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Enhancing Collaboration in Air Traffic Flow Management

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This paper extends the concept of credit points to enhance collaboration between participants in air traffic flow management. In earlier research, a preferred route selection method was presented, where users expend credit points to prioritize the flight paths for each of their pre-departure flights. This method of prioritizing flights provides a mechanism to incorporate users' preferences in air traffic management subject to airspace congestion and weather impact constraints. In the current research, the airport arrival and departure rates at the top 70 airports are incorporated. In order to analyze the equity of arrival and departure schedules, the flight distributions at those airports were constructed for the 40 largest flight operators in the United States. The credit-points concept gives airborne flights the highest priority, enabling them to better maintain their schedule. A negotiation mechanism for participants to reassess their decisions for improved operations is described. Results for violations of arrival/departure rates and airspace constraints (due to volume and weather) before and after implementing the concept, along with credit use and incurred delays are presented. Results indicate that the credit-points concept is feasible for users to incorporate their preferences of important flights. The overall delay compared to a schedule based system reduces while maintaining airspace and airport capacities. Also, the equity increases for participating users as more constraints are added due to better utilization of available airspace.

I. Introduction

AIR traffic delays are significantly affecting the performance of airlines in the United States.[1] Commercial users are sustaining increased delays, which translate to higher costs and passenger dissatisfaction. To reduce delays, enhancement is desired in the interaction between the FAA and the airspace users.[2] The airlines estimate their flight schedules in advance, but the FAA usually lacks information about their intent for efficient air traffic management. On the other hand, the users do not always have required knowledge of the constraints in the system. This prevents them from efficiently planning their flights, which have varying priorities depending on the origin-destination pair, the time of day, the route under consideration, etc. User flight planning and implementation is difficult due to the lack of a mechanism for filing route options and specifying preferences for their flights.[3]

Most traffic flow management research[4] does not incorporate users' preferences because they are not publicly known. However, there is research characterizing user's participation in the departure schedule decision-making process. Ref. 5 addresses market-based mechanisms between the FAA and competing airlines. Departure schedules with input from users are discussed in Ref. 6. A novel approach for using flight priorities to manage airspace congestion is presented in Ref. 7. The issue of algorithmic ranking of flights by users' preferences is dealt with in Ref. 8. A concept of credit points for prioritization of individual flights and optional routes is described in Ref. 9. That research did not incorporate schedule changes to flights that were airborne. It also did not account for airport arrival and departure rate constraints.

This paper expands the work reported in Ref. 9. Post-departure flights, as well as airport arrival and departure rate constraints, are incorporated. In addition, a mechanism that allows users to negotiate individual flight routes or credits is developed. The negotiation process is iterative in nature and allows users to adjust their preferences. These enhancements are tested in a simulation environment with real air traffic data. Sector congestion, arrival and

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departure rate conformance, equity, and delays are used to measure performance. This work also helps assess the feasibility and preliminary benefits of an earlier proposed concept of operations for collaboration.[10]

The concept of credit points is presented in Section II. It also addresses how credits are earned and expended by users and the overall process of flight credit and route assignment. The paper then describes a realistic simulation platform available for studying the flight paths of aircraft along available routes in Section III. Section IV describes the experiment design and performance metrics for this study. Results of the credit and route allocation process for a realistic scenario along with the effect of the negotiation process are shown in Section V. Conclusions based on present work are presented at the end in Section VI.

II. Credit Points and Route Assignment Process

In earlier research (Ref. 9), the assignment of credits was described. This process is briefly described here. The concept of credit points (analogous to artificial currency) is used during the flight credits and route assignment process. The purpose is to incorporate users' preferences of flight priorities, multiple route options and intent during the pre-departure route filing process. At the beginning of each day, the users are provided a fixed number of credits based on the size of their operations. The total number of credits for each user is five times their number of flights in a day. The credits expire at the end of each day. The number of credits provided, as well as expiration of credits, could be varied to study other operational and economic implications of this concept. For the proposed concept, it is expected that the users will typically expend between zero to ten credits for each flight based on its importance. The user credit assignment for this research is described in Section IV. In reality, the users would provide these by evaluating their individual cost functions. Even though there are ten maximum credit points assigned by any user in this research, it is not a requirement. For each flight, the user could potentially assign a different amount of credits for several route options. Whichever route the user is given, the corresponding number of credits is decremented from the user's total credits. For example, if a user with only two flights files one flight with eight credits, the second will have a maximum of two credits to file. Alternatively, if a user does not get the first choice route, the difference in the number of credits (if any) between the assigned route and the first choice route are available to the user to use with other flight routes.

This process impresses upon the user to be careful about assigning credits to routes that are based on their genuine need. This process of credit-based route reallocation is automated by the service provider. Thus, users should not be concerned about other users getting undue advantage, as the credit assignments are not made public. The credits scheme improves performance of the system (because each flight's exact assigned route is known) and incorporates users' preferences (because the scheme extracts flight criticality information from the users). The operations are predictable since post-departure flights are given highest priority and are allowed to fly the given route to minimize effect of uncertainties encountered during the en route phase.

Figure 2 provides a schematic of the main loop of the flight credits and route assignment process. In the beginning, flights belonging to multiple users are scheduled, assigned credit points (described in section IV.A) and flown along their first choice route in the simulation platform (described in Section III). Users can provide as many alternate routes as desired but in simulation it was limited to three. The congestion and convective weather impact information is evaluated every minute. All sectors are evaluated for congestion, i.e., number of aircraft higher than the monitor alert parameter or MAP, as defined by the FAA. If weather is present in a sector, the capacity of that sector is reduced. There is other ongoing research to determine the reduction in capacity due to convective weather.[11,12] In this research the capacity is reduced to 70% of MAP. Thus, if a sector capacity is reduced, the flights are reallocated on predefined alternate routes. It should be noted that only the number of flights that are in excess of available capacity are considered for route reassignment. The excess flights are those flights with lowest credit points from a credit-based ranking of flights passing through that sector at that time. If two flights have a tie then the flight that filed first is given preference.

This process differs from the current operations wherein the flights are given slots on a first come first served basis and user preference is not explicitly accounted for. Instead, this method gives a preference to higher credit flights. Once the excess flights have been reallocated to alternate routes (from a predefined list of three generated for this research or provided by the users), another run is executed to compute sector demand-capacity imbalance and the next iteration is performed. This process continues until convergence is achieved. Convergence is reached when all flights are assigned routes for reaching their destination such that no constraint is violated. However, the flights could be delayed significantly. Thus, convergence is guaranteed with unbounded delays. At the end, metrics are computed and recorded.

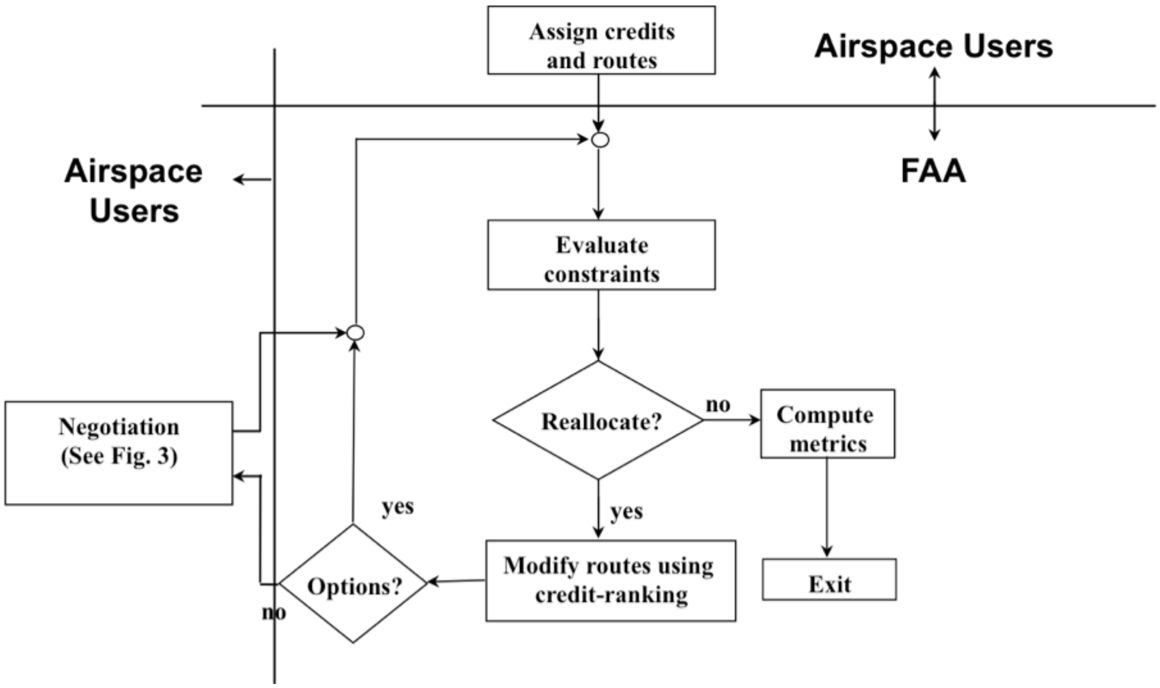

Figure 2. Main loop of flight credit and route assignment process.

In Fig. 2, the ‘Negotiation’ box on the left was missing in earlier research. In current research, a negotiation process (schematic shown in Fig. 3) is implemented. When it is time to reallocate flights, the user is allowed to utilize alternate routes through negotiation. The information flows from the ‘Negotiation’ box in Fig. 2 to the ‘From main loop’ connector at the top of Fig. 3. When negotiation process is completed, information flows back from the ‘To main loop’ connector at the bottom of Fig. 3 to the ‘Negotiation’ box in Fig. 2.

The negotiation process is described next. The flights that got their first choice route (say, R1) fall out immediately from the left most path in Fig. 3, and no negotiation is required. In the next step, the user (say, U1) with the flight (say, F1) that did not get the desired route can swap routes with another user’s (U2) flight (F2) with R1. If U2 agrees to a swap for R1, then three things happen. First, the flight F2 gets added to the list of flights for negotiation. Then F1 flies F2’s slot along R1, and lastly, U1’s credits are decremented by those assigned by U2 for F2. Thus, if a swap was agreed, F1 comes out of negotiation through the second from left (Swap route) path in Fig. 3. If a flight swap with another user is not permissible, F1 flies next optional route (R2 or R3 as available). Otherwise, the assigned credits for the next iteration may be modified. If U1 wishes to fly an available alternate route then F1 falls out of negotiation through the third from left path. If not, after U1 has made the choice on modification of credits for F1 for the next iteration, F1 is assigned a 15-minute delay and falls out of negotiation. The next flight in the list is then considered for negotiation.

Iterations are performed for flights in a 15-minute block. As described above, negotiation occurs for each of those flights. In this analysis, the user decisions are made using importance based on flight distance and the flip of a coin (when two flights have similar parameters, e.g., same flight length). In the end when all relevant flights have negotiated for routes and credits, the constraints are evaluated again. ‘To main loop’ labeled connector at the bottom of Fig. 3 links to ‘From negotiation’ labeled connector at top left of Fig. 2. It should be noted that for this analysis, the airport departure and arrival rate constraints are incorporated only at the top 70 airports in the United States (presented in Section V).

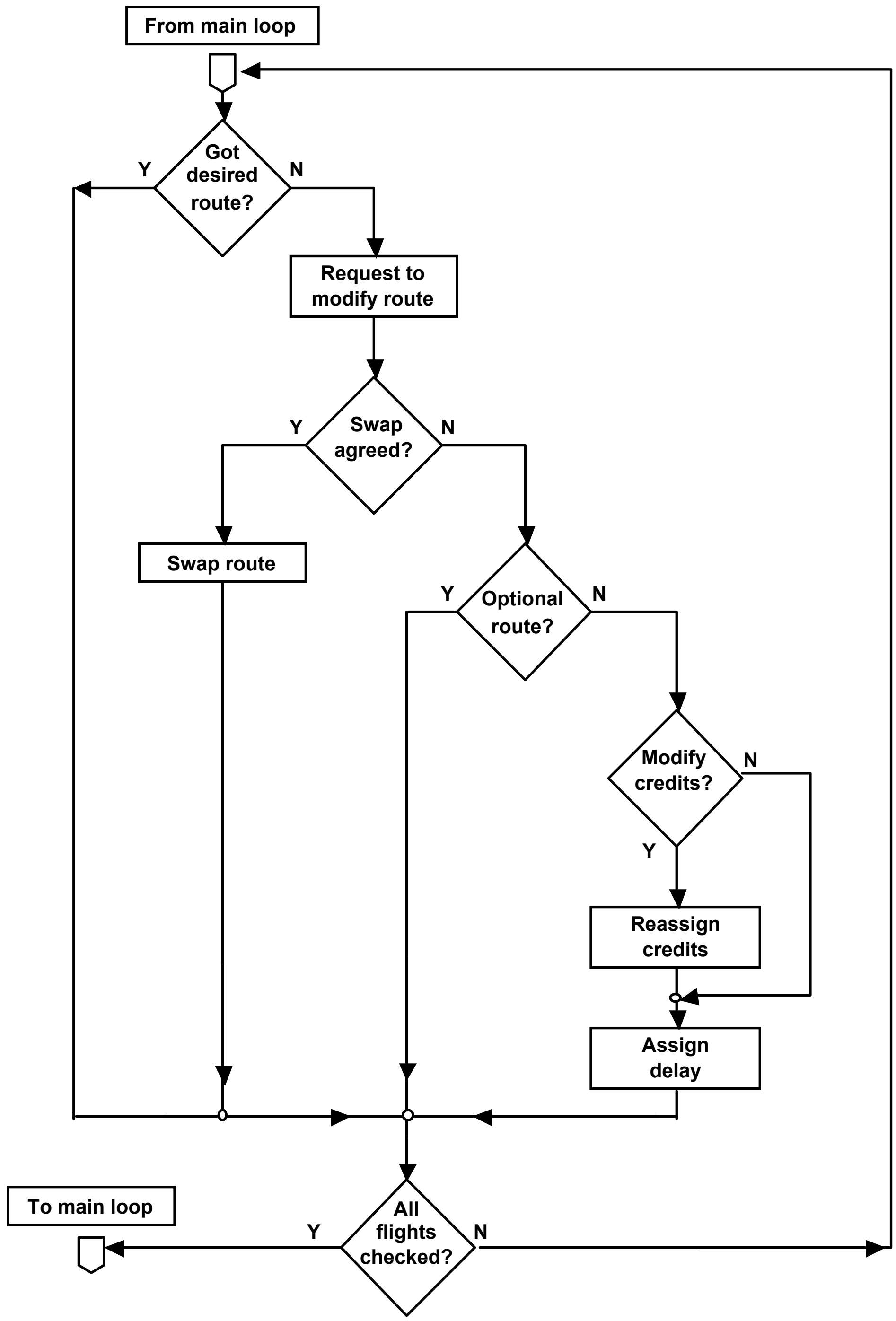

Figure 3. Negotiation process.

III. Simulation Platform and Data Sources

To assess the use of optional routes with credit points, the Future ATM Concepts Evaluation Tool (FACET)[13] developed at NASA Ames Research Center was used. FACET is a modeling and analysis system developed to explore advanced ATM concepts. It handles traffic information at various spatial levels in the National Airspace System, from the Air Route Traffic Control Center (ARTCC or Center), the sub-regions called Sectors, to individual aircraft trajectories. FACET can be used as a playback, simulation or real-time data analysis system. The simulation mode allows the user to take traffic initial conditions from a certain time. It evolves the air traffic based on available intent, consisting of flight plans that provide origin, destination, route of flight, aircraft type, cruise speed, cruise altitude and take-off time.

FACET utilizes the FAA's Enhanced Traffic Management System[14] (ETMS) provided air traffic data. Figure 1 shows a snapshot of FACET with several aircraft (blue triangles) flying along flight plans (blue) between various airports. The Center boundaries are shown in gray and state boundaries in red. The National Weather Service published Next Generation of Radar (NEXRAD) convective weather data is displayed as yellow, orange, brown and red filled polygons. These correspond to increasing levels of convective weather, respectively. Using the simulation capabilities of FACET, aircraft were flown along assigned routes. Each minute, the sector congestion and severe weather impact (as described earlier) was recorded.

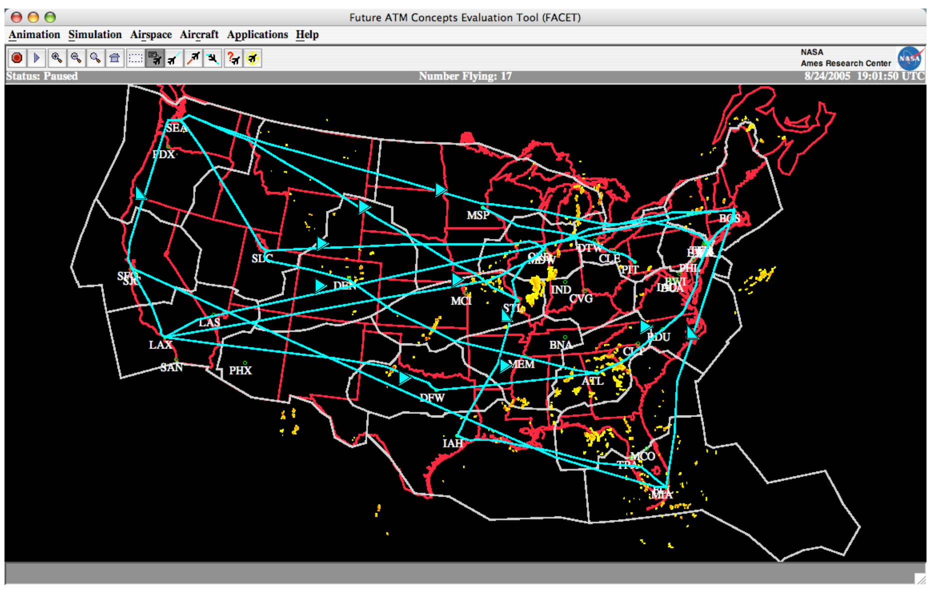

Figure 1. Display of a few flight routes between several origin-destination pairs in FACET. The triangles show aircraft and blue lines show their flight plans. NEXRAD weather filled polygons are shown as yellow, orange and red filled polygons.

IV. Experiment Design

This section describes the scenario cases studied, the route options for users and the metrics computed for performance comparison of various experiment runs.

A. Scenario Description

To understand how the credit-points concept functions with real data, actual air traffic and convective weather data were used from the same day. ETMS data are used to demonstrate the ability of this credit-points concept to handle real traffic schedules. The experiment starts with August 24, 2005 data between the hours of 3:00 pm through 7:00 pm Eastern Daylight Time (EDT). Only air traffic data above 18,000 ft was considered. A list of the top 70 airports and three alternate routes were created for each of the 4830 origin destination (70*69) pairs. Note that the flight routes from origin airport to destination airport are usually not the same as the reverse routes due to winds.

Based on daily operations, the top 40 users are considered participants in this credits scheme. To help understand the nature of operations at various airports in the country, user flight counts at two airports are presented in Fig. 4. The data demonstrates the challenge posed to the FAA in current day operations. It also presents a case for how the credit-points scheme needs to address airport arrival and departure rates with vastly different airport operations. On the left are the flight counts of the top 40 operators at Boston Logan International Airport (BOS), and on the right are the same 40 operators (not in the same order) at New Jersey's Newark Liberty International Airport (EWR). The purpose is to show the diversity of the operations at various airports in the country. Notice the difference in y-axis values. In EWR, a few users take up most of the operations (hub-like behavior). Whereas in BOS, the flights are well distributed among various users.

All flights are simulated based on their scheduled departure times, obtained from the ETMS data. They were flown in FACET with each of the top 40 users getting three route-options for the top 70 airports. This experiment was conducted with no humans in the loop and the simulator assigned credits for all flights. Credits are assigned for all flights for all users between all airport pairs before departure. The credits for the top 40 users were assigned by computing their flight origin-destination distance. Flights that travel distances greater than 2,000 nmi were assigned ten credits. For each 250 nmi reduced travel distance, the credits were reduced by one. This resulted in three credits for flights less than 500 nmi. The credit points are assigned based on distance, because it is presumed that longer distance flights are more important for users. In future research, other factors (e.g., fuel burn, difference in time of arrival, etc.)[15] will be included. All flights for other (not in top-40) users are simulated along their nominal flight plans with five credits.

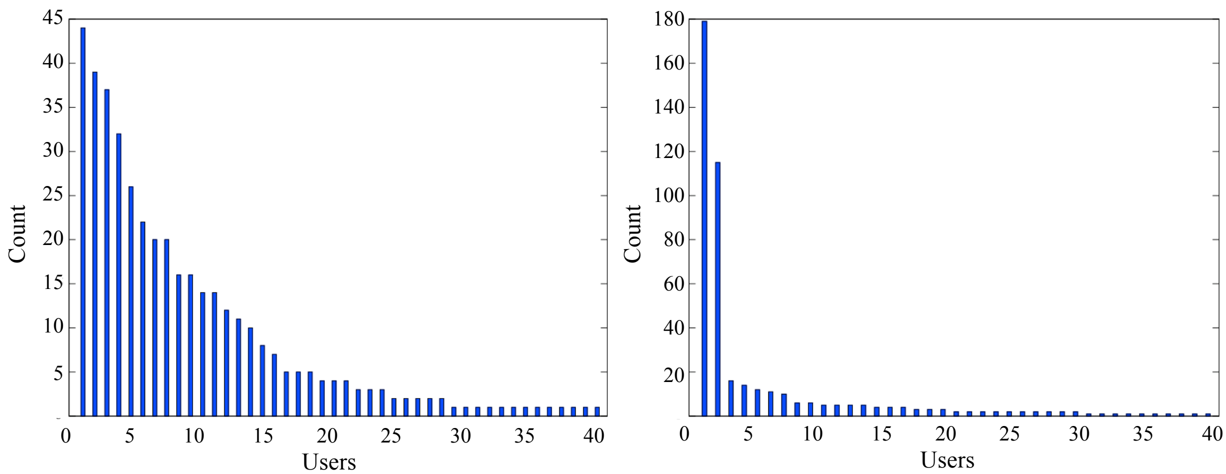

Figure 4. Number of flights for top-40 users at Boston Logan International Airport (left) and at Newark Liberty International Airport (right).

B. Performance Metrics

The performance metrics used for this research are the amount of delay incurred and the equity of solution. It is beneficial to compare strategies from a user's perspective in terms of the ground delay specified to each flight on the granted routes compared to the first choice route. Thus, total delay is the additional time taken to fly on the assigned route along with a sum of the fifteen-minute blocks of delay assigned. The number of credits expended by each user provides a metric for the users to assess their prioritization for the period of the scenario. The delays for the entire system are calculated to analyze the performance with the use of credits. Future research will explore whether this method can help define optimal solutions for the user and the FAA using the credit-points concept.

To measure the equity of solutions, the Gini coefficient[16] is computed. This is a commonly accepted metric of inequity in a population. It is defined as,

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \left| x_i - x_j \right|}{2n^2\mu} \tag{1}$$

where n is the number of delay samples, x, and μ is the mean value of distribution. A Gini value of one means perfect inequality. For comparing various experiments, the Gini value for average delay, maximum delay and credits used were computed. For example, a Gini value of zero for average delay metric means that all users received equal delays. These are presented in the next section. The comparison results for sector congestion and airport arrival and departure rate violations, with and without implementing the credits scheme are presented as well.

V. Results

In order to address the feasibility of the proposed credit-point scheme, the airspace and airport constraints were evaluated. For the purpose of this study, feasibility was defined as meeting all of these constraints and not increasing or inequitably distributing delays.

A. Airspace and Airport Constraints

After implementation of the credits scheme with reassignment of flights along alternate routes, there was no congestion observed. The number of sectors is shown in Fig. 5, with the red and blue lines showing sector congestion before and after, respectively. Figure 6 shows the airport arrival and departure rate constraint violations in 15-minute intervals. Again, the red and blue lines show the rate violation before and after, respectively. In Fig. 6 left, the blue lines show non-zero values until 5:00 pm EDT due to flights that departed before planning started at 3:00 pm EDT.

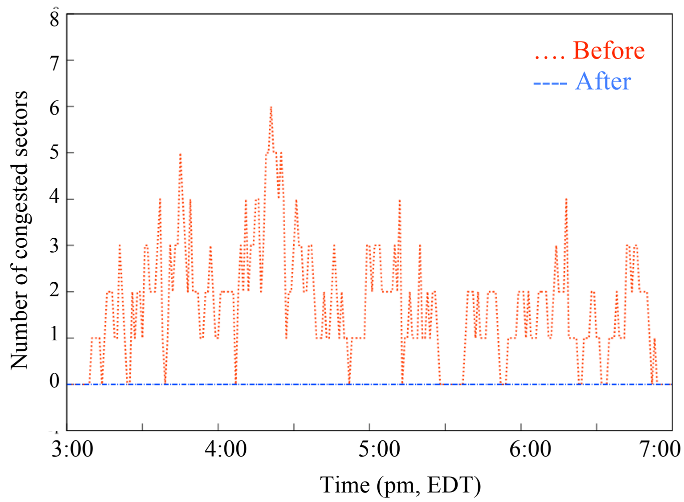

Figure 5. Number of congested sectors before (red) and after (blue) implementation of route reallocation with credit points.

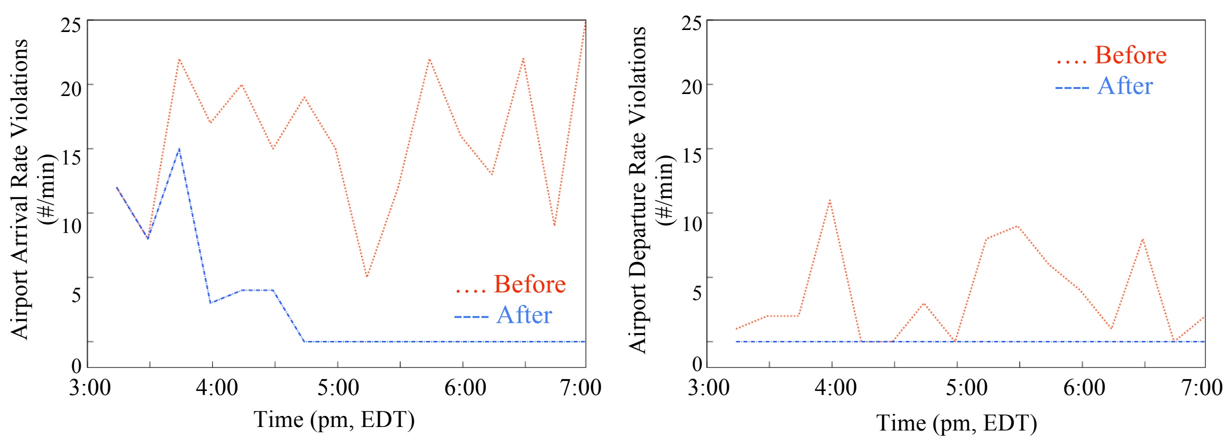

Figure 6. Number of airport arrival (left) and departure (right) constraint violations in 15-minute intervals before (red) and after (blue) implementation of route reallocation with credit points.

During the experiment, it was observed that larger users (see Fig. 4) at certain airports could dominate departure operations due to large number of credits available to them. In order to address this, the number of departing flights for each user in a 15-minute block was recorded. A process of maintaining the ratio of number of flights for each user at a given airport is utilized for the departure rates. This is accomplished by recursively providing each user with half of the available departure slots until all the available capacity is used up. There may be users with lower flight credits that get a slot when other users may have higher credit flights. This discrepancy is subsequently resolved because a reduced airport capacity (obtained by superimposing convective weather data over airports) has a reduced sector capacity in the vicinity as well. The reduced capacity in the sector pushes the lower credit flights to another route (unlikely) or a later slot (most likely). Thus, the credit-points concept ensures that users with more flights (and hence, more credits) do not adversely impact other users with fewer flights at the same airport. It, however, provides opportunity for all users to participate fairly. Thus, this concept helps flight routing and prevents sector overloading by better maintaining available airspace and airport capacities, by equitably and predictably distributing flights on available routes. It should be noted that equity and predictability are not unique to the credits concept and other scheduling algorithms may provide these characteristics as well.

B. Delay Analysis with Negotiation

For each flight of each user, the assigned delay was recorded. The experiment where all flights were flying based on the filed schedule and on their nominal route was used as the baseline case. This is equivalent to the first-come-first-served (FCFS) scheme. Figure 7 shows the instantaneous (blue) and cumulative (red) delay values for the four-hour period under consideration. As can be seen from the figure, due to higher traffic demand in the latter half (5:30 pm through 7:00 pm EDT), the delays increase more than in the first half (3:00 pm through 5:30 pm EDT). After this baseline case, the credits were assigned based on flight priorities (described above in IV.A). The results for this experiment are shown in Fig. 8 (left). It is seen that as flights get assigned on alternate routes, the instantaneous (blue) and cumulative (red) delay decreases. In the end, the cumulative delay of Fig. 7 and Fig. 8 (left) show a reduction of about 25%. Using the negotiation process described in section II, the experiment was run again. The results are shown in Fig. 8 (right). It is seen that the negotiation process has the effect of reducing the delays even further. The reduction in cumulative delay from the baseline (FCFS) case in Fig. 7 and from the non-negotiation case in Fig. 8 (left) is about 42% and 22%, respectively. Thus, the credit-points concept with negotiation is feasible and has a benefit to the users. The user preferences are accounted while maintaining predictability of operations. The system performance also improves due to better utilization of airspace, although with a distance-based utility function.

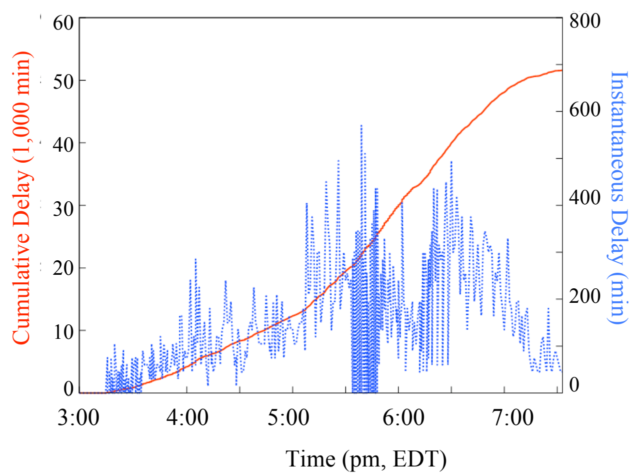

Figure 7. System-wide cumulative delay (red) and instantaneous delay (blue) for all users for the baseline (first-come-first-served) case.

In order to see the effect of using credits on individual users, the individual flight delays were categorized in terms of long (>2,000 nmi), medium (1,000 to 2,000 nmi) and short (<1,000 nmi) haul flights. In Fig. 9 for each of the top 40 participating users, the long, medium and short distance flights are represented in blue, red and green color bars, respectively. Figure 9's y-axes are difference in delays normalized with the number of flights. Figure 9 (left) presents difference between baseline case and the case where credits were assigned but without negotiation. Figure 9 (right) shows the same experiment but with negotiation process included. It is observed that all the bars move up from Fig. 9 (left) to Fig. 9 (right), which implies that the negotiation process reduced delays compared to

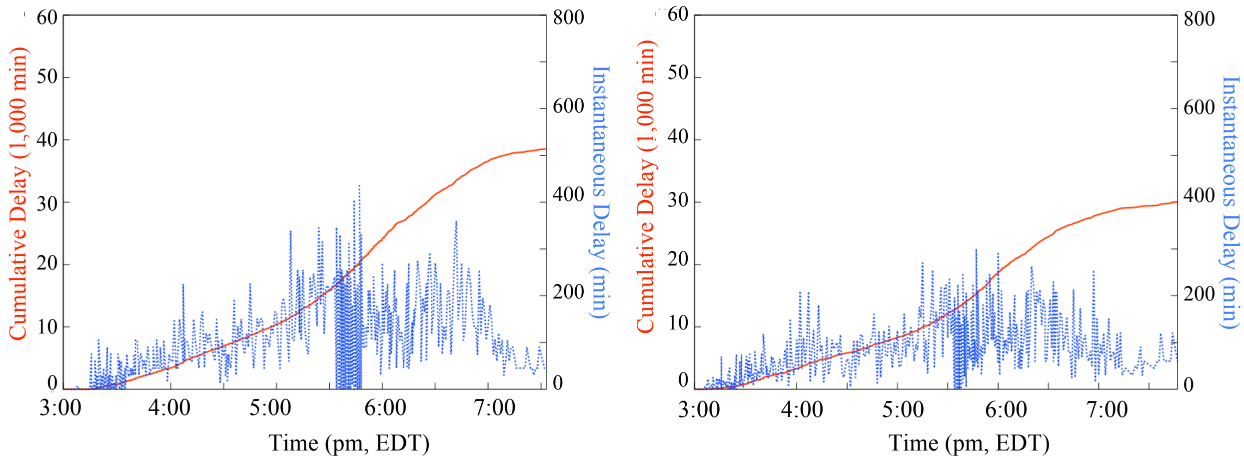

Figure 8. Cumulative delay (red) and instantaneous delay (blue) for all users using credits and route reallocation process, without (left) and with (right) negotiation.

the baseline case for all of the users. This is the result of flights getting the additional option of swapping routes with another user or increasing credits (or priority) for the next iteration. It should also be noted that there are some red and green bars, which have negative average delays, implying larger delays with the credits scheme compared to the FCFS scheme. However, they are much smaller and only the sixth user has a negative blue bar (long distance flights). The 36th user has very few flights so the red and green bars look bigger comparatively.

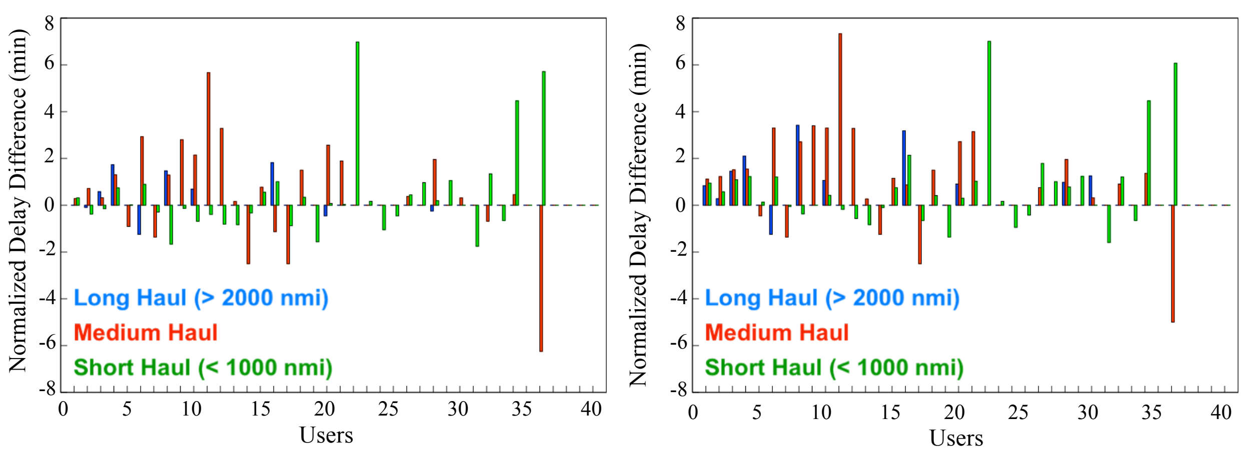

Figure 9. Normalized average delay difference between credits without (left) and with (right) negotiation with respect to the baseline case for all participating users.

C. Credits Calculation and Gini Coefficient

The total credits expended for all users are recorded. The credit points expense for one user with 865 flights is shown as a function of time in Fig. 10 with a red line (left y-axis). The resulting instantaneous delay for the same user is shown with blue line (right y-axis). It is observed from the trend of the red line that a large amount (~75%) of credits are used up for this user at the beginning of simulation. This is because the user has many flights departing in the first half with higher priority. By the time it's halfway in the planning process (~4:50 pm EDT), the user is left with no credits. This is an important lesson for participants to be cautious with credit assignment. In this case, the credits were expended based on flight lengths but the user does not incur significant delays subsequently.

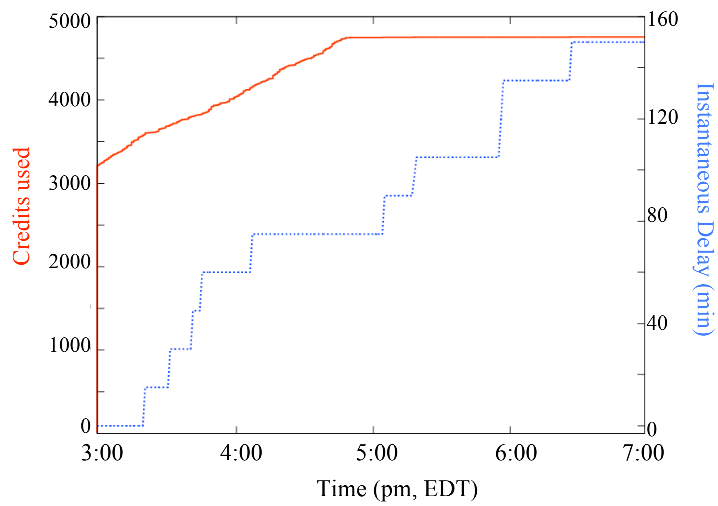

Figure 10. Number of credits used (red, left y-axis) and instantaneous delay incurred (blue, right y-axis) for one user participating in the credits scheme.

To assess equity of assigned delay solutions, the Gini coefficient[16] was calculated for all users as described in section IV.B. Table 1 represents the results of Gini coefficient calculation. The table shows data for three cases with the use of credits and alternate routes. They are congestion constraint only, congestion and weather impact constraints, and added airport arrival/departure rate constraints. As is seen from the numbers, the Gini coefficient has a downward trend as constraints are added. Optimal equality in average and maximum delay distribution would have a Gini value of 0.0, which would imply that delays are absolutely equitably distributed. The numbers in Table 1 indicate an improvement of 25% in the most constrained case. Thus, the delays are more equitably distributed among all participating users with the use of the credit-points concept.

Table 1: Computation of Gini coefficient for average and maximum delays for all participating users.

	Congestion Constraint only	Congestion and Weather Constraints	Congestion, Weather and Airport Arrival/Departure Rate Constraints
Avg. Delay (0.0 is best)	0.499	0.406	0.370
Max. Delay (0.0 is best)	0.452	0.412	0.320

VI. Conclusions

The air traffic management system can significantly benefit from collaboration between users of airspace (airlines, general aviation, etc.) and the FAA. It has been identified that during times of reduced airspace capacity, a common assessment of the system constraints between users and the FAA, and specifying multiple flight route options would be beneficial. This study presents a method of assessing the performance of the system when user flight preferences are incorporated with a credit-points concept. This research suggests delays can be reduced by allowing users to present several pre-departure route options to a system-level automation along with specification of number of credits for prioritization of each flight. It assists traffic management during constrained operations while maintaining airspace and airport demand below available capacity.

A real traffic scenario is used to study whether the concept can address airspace congestion and weather impact. The flight credits, route and delay assignment process handled all the airspace constraints completely (barring the initial transient). It reduced cumulative delays by about 25% compared to the baseline first-come-first-served algorithm. The negotiation process additionally reduced system delays by 42% compared to the baseline case. The credit-points concept provides a more equitable distribution of delays despite increasing airspace and airport constraints. The Gini coefficient, a measure of inequity in a population, demonstrated an improvement of 25% in the most constrained case. Based on these metrics, it is concluded that the credit-points concept is feasible. This method also maintains predictability of the system due to high priorities assigned to airborne flights on routes assigned before departure. In the end, it helps the airspace provider with a means to better assess resource requirements because the concept inherently satisfies airspace and airport capacities. It should be noted that the observed benefits are due to a distance-based utility function. The system performance could change based on the choice of the utility function. In ongoing research, alternate utility functions are being evaluated in the credit-points concept.

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