airspace. This network model is constructed by analyzing historically flown route segments which are subsequently aggregated into nodes and arcs based on the sequence of sectors traversed by flights. The same network model is used by both the ATSP and users, and is provided as input to the CTFM discrete event simulation.

A relatively large number of network models have been studied for Air Traffic Management (ATM) applications<sup>17-20</sup>. Based on requirements of the CTFM specification<sup>14</sup> and its integration with the Future ATM Concepts Evaluation Tool (FACET)<sup>18</sup>, we decided to use a modified version of the network representation employed by the Multicommodity Eulerian-Lagrangian Large-capacity Cell Transmission Model (CTM(L))<sup>21</sup>. Figure 2 shows an example of a network model developed to represent traffic flow passing through the ZOB center. This network was developed using traffic data simulated in FACET from the first week of May 2006.

In Figure 2, nodes and arcs are defined for all sectors contained within the modeled region of airspace which we refer to as the flow plan domain. A node in this network is created at every point where at least one flight crossed a boundary between two sectors. Similarly, an arc connecting two nodes is added to the network if there is at least one flight which crossed the two sector boundaries which are represented by these nodes. The spatial location (latitude and longitude) of each node is defined as a mean latitude and longitude of all crossing points at the boundary time (rounded to the nearest minute) of all flights in the historical data set which traversed the route segment represented by this arc.

The airspace located outside the flow plan domain provides flows into and out of the flow plan domain via arcs connecting to nodes at the flow plan domain boundary (shown in blue in Figure 2). Source nodes (shown in green) accept flow into the flow plan domain and sink nodes (shown in red) accept flow out of the flow plan domain. In our simulations, we often assume that the size of the flow plan domain is equal to the size of the inner tier. However, the spatial extent of the network model does not need to be necessarily aligned with the size of the CTFM tiers; it can be chosen more arbitrarily as an experiment parameter.



**Figure 2: Network model for air traffic flows passing through the ZOB center. The nodes and directional arcs are defined based on analysis of either historical or simulated track data. For the clarity of presentation only arcs and nodes corresponding to eastbound traffic are shown.**

## B. Flow Plan Generation Algorithm

We use this network model to generate flow plans and to facilitate flow plan collaboration between users and the service provider. Each flow plan defines a list of flows together with their nominal and alternative routes and a set of acceptable flow rates. We focus in this paper on collaborative efforts to generate the alternative routes, hence our discussion focuses on models and algorithms supporting this aspect of flow plan collaboration.

As described in Section II, the CTFM Constraint Identification algorithms conduct periodic traffic demand projections to identify demand-capacity imbalances in the considered region of airspace. Flights affected by the constraint (i.e., flights projected to enter the constraint during the time interval when the capacities of resources included in the constraint are reduced from their nominal values) are subsequently identified by the CTFM Impact Assessment algorithms and provided as input to flow planning algorithms.

The set of flights affected by the constraint is next divided into flows. Flights can be grouped into flows in many ways, for example based on their routes, aircraft type, aircraft performance characteristics, or origin-destination pair. In the current version of CTFM flow planning algorithms we use the following approach for grouping. First, for each flight in the set, a sequence of sectors in the flow plan domain is determined which the flight is projected to traverse when following its nominal flight plan (i.e., filed or currently assigned flight plan). Next, this sequence is mapped to a set of arcs in the network model which together define a network path which we refer to as the nominal path as it corresponds to the nominal flight plan. This path is connected to appropriate source and sink nodes corresponding to the centers, or airports, through which the flight entered and exited the flow plan domain, respectively. All flights whose nominal flight plans are mapped into the same network path (i.e., same source node, same sequence of arcs, and same sink node) are grouped into a flow.

We introduce parameter  $\lambda$  to define a threshold for the minimum number of flights which need to be assigned to a flow so that the flow is included in the flow plan. We use  $\lambda$  to include in the final set of flows only those which satisfy the threshold criterion. The service provider uses these flows and the Alternative Path Generation Algorithm (described next) to generate alternative paths for each flow. Once feasible alternative paths are defined, an initial flow plan consisting of a set of flows and their nominal and alternative paths is determined and communicated to users through the CTFM messaging system.

## C. Alternative Path Generation Algorithm

The Alternative Path Generation Algorithm (APGA) extends the Dual Dijkstra Search (DDS) algorithm<sup>22</sup> with several parameters important for modeling behaviors of the service provider and of users when generating alternative routes. The DDS algorithm is a network search algorithm which finds a single optimal network path and a set of alternative paths that are topologically different. APGA provides an efficient method for generating sets of distinct alternative routes for each of the flows in the flow plan. Each such set contains a spectrum of alternative route options ranging from routes located close to the nominal route to routes which are far away from it. Four additional parameters used by APGA define additional constraints regarding the generation of alternative routes. These parameters include the following:

- $\alpha$  - minimum topological separation rule. It defines the minimum topological distance (measured in terms of the number of different arcs along the two compared paths) between an alternative path and the nominal path for a flow. We use Eqs. (1) and (2) to compute topological distance between two paths,  $p'$  and  $p''$ :

$$topodist(p', p'') = \sum_{\forall a \in \mathbf{A}(p') \cup \mathbf{A}(p'')} g(a, \mathbf{A}(p'), \mathbf{A}(p'')) \quad (1)$$

where

$$g(a, \mathbf{A}(p'), \mathbf{A}(p'')) = \begin{cases} 1 & \text{if } (a \in \mathbf{A}(p') \wedge a \notin \mathbf{A}(p'')) \vee (a \notin \mathbf{A}(p') \wedge a \in \mathbf{A}(p'')) \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

and  $\mathbf{A}(p')$  denotes the set of arcs defining path  $p'$ ,  $\wedge$  defines logical “AND” operator, and  $\vee$  defines logical “OR” operator. Alternative paths which have topological distance smaller than  $\alpha$  are determined as infeasible and are filtered out from the output set.

- $\beta$  - maximum additional path cost. It defines the maximum allowed additional cost (i.e., extra travel time) for an alternative path as compared to the nominal path for a flow. Alternative paths with costs greater than  $\beta$  from the cost of the nominal path are filtered from the output set.
- $\gamma$  - topological path separation threshold. It defines the threshold distance for alternative paths which determines if alternative paths are topologically similar and hence can be grouped into the same “topological bin.” APGA outputs one optimal path for each such bin. For example, APGA groups all

alternative paths with topological distance from the nominal path greater than or equal to  $\alpha$  and smaller than  $\alpha+\gamma$  into a single bin and outputs a single optimal path for this group. Then it groups all alternative paths with topological distance between  $\alpha+\gamma$  and  $\alpha+2\cdot\gamma$  into a another bin, etc. This parameter controls how the algorithm defines topologically different paths.

- $\chi$  - total number of returned alternative paths. It defines how many topologically distinct alternative paths are returned by the APGA.

By varying the values of these four parameters we obtain distinct behavioral models for users and the service provider related to flow plan collaboration on alternative routes which are consistent with field observations. For example, relatively small values of parameters  $\alpha$ ,  $\beta$ , and  $\gamma$  model AOC behaviors resulting in alternative paths located close to the nominal path. This is consistent with the typical AOC objective of limiting delay and fuel burn for their flights when they consider alternative routes. Relatively large values for these three parameters express the service provider's behavior, who is mostly concerned about congestion at and in the vicinity of a constraint. This yields longer alternative routes located farther from the nominal path and thus farther away from the constraint. We also use the fourth parameter,  $\chi$ , to model differences in behavior of the service provider and users in terms of the number of generated alternative routes. In this case, we use small values of  $\chi$  for the service provider, who generally prefers to limit the number of alternative routes due to flow plan complexity and workload constraints, and larger values of  $\chi$  for the user, who generally prefers a larger number of alternative routes for maximal flexibility.

The initial flow plan, including the set of alternative routes generated for each flow by the service provider, is communicated through the CTFM messaging system to the users. This initial flow plan is not yet imposed as the service provider awaits feedback from users on their flow plan preferences.

#### **D. AOC Flow Ranking Preferences**

In the flow plan collaboration scheme discussed in Section II, users define their preferences regarding flow priorities as well as alternative routes and associated rankings. In this subsection we introduce algorithms for defining AOC flow ranking preferences.

The initial flow plan generated by the ATSP contains the set of all defined flows. This flow plan is communicated to each AOC whose flights are included in at least one of the flows. The AOC uses this set of flows as an input to the flow ranking algorithm described below.

An AOC first selects from the set of flows only those flows which contain flights belonging to this AOC. Only these flows are ranked by the AOC and communicated back to the ATSP. Next, the AOC ranks the flows by either the total number of flights included in the flow or by the total number of passengers on board in the flow. The choice of the ranking key is determined as a parameter of a CTFM simulation. When the ranking key is set to the total number of passengers in a flow, then the algorithm first identifies all flights belonging to this AOC which are included in the flow. Then, it checks for type of aircraft used by each flight and the total number of seats available for each aircraft type. These seat counts are subsequently multiplied by a load factor obtained from the Bureau of Transportation Statistics (BTS DB1B 2008Q1 data) which provides load factor data per origin-destination pair and airline serving this connection. Thus obtained passenger counts for each flight are added up for all flights included in a flow to determine the total number of AOC passengers in a flow.

The flows containing either the largest number of flights or the largest number of passengers are ranked first (most important), and the flows containing the smallest number of flights or passengers are ranked last (least important). The resulting ranking of flows defines the flow ranking preferences for that AOC. These preferences are communicated to the ATSP.

#### **E. AOC Route Ranking Preference**

Similar to the flow ranking preference algorithm, the AOC route ranking algorithm obtains the set of flows from the initial flow plan and extracts from it flows which contain flights belonging to the AOC. Two additional inputs are required by the AOC route ranking algorithm: the delay map<sup>12</sup>, which defines expected delays in each of the resources (sectors) in the flow plan domain, and alternative routes defined for each flow by the ATSP. Both of these inputs are generated by the ATSP and communicated to each affected AOC.

Before the AOC starts the process of ranking routes, it first uses the APGA algorithm and AOC specific values of  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\chi$  to generate alternative paths for flows containing AOC flights. As mentioned earlier, different values for parameters  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\chi$  allow for modeling distinct behaviors for users and the service provider. At the same time, they can also be used for differentiating AOC behaviors in terms of the factors they consider, such as aggressiveness and risk aversion. In particular, more aggressive AOC behavior can be characterized by small values of  $\alpha$  and  $\gamma$  (this corresponds to alternative routes generated close to the nominal path), small values of  $\beta$  (the AOC is

not accepting reroutes which significantly increase the travel time), and large values of  $\chi$  (the AOC wants to have many alternative options available). The opposite is true for modeling behavior of less aggressive AOCs. As a result of calling APGA by each AOC, a set of alternative paths is obtained for each flow  $f$  which incorporate AOC preferences. These paths, together with the nominal path for the flow and alternative paths generated by the ATSP, define the set  $\mathbf{P}(f)$  of all alternative paths considered by the AOC route ranking algorithm.

The AOC route ranking algorithm is modified version of the user route ranking algorithm<sup>13</sup> adapted to flow planning. In the modified version, only two factors are considered—the fuel burn cost along the alternative route and the impact of the alternative route on the AOC schedule—as opposed to four factors included in the original algorithm. The modified version also uses network paths as inputs compared to actual routes.

The AOC route ranking algorithm evaluates each path  $p \in \mathbf{P}(f)$  using the cost function defined by Eq. (3) :

$$CF_{AOC}(p) = \delta_1 I_{fuel}(p) + \delta_2 I_{AOCImpact}(p) \quad (3)$$

where  $\delta_1$  and  $\delta_2$  denote weights,  $I_{fuel}(p)$  denotes a fuel index for path  $p$ , and  $I_{AOCImpact}(p)$  denotes an index measuring impact on the AOC schedule (connecting flights). The formulas for calculating the indices the defined in the following sections.

#### 1. Fuel Burn Cost Index

To compute the fuel burn cost index  $I_{fuel}(p)$  we compute the fuel burn associated with each path  $Fuel(p)$  as follows:

1. Compute the total cost  $c(p)$  (mean unimpeded travel time) of path  $p^{\dagger\dagger}$ .
2. From the delay map obtained from the ATSP, compute the total delay  $d(p)$  along the path  $p$  by adding up the predicted delays in sectors used by the path.
3. Compute the fuel burn  $Fuel(p)$  for path  $p$  using Eq. (4)

$$Fuel(p) = (c(p) + d(p)) \cdot fuelcost \quad (4)$$

where  $fuelcost$  constitutes input to CTFM simulation. When fuel burn values have been computed for all paths  $p \in \mathbf{P}(f)$ , we compute the flow fuel burn cost index using Eq. (5):

$$I_{fuel}(p) = \frac{Fuel(p) - Fuel_{\min}}{Fuel_{\max} - Fuel_{\min}} \quad (5)$$

where  $Fuel_{\max} = \max_{p \in \mathbf{P}(f)}(Fuel(p))$  and  $Fuel_{\min} = \min_{p \in \mathbf{P}(f)}(Fuel(p))$ .

#### 2. AOC Impact Index

The AOC Impact index  $I_{AOCImpact}(p)$  considers the level of disruption that delaying a flow along path  $p$  can have on other AOC flights. Maintaining a low level of delay is important for flights scheduled to large hubs with a high percentage of connecting passengers. For this calculation a buffer is first defined using Eq. (6) as the difference between the estimated travel time (path cost with predicted delays) for a flow through the flow plan domain and the corresponding mean unimpeded travel time (without delay) for the nominal path.

$$Buffer(p) = c(p) + d(p) - c(p^{nom}) \quad (6)$$

where  $c(p^{nom})$  is the mean unimpeded travel time for the nominal path for a flow. When all values  $Buffer(p)$  have been computed for each path  $p \in \mathbf{P}(f)$ , we compute the AOC impact index  $I_{AOCImpact}(p)$  using Eq. (7):

$$I_{AOCImpact}(p) = \begin{cases} \frac{Buffer(p) - Buffer_{\min}}{Buffer_{\max} - Buffer_{\min}} & \text{if } Buffer_{\max} > 0 \\ 0 & \text{if } Buffer_{\max} = 0 \end{cases} \quad (7)$$

where  $Buffer_{\max} = \max_{p \in \mathbf{P}(f)}(Buffer(p))$  and  $Buffer_{\min} = \min_{p \in \mathbf{P}(f)}(Buffer(p))$ .

As in<sup>13</sup>, the cost function  $CF_{AOC}(p)$  is scaled to define the utility of each alternative path  $p \in \mathbf{P}(f)$ . The paths for each flow are subsequently ranked based on their utilities. The alternate route rankings determined in this way are subsequently communicated back to the ATSP in the flow plan preference message.

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<sup>††</sup>  $c(p)$  is computed as follows: Each arc in the flow plan domain has an associated cost. The arc costs correspond to mean unimpeded (or non-delayed) travel times (sometimes referred to as the dwell time) for flights obtained by an analysis of historical track data simulated in FACET. By adding up the costs of arcs defining a path for a flow, we can compute the total cost of each path.

## F. Service Provider Acceptance Criteria for User Flow Plan Preferences

The ATSP can use a number of criteria to accept or reject AOC flow plan preferences, with flow equity and flow planning workload being prime candidates. In the current implementation, the ATSP algorithm for accepting or rejecting AOC preferences is limited to considering only flow planning workload factor. The flow equity consideration will be added in future research.

The service provider is modeled to accept or reject AOC flow plan preferences based on considering their impact on flow planning workload. The ATSP workload related to flow planning activities is measured using a function which estimates the complexity of a flow plan based on the number of included flows, the number of alternative paths assigned to each flow, and the number of metering locations along each path. The algorithm uses two parameters to determine acceptable flow planning workload to the ASTP:

- Parameter  $\omega$  which defines the maximum threshold on the overall flow plan complexity, and
- Parameter  $\mu$  which defines the maximum number of alternative paths per flow in the flow plan.

These two parameters are defined as input parameters for each CTFM simulation.

The algorithm for accepting or rejecting AOC flow plan preferences works as follows. First, the algorithm selects a flow plan preference (which includes both flow ranking and the ranked alternative routes) from among all preferences submitted to the ATSP. Currently, this selection is performed randomly but this mechanism may be adjusted in the future to represent equity criteria. Second, the flow which has the highest ranking in the selected AOC flow plan preference is chosen, and a ranking of all alternative paths assigned to this flow is extracted. Third, the algorithm selects the highest-ranked alternative path, and checks if this path already exists in the flow plan for this flow. If not, the algorithm tentatively adds the path to the flow plan and computes the complexity of the resulting flow plan using Eqs. (8) and (9):

$$fpcomp = \sum_{f \in \mathbf{F}} \sum_{p \in \mathbf{P}(f)} \sum_{a \in \mathbf{A}(p)} isMetered(a) \quad (8)$$

$$isMetered(a) = \begin{cases} 1 & \text{if arc } a \text{ has a metering location at its tail node} \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

where summations in Eq. (8) span all flows in the flow plan, all paths  $p \in \mathbf{P}(f)$  for each flow  $f$ , and all arcs  $a \in \mathbf{A}(p)$  along the path  $p$  which are included in the flow plan domain (arcs connecting boundary nodes to either source or sink nodes are excluded). The function  $isMetered(a)$  returns 1 if there is a metering location defined at the tail node of arc  $a$ . Metering locations are defined at sector boundaries and used for defining flow rates. Since we do not consider in this paper flow rates in flow planning collaboration, it is assumed by default that  $isMetered(a)$  returns 1 for all arcs in the network model provided that the arc is assigned to a resource (sector) located in within the flow plan domain.

If the complexity of the flow plan with tentatively added path  $p$  is less than or equal to the complexity threshold  $\omega$ , then the algorithm accepts alternative path  $p$  for flow  $f$ . Otherwise, the path is rejected and removed from the flow plan and from the AOC flow plan preference. An additional check is also performed to detect flows with all ranked alternative paths removed from the preference. If such a flow is found, it is also removed from the preference and the next-ranked flow becomes the highest-ranked flow. The algorithm then proceeds, randomly selecting next flow plan preference and repeats the process described above.

When the algorithm completes processing AOC flow planning preferences, the ATSP uses the resulting flow plan and communicates it back to AOCs as the revised flow plan. This revised flow plan also is also imposed by the service provider and all flights are allocated to it. In this paper the flow plan collaboration is performed in one cycle, while the collaboration may include multiple iterations within a time window.

## IV. Experimental Results

In this section, we first describe benefit mechanisms for AOC collaboration on flow planning and metrics employed in our simulations to quantify collaboration benefits. We then introduce simulation parameters used in the computational experiments and describe the two scenarios studied: a simple scenario with two flows and a larger scenario with multiple flows. Finally, we report and analyze results of fast-time simulations involving both scenarios.

### A. Benefit Mechanism and Metrics

One of our key research hypotheses is that significant benefits can be obtained in terms of more efficient airspace utilization and reduction of delays by increasing the solution space for flow planning and incorporating user preferences when generating flow plan solutions.

The expected general trend is that more efficient flow plan solutions can be obtained by considering a larger solution space. While it is straightforward to increase the solution space size in our simulation of the flow plan collaboration process by, for example, increasing the available alternative routes, this increase must be consistent with ATSP and AOC behavior. Hence, as described in Section III, we analyzed results from field observations, and developed models of the ATSP and AOC behavior related to flow planning consistent with these observations. Since it is difficult to validate the behavioral models against real-world data, the analysis investigates a range of behaviors and identifies relative rather than absolute benefits and tradeoffs.

In the conducted simulations, we investigated various parameters defining a range of ATSP and AOC behaviors described in Section III and their impact on the solution space and obtained benefits. We measured these benefits using the following metrics: total delay, average delay per flight, total passenger delay, average delay per passenger, and total fuel burn. In order to estimate potential flow plan collaboration benefits, we compared values for these metrics obtained in the simulations in which we varied parameters defining ATSP and AOC behaviors to our baseline case. The baseline case was defined in all simulations as the cases in which the generation of flow plan solutions is conducted solely by the ATSP without any input from the AOCs.

### B. Simulation Parameters

A discrete event CTFM simulation environment was developed that models the AOCs and the ATSP as agents that collaborate through a messaging system. The simulation is time-stepped by fixed one-minute increments. The platform leverages the capabilities of the Future ATM Concepts Evaluation Tool (FACET)<sup>18</sup> for modeling the airspace system and aircraft trajectories.

The ATSP identifies constraints at 15-minute intervals (row 1 in Table 1) based on aircraft following their unimpeded trajectory. The ATSP looks up to 180 minutes from the current time when identifying constraints (row 4 in Table 1). Based on the identified constraint, the ATSP estimates the average delays that would reduce demand below capacity and mitigate the constraint based on ATSP objectives, and then sends these average delays to AOCs at 10 minute intervals (row 2 in Table 1). Depending on an analyzed scenario (see subsection C), the ATSP identifies flights impacted by the constraint every 15 or 30 minutes (row 5 in Table 1), develops an initial flow plan, and sends this flow plan to participating AOCs. After receiving this information, the AOCs make their flow ranking and alternative route ranking decisions using the delay feedback information, and send their flow plan preferences to the ATSP 4 minutes after receiving the flow plan message (row 7 in Table 1). The ATSP is modeled to evaluate these preferences within 10 minutes from generating an initial plan (row 3 in Table 1). The ATSP route travel time savings threshold (row 6 in Table 1) was set to 10 minutes.

**Table 1: General simulation parameters.**

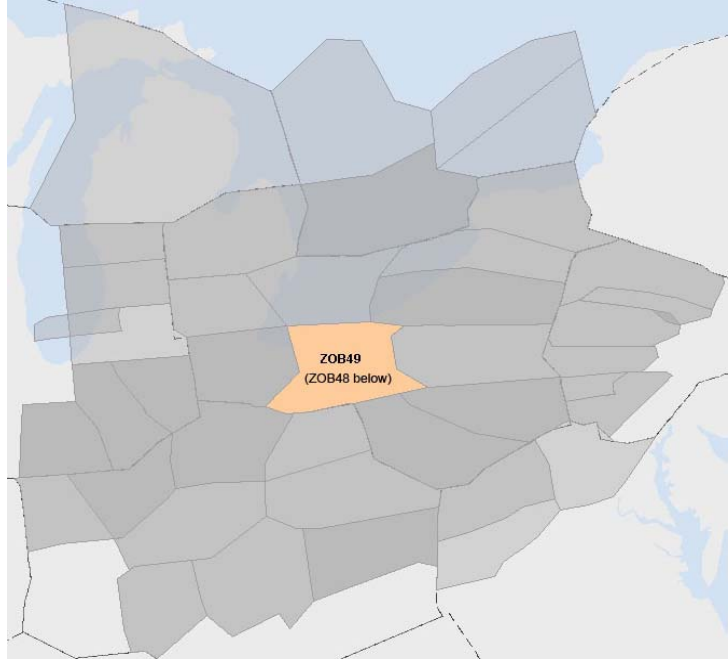
	Agent	Parameter	Value	Description
1	ATSP	Constraint identification period	15 min	The interval during which the service provider evaluates projected demand and capacity and identifies constrained sectors.
2	ATSP	Delay feedback period	10 min	The interval during which the ATSP sends delay feedback to the users.
3	ATSP	User preference evaluation delay	10 min	The interval during which the service provider waits before evaluating user preferences on flow planning.
4	ATSP	Projection time	180 min	The projected time in the future, measured from the current simulation time, that the service provider evaluates constraints.
5	ATSP	Flow planning period	15 or 30 min	The interval during which the ATSP waits before generating a revised flow plan.
6	ATSP	Route travel time savings threshold	10 min	The route travel time savings threshold (the minimum time savings for the service provider to make a route switch).
7	AOCs	Send flow plan preferences delay	4 min	The AOCs send flow ranking and alternative route ranking preferences to the ATSP at 4 min intervals.

### C. Experimental Scenarios

In the fast-time simulations we consider two scenarios involving flights traversing the ZOB Center: a simple scenario with only ten flights grouped into two flows (Scenario A), and a more complex scenario with a larger number of flows (Scenario B).

#### 1. Scenario A

Scenario A shown in Figure 3 includes ten flights arriving at LGA which are grouped into two flows: Flow 1 with five flights departing from MSP airport and entering the ZOB center from ZMP center and Flow 2 with also five flights which are departing from LAX and entering the ZOB center from ZAU center. Both flows include flights belonging to two AOCs. All flights are projected to enter the constraint spanning ZOB48 and ZOB49 sectors during the time when convective weather is forecast to impact these two sectors (21:45Z to 23:59Z). Capacities of both sectors included in the constraint are significantly reduced (set to 2 in our simulations) as a result.



**Figure 3: Flow plan domain modeled in Scenario A. The constraint is located in sectors ZOB49 and ZOB48.**

The underlying network model used in Scenario A is shown in Figure 2. The objective of experiments involving Scenario A was to test sensitivity of the parameter values and understand their impact on generated results.

The parameters used in simulations involving Scenario A are shown in Table 2.

**Table 2: Simulation parameters specific to Scenario A.**

	Agent	Parameter	Value	Description
1	ATSP	$\lambda$	1	The minimum number of flights in a flow so that the flow is included in the flow plan.
2	ATSP	$\mu$	5	The number of alternative paths which ATSP can accept per flow. This parameter, together with the flow plan complexity threshold $\omega$ , constrain the size of the solution space.
3	ATSP	$\omega$	400	The threshold on maximum flow plan complexity.
4	ATSP	$\alpha$	23	Minimum topological separation rule for ATSP alternative route generation.
5	ATSP	$\beta$	1000	Maximum additional path cost for ATSP alternative route generation.
6	ATSP	$\gamma$	3	Path separation threshold for ATSP alternative route generation.
7	ATSP	$\chi$	1	Maximum number of alternative paths for ATSP alternative route generation.
8	AOCs	$\alpha$	Varied from 2 to 25	Minimum topological separation rule for AOC alternative route generation. Studied levels: 2, 15, 20, 24, and 25.
9	AOCs	$\beta$	100	Maximum additional path cost for AOC alternative route generation.
10	AOCs	$\gamma$	1 or 3	Path separation threshold for AOC alternative route generation.
11	AOCs	$\chi$	Varied from 0 to 5	Maximum number of alternative paths for AOC alternative route generation. The value of 0 denotes the baseline case in which AOCs did not submit any flow plan preferences. Studied levels: 0 (baseline), 1, 2, 3, and 5.
12	AOCs	$\delta_1, \delta_2$	0.6, 0.4	$\delta_1$ defines fuel burn coefficient and $\delta_2$ defines the AOC impact coefficient for AOC route ranking cost function.
13	AOC	<i>fuelcost</i>	1	Cost of kg of fuel for AOC route ranking cost function.

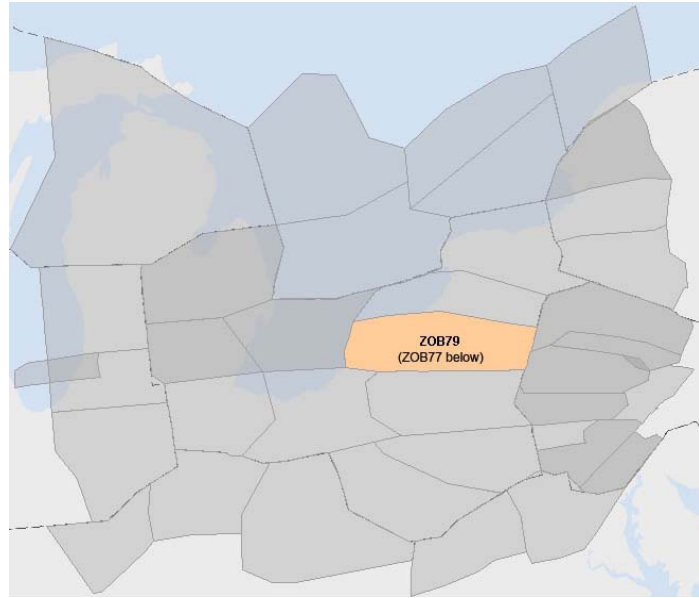
Table 2 shows that after conducting sensitivity analysis of ATSP parameters relevant to flow planning (i.e., rows 1-7 in Table 2) we fixed values for these parameters in our simulations. The assumed values are representative of ATSP behavior observed in field studies, as summarized in Section III. Table 2 also shows that we varied most relevant flow planning parameters for AOCs. In particular, we investigated the impact of three key parameters for alternative route generation algorithm, namely  $\alpha$ ,  $\gamma$ , and  $\chi$ .

Parameter  $\alpha$  was varied from 2 to 25 at five levels (row 8 in Table 2) to test the impact of generating route topologically close to (value of 2) and topologically far from (values beyond 20) the nominal path. Two levels of parameter  $\gamma$  were studied (row 10 in Table 2) and five levels of parameter  $\chi$  (row 11 in Table 2). The level 0 for parameter  $\chi$  was used to denote the baseline case in which AOCs did not generate any flow plan preferences and the flow plan solutions were produced solely by the ATSP. The values for the remaining AOC parameters shown in Table 2 were assumed fixed after determining their suitable values based on sensitivity studies.

## 2. Scenario B

The second and more complex scenario is shown in Figure 4. Scenario B involves a total of 60 flights belonging to seven AOCs (4 legacy carriers and 3 low-cost and regional carriers) which are projected to enter the constrained sectors ZOB77 and ZOB79 during the time when their capacities are severely impacted by weather. The set of 60 flights includes 10 origin-destinations pairs departing from DEN, OAK, MSP, SFO, SEA, PHX, LAX, SLC, and PDX, and arriving at one of New York area airports: LGA, JFK, or EWR. The flights were grouped into eight flows which enter the ZOB center from either the ZAU or ZID centers.

The network model used in Scenario B is similar to the one shown in Figure 2 as it was derived using the same simulated track data as for Scenario A. This time, however, a different flow plan domain is used (see Figure 4) as the constraint is modeled to occur in a different location in the ZOB center.



**Figure 4: Flow plan domain modeled in Scenario B. The constraint is located in sectors ZOB77 and ZOB79.**

The objective of experiments involving Scenario B was to analyze the relative benefits of flow plan collaboration and identify tradeoffs between increasing the size of the flow plan solution space and workload constraints. To achieve this goal, we varied key parameters defining ATSP and AOC behaviors and measured obtained benefits relative to a baseline. As before, our baseline included the cases in the AOCs did not provide any flow plan preferences, and flow plan solutions were generated only by the ATSP.

Table 3 shows the parameters and their values used in simulations involving Scenario B. After conducting sensitivity analysis of ATSP parameters (rows 1-7 in Table 2), we fixed values for all of these parameters except for  $\omega$  (row 3 in Table 2), which defines the maximum threshold on flow plan complexity acceptable to the ATSP. We studied five levels of this parameter ranging from 150 to 275. Low values of  $\omega$  (e.g., 150) model very stringent conditions on acceptable ATSP workload, resulting in very few AOC flow plan preferences accepted in the flow plan. On the other hand, high values of this parameter (e.g., 250 and above) model higher levels of workload acceptable for the ATSP and more favorable acceptance of user preferences.

Table 3 also shows that we varied key flow planning parameters modeling AOC behavior. In particular, we investigated the impact of three key parameters for alternative route generation algorithm:  $\alpha$ ,  $\gamma$ , and  $\chi$ . Parameter  $\alpha$  was varied from 2 to 20 at four levels (row 8 in Table 3) to test the impact of generating routes topologically close to (value of 2) and topologically far from (value of 20) the nominal path. Two levels of parameter  $\gamma$  were studied (row 10 in Table 3), and five levels of parameter  $\chi$  (row 11 in Table 3). The level 0 for parameter  $\chi$  was used to denote the baseline case. The values for the remaining AOC parameters shown in Table 3 were assumed fixed after determining their suitable values based on sensitivity studies.

**Table 3: Simulation parameters specific to Scenario B.**

	Agent	Parameter	Value	Description
1	ATSP	$\lambda$	1	The minimum number of flights in a flow so that the flow is included in the flow plan.
2	ATSP	$\mu$	5	The number of alternative paths which ATSP can accept per flow. This parameter, together with the flow plan complexity threshold $\omega$ , constrain the size of the solution space.
3	ATSP	$\omega$	Varied from 150 to 275	The threshold on maximum flow plan complexity. Studied levels include: 150, 200, 225, 250, and 275.
4	ATSP	$\alpha$	21	Minimum topological separation rule for ATSP alternative route generation.
5	ATSP	$\beta$	50	Maximum additional path cost for ATSP alternative route generation.
6	ATSP	$\gamma$	3	Path separation threshold for ATSP alternative route generation.
7	ATSP	$\chi$	1	Maximum number of alternative paths for ATSP alternative route generation.
8	AOCs	$\alpha$	Varied from 2 to 20	Minimum topological separation rule for AOC alternative route generation. Studies levels include 2, 10, 15, and 20.
9	AOCs	$\beta$	10 or 20	Maximum additional path cost for AOC alternative route generation. The value of 10 was used for low cost and regional carriers and the value of 20 for legacy carriers.
10	AOCs	$\gamma$	Varied from 1 to 3	Path separation threshold for AOC alternative route generation.
11	AOCs	$\chi$	Varied from 0 to 4	Maximum number of alternative paths for AOC alternative route generation. The value of 0 denotes the baseline case in which AOCs did not submit any flow plan preferences. Studied levels: 0 (baseline), 1, 2, 3, and 4.
12	AOCs	$\delta_1, \delta_2$	(0.4, 0.6) or (0.7, 0.3)	$\delta_1$ defines fuel burn coefficient and $\delta_2$ defines the AOC impact coefficient for AOC route ranking cost function. Value pair (0.4, 0.6) was used for legacy carriers and value pair (0.7, 0.3) was used for low cost and regional carriers.
13	AOC	<i>fuelcost</i>	1	Cost of kg of fuel for AOC route ranking cost function.

In addition to parameters modeling ATSP and AOCs behaviors, we also varied the capacities of sectors in the simulation to model the impact of a constraint’s severity. In particular, we studied two levels for sector capacity factor: 20 and 30. These capacities were used for all sectors in the simulation, except for sectors included in the constraint. The capacities of sectors ZOB77 and ZOB79 included in the constraint were kept fixed and equal to 4.

#### D. Scenario A Results

As described earlier, the purpose of simulations involving Scenario A was to observe AOC and ATSP behaviors during collaborative flow planning and alternative route determination. The simulations tested various levels of the most significant parameters defining those behaviors as well as their impact on measured benefits.

Figure 5 shows the impact of the number of AOC reroutes (parameter  $\chi$ ) on total delays (in minutes) measured in the simulations. The horizontal axis shows 5 levels of this parameter with value of 0 denoting the baseline case in which AOC flow plan preferences are not provided. The baseline case, however, includes one alternative route per flow which is generated by the TMU.

Figure 5 shows the benefits of reduced total delays by incorporating user preferences in the flow planning process. When just a single AOC-proposed alternative route per flow is considered, immediate benefits are observed and delays are reduced by more than 30% relative to the baseline. Figure 5 also shows that no additional benefits were observed when AOCs generated a larger number of reroutes. As we show in subsection E, this is not a general trend but a result of a very simple scenario analyzed.

The second investigated parameter which is important for modeling the AOC behavior is the minimum topological distance from the nominal path. Figure 6 shows the impact of varying the values of  $\alpha$  from 2 to 25.

Small values of  $\alpha$  correspond to alternative paths which are located (topologically) close to the nominal path. Large values of this parameter produce paths located far away from the nominal path. In all experiments shown in Figure 6, except for baseline case,  $\chi$  was equal to 3 (AOCs generated 3 alternative routes per flow).

Paths located close to the nominal path should have shorter travel times than paths located far away and hence we should observe higher benefits in terms of delay reduction when  $\alpha$  assumes small values. This hypothesis is confirmed by simulation results presented in Figure 6, which shows that the highest benefits (reduced delays) are obtained when  $\alpha$  is between 2 and 15. Values of  $\alpha$  above 15 result in decreasing benefits, and values above 24 result in delays that are longer than the baseline (shown as a gray dashed line). This is because the paths are located too far from the nominal path and hence require longer travel times.

The fact that  $\alpha$  values of 2–15 generate the same benefits is a result of using a particular instance of the network model used in the scenario. The set of shortest paths generated by APGA contains paths whose topological distance from the nominal path is close to or equal to 15. Since the parameter  $\alpha$  defines the minimum required topological distance, in both cases the same set of shortest paths is obtained and hence identical benefits are produced.

The next section describes our findings from fast-time simulations with the more complex Scenario B.

### E. Scenario B Results

We used this scenario to conduct analyses of flow plan collaboration benefits relative to the baseline. We also investigated the tradeoffs between the size of the space of flow plan solutions and ATSP workload in implementing these flow plans. As before, we also varied key parameters defining the ATSP and AOCs behaviors.

Figure 7 shows the relationship between the number of alternative routes generated by AOCs and included in their flow plan preferences and the total delays measured in the simulations. A larger number of generated alternative routes provides more options to the AOCs and increases the size of the solution space. As Figure 7 shows this increase offers significant benefits of reducing the total delays when compared to the baseline case, which is denoted by value 0. The trend shown in Figure 7 is more complex than the one reported earlier for Scenario A (see Figure 5). This is expected as Scenario B is more complex than Scenario A and a more complex flow plan solution is necessary to resolve the demand-capacity imbalance.

Figure 7 demonstrates that increasing the number of reroutes generated by AOCs beyond 1 provides additional benefits of reduced delays. However, the obtained results show that this trend saturates at  $\chi=4$  and no additional benefits are identified beyond this point. This illustrates the tradeoff between more flexible flow plan solutions generated by the AOCs and the workload constraints imposed by the ATSP. The results presented in Figure 7 were

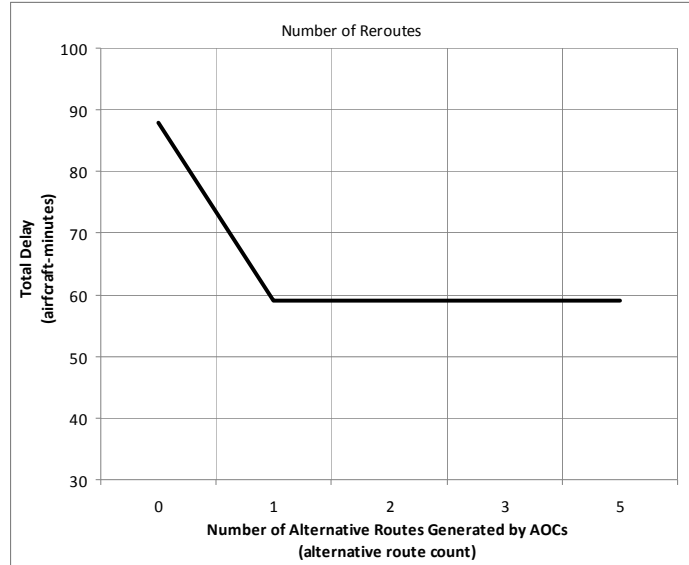


Figure 5: Impact of the number of AOC reroutes on total delays in Scenario A.

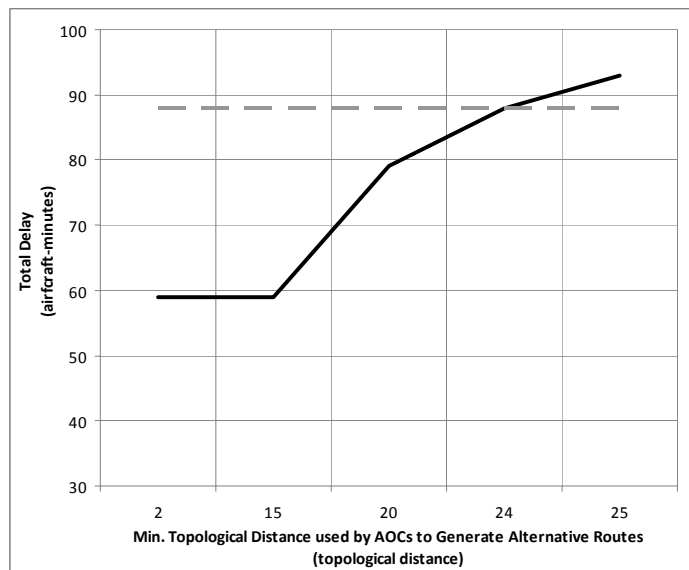
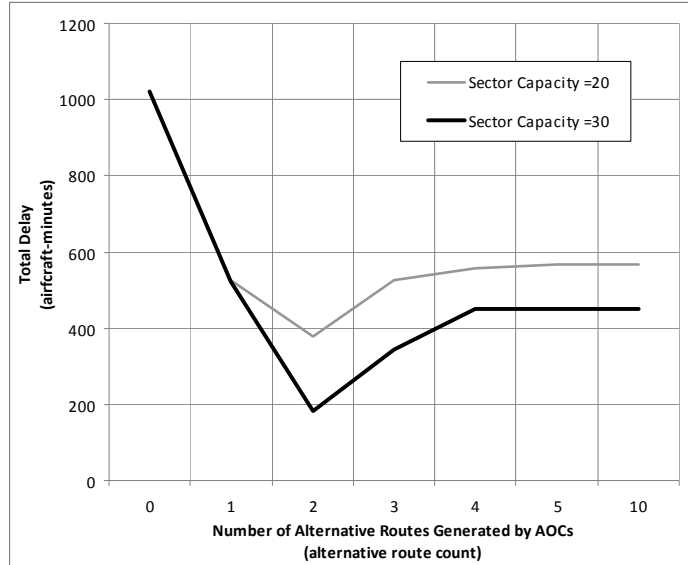


Figure 6: Impact of the AOC topological distance on total delays in Scenario A.

generated assuming the maximum allowed flow plan complexity threshold  $\omega=200$ . Figure 7 also shows that in this scenario the largest benefits are obtained when the AOCs generate 2 reroutes for each flow.

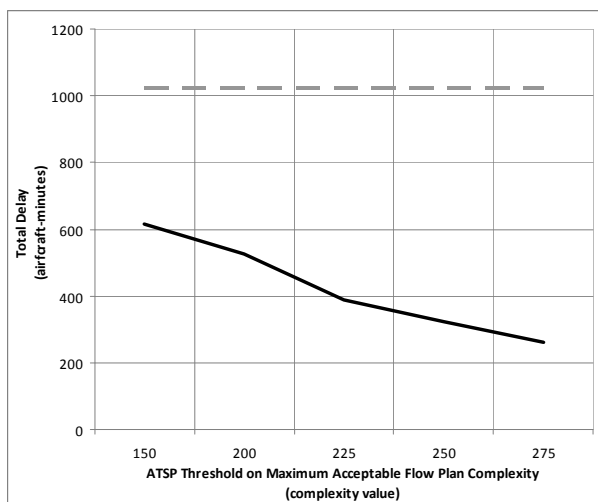
The capacities of sectors included in the constraint were kept fixed in the simulations whose results are included in Figure 7. We, however, varied the capacities of other sectors in the simulation to analyze the impact of the severity of the demand-capacity imbalance on obtained benefits. Figure 7 shows that the severity of the imbalance has indeed some impact on the obtained benefits but the overall trend is similar. It shows that larger delays (hence, smaller benefits) were obtained when sector capacities were set to 20 as opposed to 30. This is because there is less capacity available on the alternative routes and hence they are less useful as alternative solutions to relieve the main constraint.



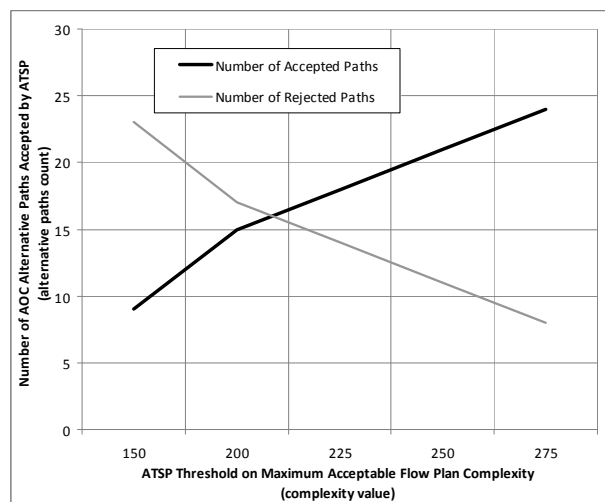
**Figure 7: Impact of the AOC number of reroutes on total delays in Scenario B.**

In order to understand the tradeoffs between the size of the solution space and workload constraints, we varied the value of  $\omega$  which defines the maximum acceptable flow plan complexity for the ATSP. Figure 8 presents results of these studies. It shows that  $\omega$  has significant impact on achievable benefits of collaborative flow planning. If the ATSP imposes very stringent workload constraints as modeled by  $\omega=150$  then the benefits can be significantly reduced even though the delays are still smaller than for the baseline case (depicted by the gray dashed line). When the ATSP is willing to consider more complex flow plan solutions, as modeled by values of  $\omega$  greater than 250, then the delays can be reduced by more than half when compared to  $\omega=150$ .

This can be further explained by analyzing the number of reroute alternatives which are accepted by the ATSP as a function of the flow plan complexity threshold. Figure 9 illustrates this relationship. It shows the number of accepted and rejected paths for each of the simulations whose results were included in Figure 8. Figure 9 shows that with the increasing the value of  $\omega$ , the ATSP is accepting more alternative paths than rejecting them. Thus, as Figure 9 shows, the benefits from flow plan collaboration are obtained as product of increased flexibility of rerouting options available in more complex flow plan solutions and relaxed workload constraints imposed by the ATSP.



**Figure 8: Impact of the ATSP workload constraints on total delays in Scenario B.**



**Figure 9: Relationship between the ATSP maximum flow plan complexity threshold and the number of accepted and rejected AOC preferences.**

## V. Conclusions

This paper presented results of preliminary analysis of the benefits expected from collaboration between the users and service providers on one aspect of flow planning, namely the provision of alternative route options to mitigate a local constraint. We introduced a collaboration scheme and described models supporting a fast-time simulation of this collaboration. The simulation was used to demonstrate and quantify how flow planning collaboration can improve the utilization of airspace resources through the negotiation of alternative routes. We showed using simple scenarios that increasing the solution space by allowing more route options provided by users offers significant benefits relative to the baseline in which no user preferences are considered. We also identified tradeoffs between increased flexibility through additional routing options available in more complex flow plan solutions and the increased service provider workload due to the flow plan complexity.

This research will be extended to other aspects of collaborative flow planning, including collaboration on flows and flow rates. We will also continue refining our models of the behavior for users and the service provider used in the fast-time simulation. Finally, we will strive to provide more rigorous validation of our models and collaboration schemes beyond currently employed methods based on field observations.

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## VII. References

- <sup>1</sup>Wojcik, L. A. "Three principles of decision-making interactions in traffic flow management operations," *4th USA/Europe Air Traffic Management R&D Seminar, December 3-7, 2001*. Santa Fe, NM, 2001.
- <sup>2</sup>Wambsganss, M. "Collaborative decision making through dynamic information transfer," *Air Traffic Control Quarterly* Vol. 4, No. 2, 1997, pp. 107–123.
- <sup>3</sup>Vossen, T., Ball, M. O., Hoffman, R. L., and Wambsganss, M. "A general approach to equity in traffic flow management and its application to mitigating exemption bias in ground delay programs," *Air Traffic Control Quarterly* Vol. 11, 2003, pp. 277-292.
- <sup>4</sup>Idris, H. R., Evans, A. D., Vivona, R. A., Krozel, J. A., and Bilimoria, K. D. "Field observations of interactions between traffic flow management and airline operations," *AIAA 6th Aviation Technology, Integration and Operations (ATIO) Conference, September 25-27, 2006*. American Institute of Aeronautics and Astronautics, Wichita, KS, 2006, pp. AIAA 2006-7721.
- <sup>5</sup>Green, S. M., Bilimoria, K. D., and Ballin, M. G. "Distributed air-ground traffic management for en route flight operations," *Air Traffic Control Quarterly* Vol. 9, No. 4, 2001, pp. 259-285.
- <sup>6</sup>Klopfenstein, M., Wilmouth, G. E., Smith, P. J., Spencer, A., Mintzer, M. J., and Sud, V. "Congestion management via user submitted multiple routing options and interactive flight lists," *AIAA 5th Aviation, Technology, Integration, and Operations Conference (ATIO), September 26-28, 2005*. American Institute of Aeronautics and Astronautics, Arlington, VA, 2005, pp. AIAA 2005-7436.
- <sup>7</sup>Sheth, K. S., and Gutierrez-Nolasco, S. "Incorporating user preferences in collaborative traffic flow management," *AIAA Guidance, Navigation and Control Conference and Exhibit, August 18-21, 2008*. AIAA Press, Honolulu, Hawaii, 2008, pp. AIAA 2008-7398.
- <sup>8</sup>Sheth, K. S., and Gutierrez-Nolasco, S. "Enhancing collaboration in air traffic flow management," *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), September 21-23, 2009*. American Institute of Aeronautics and Astronautics, Hilton Head, SC, 2009, pp. AIAA 2009-7128.
- <sup>9</sup>Sheth, K. S., Gutierrez-Nolasco, S., Courtney, J. W., and Smith, P. A. "Simulations of credits concept with user input for collaborative air traffic management," *AIAA Guidance, Navigation, and Control Conference, August 2-5, 2010*. American Institute of Aeronautics and Astronautics, Toronto, Canada, 2010, pp. AIAA 2010-8079.
- <sup>10</sup>Idris, H. R., Vivona, R. A., Penny, S., Krozel, J. A., and Bilimoria, K. D. "Operational concept for collaborative traffic flow management based on field observations," *5th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, September 26-28, 2005*. American Institute of Aeronautics and Astronautics, Arlington, VA, 2005, pp. AIAA 2005-7434.
- <sup>11</sup>Garcia-Chico, J. L., Idris, H. R., Krozel, J. A., and Sheth, K. S. "Task analysis for feasibility assessment of a collaborative traffic flow management concept," *AIAA 6th Aviation Technology, Integration, and Operations Conference*. American Institute of Aeronautics and Astronautics, Anchorage, AL, 2008, pp. AIAA-2008-8909.
- <sup>12</sup>Henderson, J., Idris, H. R., Kicing, R., and Krozel, J. A. "Analysis of increasing user flow management responsibility using shared delay information," *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), September 21-23, 2009*. American Institute of Aeronautics and Astronautics, Hilton Head, SC, 2009, pp. AIAA 2009-7126.

- <sup>13</sup>Henderson, J., Idris, H. R., Kicing, R., Krozel, J. A., Wang, D., and Sheth, K. S. "Airline and service provider collaborative algorithms for flight route and delay decisions," *AIAA Guidance, Navigation, and Control Conference, August 10-13, 2009*. American Institute of Aeronautics and Astronautics, Chicago, IL, 2009, pp. AIAA 2009-6255.
- <sup>14</sup>Idris, H. R., Garcia-Chico, J. L., Krozel, J. A., Arora, N., and Doble, N. A. "Subtopic 16: Feasibility and benefit assessments of a concept of operations for collaborative traffic flow management ". L-3 Communications and Metron Aviation, Inc., Billerica, MA; Herndon, VA, 2007.
- <sup>15</sup>Henderson, J., Idris, H. R., Fergusson, S., Krozel, J. A., and Kicing, R. "User and service provider collaboration on flight route and delay under uncertainty," *AIAA Guidance, Navigation and Control (GNC) Conference, August 2-5, 2010*. American Institute of Aeronautics and Astronautics, Toronto, Canada, 2010, pp. AIAA-2010-8080.
- <sup>16</sup>Wolfe, S. R., Jarvis, P. A., Enomoto, F. Y., Sierhuis, M., and van Putten, B.-J. "A multiagent simulation of collaborative air traffic flow management," *Multi-Agent systems for traffic and transportation engineering*. IGI Global, Hershey, PA, 2009.
- <sup>17</sup>Sridhar, B., Soni, T., Sheth, K. S., and Chatterji, G. B. "An aggregate flow model for air traffic management," *AIAA Guidance, Navigation, and Control Conference and Exhibit, August 16-19, 2004*. American Institute of Aeronautics and Astronautics, Providence, Rhode Island, 2004, pp. AIAA 2004-5316.
- <sup>18</sup>Bilimoria, K. D., Sridhar, B., Chatterji, G. B., Sheth, K. S., and Grabbe, S. R. "FACET: Future ATM concepts evaluation tool," *3rd USA/Europe Air Traffic Management R&D Seminar, June 13-16, 2000*. Napoli, Italy, 2000.
- <sup>19</sup>Menon, P. K., Sweriduk, G. D., and Bilimoria, K. D. "New approach for modeling, analysis, and control of air traffic flow," *Journal of Guidance, Control, and Dynamics* Vol. 27, No. 5, 2004, pp. 737-744.
- <sup>20</sup>Sweet, D. N., Manikonda, V., Aronson, J. S., Roth, K., and Blake, M. "Fast-time simulation system for analysis of advanced air transportation concepts," *AIAA Modeling and Simulation Technologies Conference and Exhibit, August 5-8, 2002*. Monterey, CA, 2002, pp. AIAA 2002-4593.
- <sup>21</sup>Sun, D., and Bayen, A. M. "Multicommodity Eulerian-Lagrangian large-capacity cell transmission model for en route traffic," *Journal of Guidance, Control, and Dynamics* Vol. 31, No. 3, 2008, pp. 616-628.
- <sup>22</sup>Fujita, Y., Nakamura, Y., and Shiller, Z. "Dual Dijkstra search for paths with different topologies," *IEEE International Conference on Robotics & Automation, September 14-19, 2003*. IEEE Press, Taipei, Taiwan, 2003, pp. 3359-2264.