SENSISTIVTY OF SYSTEM PERFORMANCE & EQUITY TO USER COOPERATION IN THE ARRIVAL FLOW: GUIDELINES FOR NEXTGEN

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Abstract:

Incentives for users to take actions to seek preferential allocation of resources exist when demand for air transportation resources (e.g. slots at metering fixes) exceeds the available capacity. Researchers have documented actions by users of the National Airspace System (NAS) to advantageously position a flight for a preferential slot allocation through the First-Come-First-Serve (FCFS) allocation used by Air Traffic Control (ATC). NextGen concepts-of-operations (e.g. 4-D trajectories) will provide alternative mechanisms for users position flights for advantageous slot allocation. Will this degrade or enhance system performance and equity?

This paper describes an analysis of the impact of users positioning flights for advantageous slot allocation on system performance and equity for an arrival flow to a metering fix. The results indicate that the combinatorics of all possible FCFS allocations create a range of performance and equity. Analysis demonstrates that user positioning for advantageous slot allocation under FCFS represents a subset of the possible combinations of FCFS slot allocations and does not result in degraded performance or equity. A case-study analysis of an arrival flow for La Guardia demonstrates that system performance and equity are robust to user positioning for advantageous FCFS slot allocation. The implications of these results for NextGen concepts-of-operations is that although the mechanisms for advantageous positioning for FCFS allocation will change, the impact on system performance & equity will not. In addition, there is evidence that the NextGen availability of system-wide information will incentivize user cooperation further enhancing NAS system performance and equity. These and other results are discussed.

INTROUCUTION

Every society has rules for sharing publicly owned and/or operated resources among it's members (1). These rules determine the overall performance of the system and the efficiency in use of the common resources. These rules also inherently determine the equity in allocation of the jointly used resources.

When the demand for public resources is in excess of the available capacity, users of the resource are incentivized to take (legal) actions to improve the probability of being allocated the scarce resource. In some, cases these user actions can result in additional costs or non-monetized penalties to other users of the resource. These additional costs or non-monetized penalties may or may not be distributed proportionally.

During peak periods of operation, the National Airspace System (NAS) is frequently in a position where the capacity of the resources is unable to meet the scheduled or actual flight demand (2). The resources in question include time-based slots at gates, taxiways, departure runways, airway entrance and exist fixes, arrival metering fixes, and arrival runways. Traffic Flow Management (TFM) allocates scarce resources using a Ration-by-Schedule scheme to balance future demand with capacity. Air Traffic Control (ATC) Centers, TRACONs and Towers allocate scarce resources under a First-Come-First-Serve basis for real-time flow of traffic.

To provide the best quality service to their customers and to minimize operational costs, users of NAS take (legal) actions to position their flights for preferential allocation of the slots either by TFM or by ATC (3, 8, 9). Concepts-of-operations proposed for NextGen will also have opportunities to advantageously position flights (4).

This paper describes an analysis of system performance (e.g. delays) and equity for airlines for an arrival flow to metering fix. The analysis assumes that the arrival flow includes slots that are over-subscribed and must be allocated by a First-Come-First-Serve scheme. The analysis specifically investigates the impact of a NAS user systemically advantageously positioning flights for preferential slot allocation by FCFS. A case-study for an arrival flow to LGA is provided. The results of this analysis can be summarized as follows:

- <u>System Performance</u> for an arrival flow with over-subscribed slots exhibits a range of performance delays dependent on: (i) the number of slots over-subscribed, (ii) the number of flights in over-subscribed slots, (iii) the number of flights that must be shifted following the slot allocation, and (iv) the separation distance of the lead-follow pairs.

- <u>System Performance in the presence of systemic advantageous flight positioning for FCFS slot allocations</u> is evenly distributed across the range of system performance generated by the random FCFS.

- <u>Equity for Airlines</u> is impacted by the percentage of an airline's flights forecast to the over-subscribed slots and the percentage of an airline's flights in the subsequent shift.

- Equity in the presence of systemic advantageous flight positioning for FCFS slot allocations will not be significantly improved or degraded. One advantageous flight positioning only provides the opportunity (but not the right) to be allocated the lead slot by FCFS. Two flights affected by the shift following over-subscribed slot allocation are always penalized.

- LGA Case Study demonstrated that a relatively over-subscribed arrival flow (274 flights out of 523 flights) with a relatively homogeneous fleet mix (90% Medium) and diverse airline profile (23 airlines with 31% to 1% of the total traffic) is largely robust to advantageous positioning for FCFS slot allocation. System performance was evenly distributed in the FCFS range. Further, no significant inequities emerged as a result of systemic advantageous flight positioning.

NextGen concepts-of-operations that are predicated on unbounded scheduling and/or randomly sequenced, metered arrivals with an FCFS allocation scheme, will yield the opportunity for advantageous position-shifting. The means of the achieving the advantageous position shift will change (e.g. 4-D trajectory contract instead of increased speed), but not the dynamics of arrival flows.

Counter-intuitively, the availability of more complete information about the flows and their system performance available in NextGen (e.g. SWIM) would likely not result in an increase in advantageous positioning. Instead, SWIM would enable users to better understand the opportunities for improving the efficiency of the overall flows, and the relative neutrality of gaming. For more on NAS user collaboration resulting from shared information, see (8), (9).

This analysis also demonstrated that systemic manipulation of the sequence of Weight Class Groupings (instead of FCFS) in the arrival can minimize the throughput and reduce delays. NextGen should consider this in the concepts-of-operations.

This paper is organized as follows: Section 2 provides an overview of the dynamics of slot allocation and slot shifting from a First-Come-First-Serve allocation scheme. Section 3 describes the results of a comparison of system performance and equity for advantageous positioning for preferential slot allocation for an LGA arrival flow. Section 4 provides a conclusion and discusses the implication of these results.

SYSTEM PERFORMANCE AND EQUITY IN AN ARRIVAL FLOW

The arrival flow at a metering fix during peak operations has been shown to exhibit an exponential distribution for inter-arrival time between aircraft (5). By random occurrence, or due to actions by the airlines or flight-crews, a large number of the flights will arrive at the metering fix in the same time slot or closely separated. Other flights, in the tail of the distribution, will be preceded by unused slots.

Flights anticipated to arrive in slots without appropriate separation distance are re-allocated slots by Air Traffic Control (ATC). The method for fair re-allocation of these slots in the U.S. is First-Come-First-Serve (FCSF). Under FCFS slot re-allocation, one of two flights vying for the same slot is randomly selected and delayed to a later slot, allowing the other flight claim the original slot. This behavior has impact on the delay performance of individual flights.

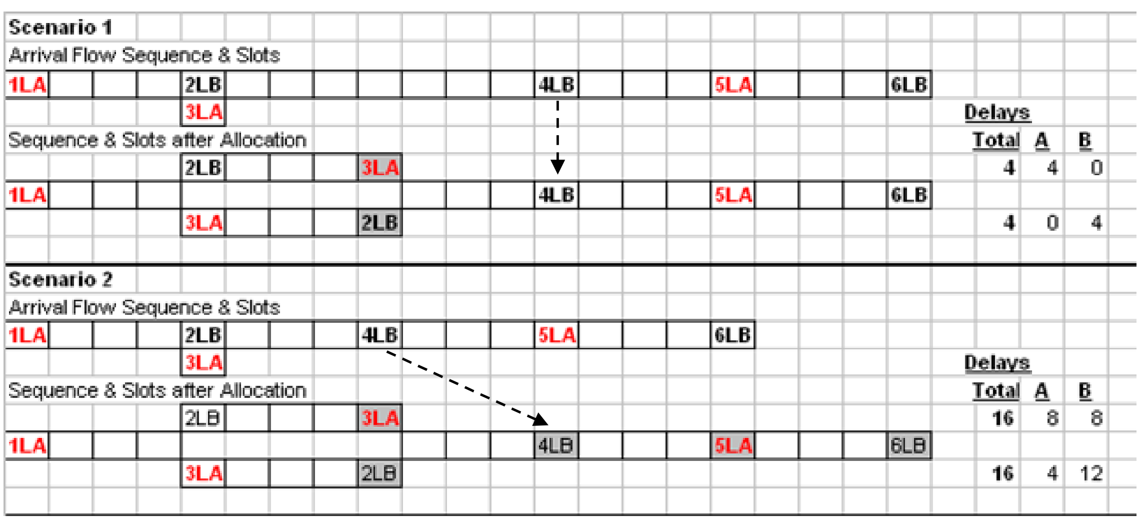
The System Performance of the re-allocation of slots is determined by the following properties of the arrival flow:

(i) the number of slots over-subscribed
(ii) the number of flights in over-subscribed slots
(iii) the number of flights that must be shifted following the slot allocation
(iv) the separation distance of the lead-follow pairs (i.e. fleet-mix)

The Equity between Airlines following the re-allocation of slots is determined by the following properties of the arrival flow:

(i) the number of over-subscribed slots each airline plans to use
(ii) the number of flights for each airline in each of the over-subscribed slots
(iii) the number of flights for each airline that must be shifted following the slot allocation
(iv) fleet-mix of the airlines

Figures 1 and 2 illustrate the relationship between the properties of the arrival flow and System Performance and Equity. The example includes an arrival flow with six flights with one slot conflict. Each flight is labeled with a flight index, aircraft weight class (Large or Small) and Airline (A or B). For example, "2LB" represents a flight second in the original arrival flow. This flight is Large weight class grouping and is flown on behalf of Airline B. Flights delayed by a conflict or by "bumping" following re-allocation are shown with a gray background. It should be noted that the "original" arrival flow and sequence of slots is the mental model a controller would hold based on arriving traffic. The results of the controllers actions using FCFS result in the sequence



System Performance and Equity after re-allocation of slots for conflict for 2LB and 3LA. Scenario 1 arrival flow is able to absorb delayed flights. Scenario 2, arrival flow is not able to absorb delayed flights.
Figure 1.

and slot after the allocation.

Figure 2 illustrates the impact of the absorption capacity of the arrival flow to deal with flight delayed following re-allocation to resolve a conflict.

Scenario 1 illustrates the case when the arrival flow is able to absorb the slot conflict. In the first solution, 3LA is delayed. In the second solution 2LB is delayed. No other flights are shifted. The result is a system performance with only a 4 slot delay for either solution. However in each solution airline equity is not neutral. One of the airlines is penalized more than the other.

Scenario 2 illustrates the case when the arrival flow is not able to absorb the slot conflict. In the first solution, 3LA is delayed. This delay results in shifting 4LB, 5LA, and 6LB. The system performance exhibits a 16 slot delay. Airline equity is neutral.

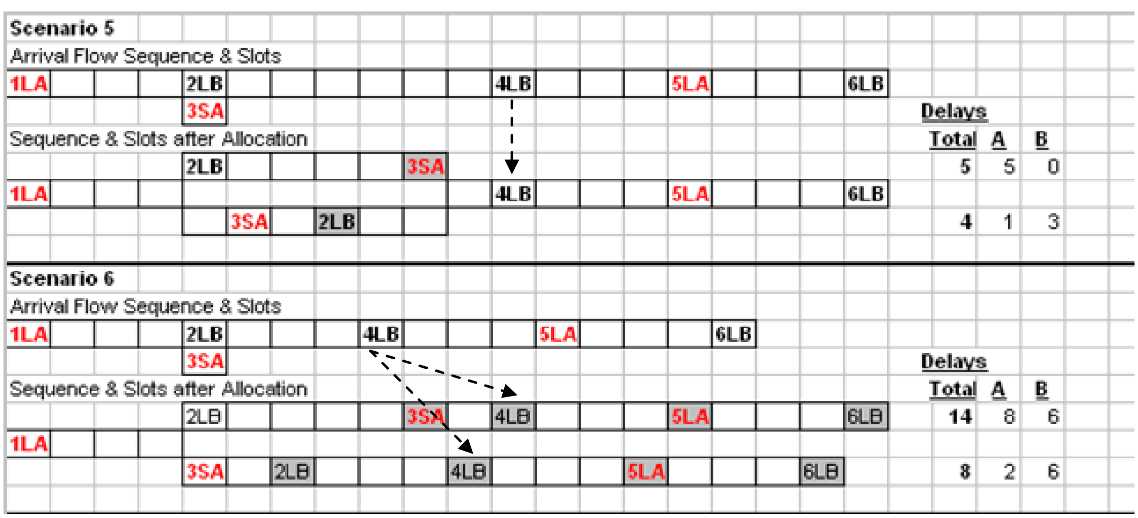
In the alternative solution to Scenario 2, 2LB is delayed. This delay results in the shifting of 4LB, 5LA, and 6LB. As in the first solution, the system performance exhibits a 12 slot delay. However, airline equity is no longer neutral. Airline B now absorbs 12 delay slots, compared with Airline A that accrues only 4 slots.

When the arrival flow is able to absorb the delay, the impact on System Performance is localized, however a relatively smaller penalty must be accrued by one airline. When the arrival flow is not able to absorb the delay, the delays propagate resulting in poor System Performance. The Equity to Airlines is determined by the number of flights for each airline impacted by the "shifting."

Figure 3 illustrates the impact of fleet mix on the System Performance and Equity for Airlines. In this case a Large (2LB) and a Small (3SA) vie for the same slot.

In Scenario 5, the arrival sequence is able to absorb the delay resulting from the resolution of the conflict for 2LB and 3SA. In either allocation solution, the delays are localized and are accrued by the airline that is delayed. In this scenario, the difference in fleet mix results in an asymmetry in performance and equity.

In Scenario 6, the arrival sequence is not able to absorb the delays resulting from



System Performance and Equity after re-allocation of slots for conflict for 2LB and 3LA. Scenario 5 arrival flow is able to absorb delayed flights but asymmetry in performance and equity occurs due to fleet mix. Scenario 2, arrival flow is not able to absorb delayed flights. Asymmetry in performance and equity is increased.
Figure 2.

the resolution of the conflict for 2LB and 3SA. In the first allocation solution, the 3SA must be delayed 3 slots to meet the separation distance requirements, resulting in a total of 6 delay slots. In the alternative allocation solution, 2LB is only delayed 2 slots to satisfy the separation distance requirements. The result is a total of 8 delay slots. The asymmetry in performance and equity due to the inability to absorb the re-allocated flight and the fleet mix is exaggerated.

When the arrival flow is able to absorb the delay, the impact on System Performance is again localized. When the arrival flow is not able to absorb the delays, the delays propagate resulting in degraded performance. Unlike scenarios 1 and 2 (above), the magnitude of the delays are determined by the fleet mix. Airline equity is also affected by the fleet mix. When the Airline with the smaller aircraft is delayed by the reallocation, this airline is penalized more than if the airline was operating a larger aircraft.

The theoretical examples above introduce two important ideas: *Localization* and *Range of Performance.* The ability of the arrival flow to absorb flights from over-subscribed slots can localize the effects of the re-sequencing and slot allocation. This is illustrated in Figure 2 where the sequence and slot allocation branches join. This is a key parameter in the determining the impact of system performance and equity.

The sequence and slot allocation tree also provides insight into the range of system performance and equity that is possible from an arrival flow with oversubscribed slots. The location of unused slots and the differences in separation distances required alternative lead-follow pairs yields a *range of performance* for the arrival flow. Any point of the range in performance can be achieved by random FCFS. Advantageous flight positioning, by definition, will represent one branch and it's associated performance and equity.

CASE STUDY: LAGUARDIA ARRIVAL FLOW

A case study of the arrival flow to La Guardia is used to illustrate the phenomena described above. La Guardia was chosen as it has a single runway arrival with a single metering fix. Also, the scheduled arrivals for La Guardia exhibit a significant number of over-subscribed slots, a large number of airlines, and a homogeneous fleet mix. These properties reduce the overall complexity of the properties that impact system performance and equity.

Properties of the Arrival Flow

The arrival flow includes 523 flights from 06:00 to 21:59 Eastern Time. The number of flights and the percentage of overall traffic operated by each airline are provided in Table 1. Airline 21 operated 31.5% of the overall arrival traffic. Airline 1 and Airline 7 operate 22% and 20%. Seventeen airlines operate fewer than 13 flights in the arrival flow. The breakdown of the fleet mix is also described in Table 1. Ninety percent of the flights are classified as Medium, 7% as Boeing 757 and 3% as small.

The assignment of slots was derived from the scheduled arrival time for the purpose of the study. Figure 3 illustrates the number of slots in which one or more flights

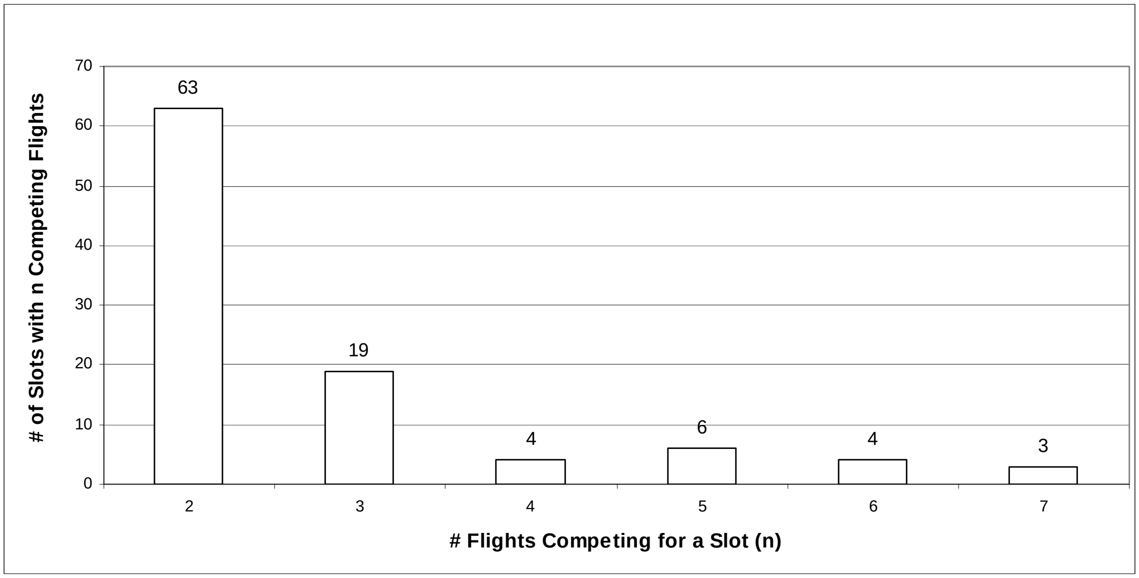
Airline	# of Flights	% of Total Flights	Fleet Mix by Weight Class Grouping				Estimated Total Seats
			Heavy	B757	Medium	Small	
1	**113**	**0.21**	0	7	106	0	11028
2	11	0.02	0	0	11	0	1178
3	8	0.01	0	1	7	0	982
4	1	0.01	0	0	1	0	50
5	1	0.01	0	0	1	0	106
6	13	0.02	0	0	13	0	1404
7	**105**	**0.20**	0	17	88	0	11937
8	6	0.01	0	0	1	5	60
9	2	0.01	0	0	2	0	248
10	1	0.01	0	0	0	1	5
11	8	0.01	0	0	8	0	1200
12	2	0.01	0	0	2	0	100
13	1	0.01	0	0	0	1	8
14	2	0.01	0	0	1	1	26
15	1	0.01	0	0	0	1	9
16	8	0.01	0	0	8	0	848
17	10	0.02	0	0	10	0	1301
18	21	0.04	0	5	16	0	3004
19	14	0.03	0	0	14	0	1442
20	25	0.05	0	8	17	0	3510
21	**165**	**0.32**	0	0	159	6	10740
22	1	0.01	0	0	0	1	18
23	4	0.01	0	0	4	0	188
TOTAL	**523**	**1.00**	**0**	**38**	**469**	**16**	**49392**

Table 1: Summary of airline and fleet mix breakdown for arrival flow into LGA

contented for the same slot. Sixty three of the ninety nice slots have 2 flights in contention. Three slots have 7 flights in contention.

System Performance and Equity for Airlines following Slot Re-allocation

The arrival flow was processed to re-allocate and shift flights in a two step process. First, the flights were re-sequenced into all the possible combinations. This process effectively created a tree of all possible sequences that could occur. Second, each branch of the tree applied the rules for pair-wise arrival separation distance to flights that were not appropriately separated. This process resulted in a sequence and slot tree. Each branch in the tree exhibits different System Performance and Equity. Branches can be sorted and grouped by different criteria for the purpose of analysis.



Histogram of number of flights contending for a given slot.
Figure 3

Due to the prohibitively large number of combinations of the (random) FCFS branches, a random sample of 5000 branches were selected for System Performance and Equity of Airline analysis. The statistics for the random sample of the (random) FCFS branches are:

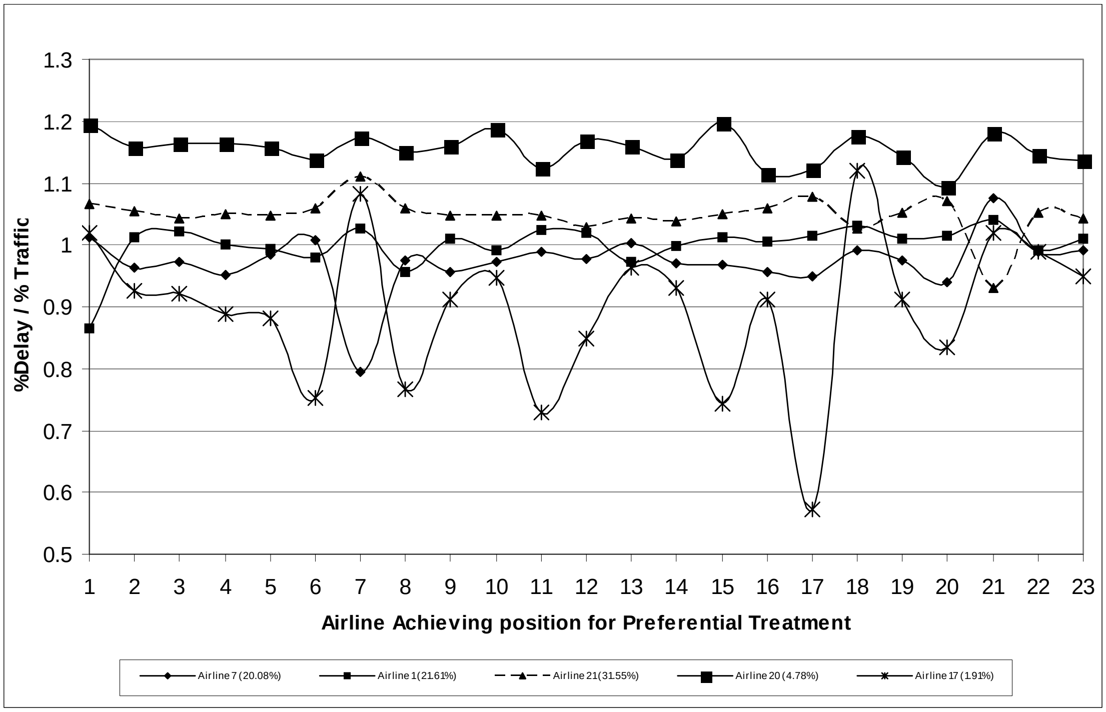
- Average total flight delay – 50.63 hours total delay (5.807 minutes per flight)
- Maximum total flight delay (worst-case) – 60.1 hours (6.893 minutes per flight)
- Minimum flight delay (best-case) - 41.4 hours (4.75 per flight)

The branches in which systematic advantageous flight positioning by an airline resulted in the airline always being allocated the first slot were also computed. The distribution of the total delay when airlines achieved advantageous slots ranged across the distribution described above. The *average* system performance when each airline was awarded the first slots ranged from 42.7 hours (4.9 minutes per flight) to 44.9 hours (6.4 minutes per flight).

Equity for Airlines

A comparison of equitable allocation of delays between airlines can be computed using %Delay/% Traffic metric. This metric provides the percentage of the overall delays accrued by an airline divided by the percentage of overall traffic operated by the airline. A value greater than 1 indicates that the airline accrued proportionally more delay than it's share of traffic, A value less than 1 indicates that he airline accrued proportionally less delay that it's share of traffic.

Figure 4 illustrates the %Delay/%Traffic metric for 5 airlines for each of the Sequence & Slot Allocation branches in which an airline achieves an advantageous



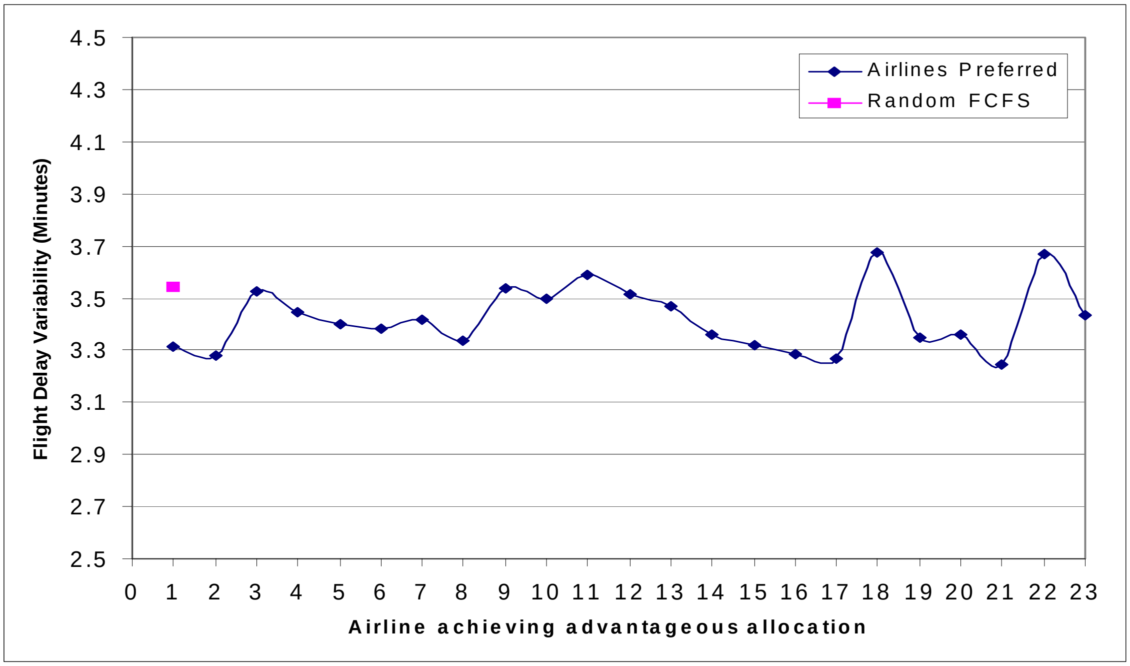
Percentage of average delay accrued by 5 airlines for Sequence & Slot Allocation branches for each airline achieving position for preferential treatment. Airline 21 (31% of traffic) and Airline 20 (5% of traffic) tend to be penalized in excess of their percentage of traffic.
Figure 4

position to receive preferential slot allocation. None of the airlines is able to significantly adjust the equity in their favor by advantageous positioning. However, airlines with a lower proportion of traffic (e.g. Airline 17 – 2% of total traffic) are subject to larger swings in delay proportional to their traffic.

Figure 5 shows the delay variability for each of the sequence and slot branches in which a given airline positioned to take the first slot is awarded the slot. Delay Variability is the standard deviation of the total flight delay for all of the flights. When Delay Variability is a small number, this implies slot re-allocation did not result in a wide range in delays across all the airlines. The average Delay Variability was 3.4 minutes with a maximum of 3.7 minutes and minimum of 3.2 minutes.

CONCLUSIONS

System Performance (represented by flight delays) for an arrival flow using FCFS slot allocation is a function of: (i) the number of over-subscribed slots, (ii) the number of flights forecast to an over-subscribed slot, (iii) the subsequent shifting of flights required by the sequencing and slot allocation. Fleet mix plays a secondary role by determining the magnitude of delays by the separation distance required in the slot allocation and slot shifting. As a consequence, advantageous positioning by an airline for preferential slot allocation in FCFS cannot impact system performance unless, the airline competes



Delay Variability for sequence and slot branches in which a given airline advantageously positioned to receive preferential FCFS slot allocation. Figure 5.

directly for a large majority of the over-subscribed slots, the airline is not impacted by the shift following the allocation, and the airline has a fleet mix that requires the largest separation distances.

Equity for Airlines is impacted by the percentage of flights forecast to the over-subscribed slots and the percentage of flights in the subsequent slot shift. Like system performance, equity for airlines is not affected by advantageous positioning by an airline for preferential slot allocation in FCFS unless the airline dominates all over-subscribed slots and is not impacted by position shifting.

The LGA Case Study demonstrated that a relatively over-subscribed arrival flow (274 flights out of 523 flights) with a relatively homogeneous fleet mix (90% Medium) and diverse airline profile (23 airlines with 31% to 1% of the total traffic) is largely robust to advantageous positioning for FCFS slot allocation. Further, no significant advantage over other airlines is achieved by a given airline's actions.

Guidelines for NextGen

NextGen concepts-of-operations that are predicated on unbounded scheduling and/or un-metered arrivals that is arbitrated by an FCFS allocation scheme (whether it be by ATC vectors or by 4-D contract negotiation) will yield the opportunity for advantageous position-shifting. Whereas the means of the achieving the advantageous position shift (e.g. 4-D trajectory contract instead of increased speed) will change, the dynamics of arrival flows will not.

One of the observations that is the result of this research is that the systemic manipulation of the sequence of Weight Class Groupings (instead of FCFS) in the arrival flow can maximize the throughput and reduce delays. NextGen may want to consider alternative allocation schemes that maximize throughput for all parties at the expense of localized delays for local slot manipulation. See Beasley et al, (6) for examples.

One of the concerns raised about NextGen is the widespread availability of real-time information through System Wide Information Management (SWIM) would increase the level of gaming. This research indicates that increased information may, in a large number of cases, enable users to better understand the opportunities for improving the efficiency of the overall flows, and the relative futility of gaming. See (8) and (9) for history of information sharing amongst airlines. This is an area for future research.

Future Work

There are threads of future work. The first, is to develop the infrastructure to run simulations for further. The second, is to design and run experiments using the simulation.

Several improvements to the algorithm that generates the sequence and slot allocation tree are planned. These improvements include changes to improve the speed of computation and to take advantage of sparse matrix techniques to reduce the combinatorics. Other changes include the addition of a "compression" function to enable the arrival flow to close open slots, parameters associated with separation distance distributions to take into account ATC "buffers," environmental (fuel, noise, and emissions) metrics in addition to delays.

The above algorithms form the basis of a web-based software application that is a variant of the "Game of Life" to play out games in an arrival flow. In this software application, the experimenter can load a schedule, set rules for individual agent's flight positioning, set rules for allocation (e.g. FCFS or priority), and display of system performance and equity statistics.

This infrastructure will be used to run experiments to seek patterns in system performance, equity, and behavior for different schedules, flight agent rules, and allocation schemes. These experiments will demonstrate the efficiency enhancements that result in cooperation from NextGen concepts-of-operations.

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