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Fast-Time Study of Airline-Influenced Arrival Sequencing and Scheduling

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The basic objective of arrival sequencing and scheduling in air traffic control automation is to match traffic demand and airport capacity while minimizing delays. The principle underlying practical sequencing and scheduling algorithms currently in use is referred to as first-come-first-served (FCFS). Although this principle generates fair schedules when delays must be absorbed, it does not take into account airline priorities among individual flights. The development of new scheduling techniques that consider priorities expressed by air carriers will reduce the economic impact of air traffic management (ATM) restrictions on the airlines. This will also lead to increased airline economic efficiency by affording airlines greater control over their individual arrival banks of aircraft. NASA is exploring the possibility of allowing airlines to express relative arrival priorities to ATM through the development of new sequencing and scheduling algorithms that take into account airline preferences. A method of scheduling a bank of arrival aircraft according to a preferred order of arrival instead of according to an FCFS sequence based on estimated time of arrival at the runway is investigated. Fast-time simulation is used to evaluate this scheduling method in terms of the algorithm's ability to produce a preferred order of arrival and in terms of its ability to minimize delays (scheduling efficiency). Results show that compared with FCFS scheduling, the alternative scheduling method is often successful in reducing deviations from the preferred bank arrival order while causing little or no increase in delays that must be absorbed.

Introduction

THE continued growth of air traffic within the United States, combined with the use of hub and spoke operations by air carriers, has led to increased congestion and delays in the terminal airspace surrounding the nation's busier airports. The problem of congestion is exacerbated at hub airports, where air carriers schedule large numbers of flights to arrive and depart within a short time period. To air carriers, hubbing makes good economic and competitive sense.[1] At the same time, however, hubbing operations often lead to overcapacity periods and precipitate delays that can directly impact the economic efficiency of an air carrier's flight operations. To ensure that the safe capacity of the terminal area is not exceeded, air traffic management (ATM) often places restrictions on arriving flights that are transitioning from en route airspace to terminal airspace. The constraint of arrival traffic is commonly referred to as arrival flow management and includes techniques such as time-based metering, vectoring, and the imposition of ground delays or miles-in-trail restrictions. Arrival flow management is typically performed without consideration for the relative priority that airlines may place on individual flights, based on factors such as crew criticality, passenger connectivity, critical turnaround times, gate availability, on-time performance, fuel status, or runway preference. The development of new arrival flow management techniques that consider priorities expressed by air carriers will allow airlines to have greater control over individual arrival banks. This will lead to increased airline economic efficiency and reduce the economic impact of ATM restrictions on the airlines.

Air traffic control automation tools are being used in arrival flow management to enable collaboration between air carriers and ATM and to assist controllers in efficiently matching traffic demand and airport capacity. The self-managed arrival resequencing tool (SMART) allows air carriers to affect arrival demand through self-imposed ground delays or through company speed control.[2] The collaborative decision making program's flight schedule monitor allows air carriers and ATM to use more efficiently available arrival slots during Federal Aviation Administration- (FAA) imposed ground delay programs.[3] NASA and the FAA have designed and developed a suite of software decision support tools (DSTs) to improve the efficiency of high-density airspace.[4] Collectively known as the Center-TRACON Automation System (CTAS), these tools use sequencing and scheduling algorithms to automatically plan the most efficient landing order and landing times for arriving aircraft.[5] Operational evaluation of the CTAS tools has shown them to be effective in improving airport throughput and reducing delays while maintaining controller workload at a reasonable level.[6]

One of the CTAS tools, the traffic management advisor (TMA), is currently being used at the Fort Worth Air Route Traffic Control Center to perform arrival flow management of traffic into the Dallas/Fort Worth airport (DFW). The TMA is a time-based planning tool that assists traffic management coordinators and Center controllers in efficiently balancing arrival demand with airport capacity.[6] The primary algorithm in the TMA is a real-time scheduler that generates efficient landing sequences and landing times for arrivals within about 200 n mile from touchdown.[7] Aircraft are scheduled so that they arrive in a first-come-first-served (FCFS) order based on an estimated time of arrival (ETA) at the runway. Although FCFS scheduling establishes a fair order based on estimated times of arrival, it does not take into account individual airline priorities among incoming flights. As part of its collaborative arrival planning research and development program, NASA Ames Research Center is exploring the possibility of allowing airlines to express relative arrival priorities to ATM through the development of new CTAS sequencing and scheduling algorithms that take into account airline arrival preferences.[8]

Priority-Scheduling

For most airlines, the schedule that is determined internally by the airline to satisfy its business and economic objectives is an ideal

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schedule. This schedule is ideal in the sense that the everyday realities of operating an airline and interacting with the various elements of the National Airspace System (NAS) largely preclude this ideal schedule from ever being achieved. Because of the uncertainties throughout both the airline (equipment breakdowns, maintenance problems, personnel shortages) and the NAS (weather, ground delays, ATM restrictions), aircraft often arrive in the terminal airspace in an order that does not match the ideal order of the airline schedule. Current arrival flow management using FCFS sequencing and scheduling algorithms will likely result in aircraft arriving at the runways in an order that does not match the preferred arrival order. The ability to specify the preferred arrival order within the air carrier's own arrival bank is useful for maximizing bank integrity and minimizing bank time, that is, the exchange of passengers/cargo, and aircraft servicing.[9] It is important to distinguish between "scheduling" or "schedule" in the context of airline operations, and "scheduling" or "schedule" in the context of air traffic control automation. The former refers to the daily scheduled times of departure and arrival that an airline determines for all of its flights, whereas the latter refers to the process of automatically choosing 1) the order or sequence in which the aircraft should land or cross a particular fix and 2) the time that each aircraft in the sequence should pass over a specified fix.[7]

Earlier studies have shown that scheduling aircraft according to an FCFS sequence based on ETA at the runway produces a schedule that is considered to be both fair to air carriers and that is efficient in terms of minimizing delays.[5] These studies also have shown that the resulting scheduled arrival sequence at the runway will, for the most part, match the FCFS sequence that is input to the scheduling algorithm. Because the scheduling algorithm attempts to preserve the input sequence, specifying a preferred sequence will result in a schedule that closely approximates the preferred arrival order. The concept of "priority scheduling" is then defined as the scheduling of a bank of arrival aircraft according to a preferred order of arrival.

Scope

The purpose of the present study is to examine a CTAS-derived priority-scheduling technique in terms of the algorithm's ability to produce a specified order of arrival and in terms of its ability to minimize delays. The study is not presented as an operational concept and is not intended to determine the operational viability of the scheduling technique. The output of the simulation is used only to compare the effectiveness and efficiency of the priority and the FCFS scheduling techniques. This is a crucial step in the determination of operational viability for any CTAS-derived scheduling technique; a significant loss in scheduling efficiency would render the technique operationally infeasible.

Fast-Time Simulation

A fast-time simulation originally developed for statistical evaluation of CTAS sequencing and scheduling algorithms has been modified for use in this investigation.[8,10] In contrast to real-time simulation or field tests, which would require on the order of 90 min to examine a single traffic rush period, the fast-time simulation allows examination of large numbers of statistically similar rush periods in a matter of minutes. For each simulated traffic situation, the deviation of a designated bank's scheduled arrival order from the preferred arrival order can be determined. The impact of priority scheduling on delays is also determined by comparing delays for priority scheduling and FCFS scheduling. The fast-time simulation comprises three major components: an airport model, a statistical model of the arrival traffic flow, and the scheduler.

Airport Model

The arrival airspace at DFW is divided into Center and TRACON regions, with the TRACON encompassing the airspace within approximately 40 n mile of the airport. Arrival traffic is merged at four waypoints on the Center-TRACON boundary, which correspond to the four primary arrival directions. These waypoints are referred to as feeder gates because during heavy traffic periods aircraft are funneled through these gates as a means of controlling or metering the flow rate into the terminal area.[7] Traffic flowing to each gate is separated into two independent streams that are vertically separated by 2000 ft at the feeder gate. This allows jet and turboprop aircraft, which have significantly different airspeed ranges, to cross the feeder gates independently and avoid conflicts due to overtakes near the gates.

The airport is modeled according to the landing practices at DFW with four feeder gates and three runways available for landing. The runways are considered to be independent so that no stagger requirements are necessary for scheduling. The airport model comprises the minimum flight times from each feeder gate to all landing runways for each independent stream. These TRACON transition times were obtained from an analysis using the minimum flight times measured for several traffic samples.[11] The TRACON transition times vary with feeder gate, aircraft type, runway assignment, and airport configuration. The airport model contains transition times for both airport configurations at DFW: north flow, with arrival traffic arriving/departing in a northerly direction, and south flow, with traffic arriving/departing in a southerly direction. Note that since the data used in this simulation were collected, a fourth arrival runway has been added at DFW. However, the three-runway model and traffic data are sufficient for purposes of this investigation.

Traffic Model

The traffic model is based on actual traffic data recorded during six rush periods at DFW. Although the traffic data were recorded over a span of several months, the mix of aircraft type remained nearly constant for each traffic sample. The data were recorded during the "noon balloon", a daily arrival rush lasting approximately 90 min. The noon balloon was chosen as the basis for the traffic model because during this arrival rush demand exceeds airport capacity and air traffic managers impose time-based metering restrictions through CTAS sequencing and scheduling algorithms. Data recorded during the six rush periods include the aircraft type, aircraft identification, arrival stream, and the ETA at the feeder gate (ETA_{FG}). The average of these ETA for the six rushes is taken as the nominal ETA_{FG}. Errors in aircraft time of arrival in Center airspace are modeled by adding an approximately Gaussian distribution to the nominal ETA at the feeder gate. The maximum range of the variation in the ETA_{FG} is specified as an input to the simulation and is referred to as the Center arrival error.

Bank Definition

Although an actual arrival bank of aircraft for an airline may consist of between 30 and 50 aircraft, in this study it is assumed that a bank comprises a single group of up to 20 aircraft belonging to one airline and its subsidiary carrier. With a majority of the flights in the traffic model belonging to American Airlines (AAL) and American Eagle (EGF), these flights are used to form arrival banks. The bank is not a contiguous set of aircraft because aircraft belonging to other airlines are interspersed among the bank aircraft, as would be the case in a real traffic situation. The bank of aircraft is defined by specifying the first member of the bank and the number of aircraft belonging to the bank. For the purposes of this simulation, we assume that the preferred order of arrival at the runway equals the order of arrival based on the minimum ETA at the runway with no Center arrival error. Each of the bank aircraft is assigned a priority ranking that is simply equal to the preferred order of arrival for the aircraft within the bank. The minimum ETA at the runway (ETA_{RWY}) is calculated by adding the TRACON transition times for each of the three runways to the nominal ETA_{FG} and selecting the minimum of the three resulting values. This ETA_{RWY} represents the earliest possible time of arrival for an aircraft provided that the aircraft could fly to the runway with no delay.

For example, consider the list of aircraft shown in Table 1, which represents a portion of a single arrival rush where AAL1150 has been designated as the lead aircraft in the bank, and the number of aircraft in the bank has been specified as five. The number in the first column represents the sequence number or position of the aircraft within the arrival rush when the aircraft are time ordered according to increasing ETA_{RWY}. Each arrival rush or traffic sample consists of 108 aircraft. In the example in Table 1, the aircraft belonging to the defined bank range from the 57th aircraft to the 65th aircraft in the arrival rush (AAL1554). The resulting bank aircraft are denoted by bold text for purposes of illustration. This example shows

Table 1 Bank definition and preferred arrival order

Sequence number	Aircraft identification	ETA_{RWY}, s	Priority
54	DAL910	3000	——
55	DAL428	3034	——
56	UAL359	3036	——
57	**AAL1150**	**3060**	**1**
58	**EGF628**	**3116**	**2**
59	DAL1086	3120	——
60	ASE924	3123	——
61	DAL2062	3180	——
62	**AAL1934**	**3240**	**3**
63	**AAL1428**	**3285**	**4**
64	DAL1670	3300	——
65	**AAL1554**	**3345**	**5**
66	AAL410	3376	——
67	DAL756	3531	——
68	DAL431	3546	——

Table 2 Actual arrival order (Center arrival error = ± 5 min)

Sequence number	Aircraft identification	ETA_{RWY}, s	Priority
54	DAL428	2972	——
55	**AAL1150**	**3007**	**1**
56	DAL1670	3086	——
57	EGF006	3089	——
58	DAL834	3146	——
59	DAL2062	3206	——
60	UAL359	3206	——
61	ASE924	3212	——
62	**AAL1428**	**3212**	**4**
63	**AAL1934**	**3266**	**3**
64	**AAL1554**	**3272**	**5**
65	**EGF628**	**3300**	**2**
66	AAL410	3326	——
67	DAL431	3441	——
68	DAL756	3624	——

that aircraft belonging to other airlines are interspersed among the arrival aircraft that comprise the bank. The second column is the aircraft identifier and the third column is each aircraft's corresponding minimum ETA_{RWY}. The fourth column shows the priority ranking assigned to each of the aircraft belonging to the bank based on this preferred order of arrival.

The actual order of arrival for aircraft in a traffic rush period is modeled by adding the Center arrival error to the nominal ETA_{FG}. The Center arrival error represents the uncertainties in the NAS that cause the same flight to arrive in Center airspace at different times on different days. Because the minimum ETA_{RWY} is calculated by adding a TRACON transition time to the ETA_{FG}, the minimum ETA_{RWY} will also vary. As a result, when the aircraft are ordered according to increasing ETA_{RWY}, the actual order for the bank aircraft will differ from the preferred arrival order. In addition, the number of aircraft interspersed among the arrival bank may vary because the variation in arrival time is modeled for all aircraft in the traffic rush, not only those belonging to the specified bank. Table 2 shows the resulting estimated arrival order for the specified bank when a Center arrival error having a range of up to ±5 min is added to the traffic sample.

FCFS Scheduling

The FCFS scheduler is intended to approximate the sequencing and scheduling algorithms presently used in CTAS at the Fort Worth Center. A detailed description of the actual scheduling algorithm can be found in Ref. 7. Aircraft are sequenced and scheduled to be FCFS at both the feeder gates and runways while meeting feeder gate and runway threshold separation constraints. Because scheduling is done in time rather than distance, the prescribed minimum separation criteria are translated into minimum time separations at both the feeder gates and the runway threshold. For aircraft crossing the feeder gate, the minimum in-trail separation requirement for aircraft is 5 n mile, which is translated to a 60-s time separation for

Table 3 FCFS sequence and resulting schedule (Center arrival error = ± 5 min)

	Priority sequence		Resulting schedule	
Sequence number	Aircraft identification	ETA_{RWY}, s	Aircraft identification	STA_{RWY}, s
54	DAL428	2972	DAL428	3483
55	**AAL1150 (1)**	**3007**	**AAL1150 (1)**	**3507**
56	DAL1670	3086	DAL1670	3540
57	EGF006	3089	EGF006	3593
58	DAL834	3146	DAL834	3601
59	DAL2062	3206	DAL2062	3627
60	UAL359	3206	UAL359	3695
61	ASE924	3212	ASE924	3737
62	**AAL1428 (4)**	**3212**	**AAL1934 (3)**	**3768**
63	**AAL1934 (3)**	**3266**	**AAL1428 (4)**	**3789**
64	**AAL1554 (5)**	**3272**	**AAL1554 (5)**	**3843**
65	**EGF638 (2)**	**3300**	**EGF628 (2)**	**3895**
66	AAL410	3326	DAL431	3952
67	DAL431	3441	AAL410	3953
68	DAL756	3624	DAL756	4005

purposes of this simulation. The separation criteria at the runway threshold are a function of both aircraft weight class and landing order as determined by the FAA's wake vortex safety rules. Airport acceptance rate (AAR) is taken into consideration by limiting the number of aircraft that are allowed to enter the TRACON in sliding 10-min intervals, and the scheduler balances flights between runways to minimize overall delay.

The FCFS sequence is established by time ordering arrival aircraft according to increasing ETA_{RWY}. Beginning with the first aircraft in the sequence, each aircraft is tentatively scheduled to each of the three runways, while it is ensured that the prescribed minimum time separation between aircraft at the runway thresholds is met for each subsequent aircraft. The runway that results in the earliest scheduled time of arrival for the aircraft at the runway (STA_{RWY}) is then chosen as the landing runway. Scheduling to the runway automatically provides the correct amount of traffic to load the runways equally when traffic is heavy (runway balancing), and directs aircraft to the closest available runway. The STA at the feeder gate (STA_{FG}) is determined by subtracting the sum of the TRACON transition time and any TRACON delay from the previously calculated STA_{RWY}. Finally, if STA_{FG} for two flights are less than the required 60 s apart, the scheduled times will be altered to meet the required separation at the feeder gate.

Table 3 shows the resulting order of arrival when the aircraft are scheduled according to an FCFS sequence. The priority ranking of each bank aircraft is shown in parenthesis following the aircraft identifier. The second and third columns in Table 3 show the FCFS sequence that is input to the scheduler, with the aircraft time ordered according to increasing ETA_{RWY}. The fourth and fifth columns are the resulting schedule, with aircraft time ordered according to increasing STA_{RWY}. Note that the resulting scheduled order of arrival at the runway does not precisely match the FCFS sequence based on ETA_{RWY} that is input to the scheduler. Because the schedule must meet in-trail separation criteria at both the feeder gate and the runway threshold, and the separation criteria at the runway threshold are a function of aircraft weight class and landing order, the FCFS sequence may not be preserved at the runway. Among the aircraft belonging to the designated bank, flights AAL1934 and AAL1428 have shifted positions from the sequence that is input to the scheduler (as have aircraft DAL431 and AAL410, which do not belong to the designated bank). In this case, the position shift has resulted in a scheduled sequence that does more closely match the ideal or desired order of arrival than does the input FCFS sequence based on ETA_{RWY}. However, it is purely fortuitous that the resulting schedule more closely matches the preferred order, and depending on the magnitude of the Center arrival error, the scheduled order may actually deviate further from the preferred order.

Priority Scheduling

The priority-scheduling algorithm is identical to the FCFS algorithm with one exception: instead of time ordering the aircraft

Table 4 Priority sequence and resulting schedule (Center arrival error = ± 5 min)

	Priority sequence		Resulting schedule	
Sequence number	Aircraft identification	ETA_{RWY}, s	Aircraft identification	STA_{RWY}, s
54	DAL428	2972	DAL428	3483
55	**AAL1150 (1)**	**3007**	**AAL1150 (1)**	**3507**
56	DAL1670	3086	DAL1670	3540
57	EGF006	3089	EGF006	3593
58	DAL834	3146	DAL834	3601
59	DAL2062	3206	DAL2062	3627
60	UAL359	3206	UAL359	3695
61	ASE924	3212	ASE924	3737
62	**EGF628 (2)**	**3300**	**AAL1934 (3)**	**3782**
63	**AAL1934 (3)**	**3266**	**EGF628 (2)**	**3789**
64	**AAL1428 (4)**	**3212**	**AAL1428 (4)**	**3843**
65	**AAL1554 (5)**	**3272**	**AAL1554 (5)**	**3895**
66	AAL410	3326	DAL431	3952
67	DAL431	3441	AAL410	3953
68	DAL756	3624	DAL756	4005

according to increasing ETA_{RWY} prior to scheduling, the arrival aircraft belonging to the designated bank are ordered according to their priority ranking, which establishes the bank aircraft in the preferred arrival order. Note that only the aircraft belonging to the bank are reordered according to their priority ranking and that other aircraft in the traffic sample are still sequenced in an FCFS order based on ETA_{RWY}. By reordering only the bank aircraft and scheduling the remaining aircraft according to an FCFS sequence, the impact of the reordering on scheduling efficiency is minimized. Table 4 shows the resulting order of arrival when the bank aircraft are scheduled according to the preferred sequence of arrival. The second and third columns show the priority sequence that is input to the scheduler, with the bank aircraft ordered according to their priority ranking and the remaining aircraft time ordered according to increasing ETA_{RWY}. The fourth and fifth columns show the resulting schedule time ordered according to STA_{RWY}. As was the case with FCFS scheduling, the resulting order of arrival does not match the sequence that was input to the scheduler because the schedule must meet separation criteria at the runway threshold that are a function of aircraft weight class and landing order. Although the resulting scheduled bank order does not precisely match the preferred order, it does indeed match more closely the preferred bank order than does the FCFS schedule shown in Table 3.

Order Deviation

The purpose of this study is to compare the performance of the FCFS and priority-scheduling algorithms in terms of their ability to produce a preferred order of arrival while minimizing delays. The performance of the priority-scheduling algorithm is not measured in absolute terms, but is measured relative to the performance of the FCFS algorithm, which is considered to be a baseline. For this study, the primary measure of the effectiveness of the algorithm is its ability to produce a preferred order of arrival. To quantify the effectiveness of the priority-scheduling method relative to the FCFS method, we need a measure of how closely the scheduled order of arrival for a designated bank matches the preferred arrival order. We first define a position shift (PS) for an aircraft as the difference between the aircraft position in the preferred bank order and the sequence number in the scheduled bank order as

$$PS = N_{\text{Preferred}} - N_{\text{Scheduled}}$$

where N is the sequence number of the aircraft within the bank.

Table 5 illustrates the calculation of the PS for each of the aircraft in the bank defined in Table 1. The position shift of each aircraft is calculated for both FCFS scheduling (Table 3) and priority scheduling (Table 4). Note that a positive PS indicates that an aircraft is scheduled ahead of its preferred position in the bank, and a negative position shift indicates that an aircraft is scheduled behind its preferred position in the bank. For example, the sequence number of flight EGF628 in the preferred order of arrival is 2, whereas its

Table 5 Calculation of position shift for a bank of aircraft

Sequence number in bank	Preferred order	FCFS schedule	Position shift for FCFS schedule	Priority schedule	Position shift for priority schedule
1	AAL1150	AAL1150	0	AAL1150	0
2	EGF628	AAL1934	−3	AAL1934	−1
3	AAL1934	AAL1428	1	EGF628	1
4	AAL1428	AAL1554	1	AAL1428	0
5	AAL1554	EGF628	1	AAL1554	0

sequence number in the FCFS schedule is 5 and its sequence number in the priority schedule is 3. This results in a PS of −3 for the FCFS schedule and −1 for the priority schedule and reflects that EGF628 is scheduled three slots behind its preferred position in the bank using FCFS scheduling, and one slot behind the preferred position using priority scheduling.

Because we are interested in how closely the overall bank order matches the preferred order, we want a single measure that will indicate the deviation from the preferred order for a bank of any length. We then define the order deviation (OD) for a bank as the algebraic sum of the absolute value of the PS for each aircraft in the bank divided by the number of aircraft in the bank:

$$OD = \frac{\sum_{\text{no. of bank aircraft}} |PS|}{\text{no. of bank aircraft}}$$

It can be seen from this definition that if the OD for a bank of aircraft equals zero, then the scheduled bank order is the same as the preferred bank order. More importantly, the larger the value of the OD, the further the scheduled bank order deviates from the preferred order. This will allow us to easily compare the relative effectiveness of the FCFS and priority-scheduling methods in producing the preferred order of arrival. Note that the OD measures are used only to indicate the performance of the priority-scheduling algorithm relative to the FCFS algorithm. To determine the operational significance of OD, further studies would have to be performed that, for example, would investigate and quantify the relationship between OD and Center arrival error and determine what magnitude of OD is considered to be operationally significant to an air carrier. However, given the importance of arrival order to airline economic efficiency, a measure such as OD can provide a basis for determining the operational viability of the priority-scheduling algorithm and is a critical topic for further work.

The order deviations for each scheduling method using the example in Table 5 are calculated here. Because the priority-scheduling scheme results in the designated bank arriving in an order that more closely matches the preferred arrival order, the OD for the priority scheduled bank is smaller than that for the FCFS scheduled bank:

$$OD_{\text{FCFS}} = (|0| + |-3| + |1| + |1| + |1|)/5 = 1.2$$

$$OD_{\text{Priority}} = (|0| + |-1| + |1| + |0| + |0|)/5 = 0.4$$

To investigate the statistical performance of the two scheduling methods, a large number of traffic samples are generated for a specified bank. To compare the effectiveness of FCFS scheduling and priority scheduling for a large number of traffic samples, we define the average OD as the sum of the ODs for each traffic sample divided by the number of traffic samples:

$$OD_{\text{Average}} = \frac{\sum_{\text{no. of traffic samples}} OD}{\text{no. of traffic samples}}$$

Simulation Inputs/Outputs

Inputs to the fast-time simulation include the aircraft identifier of the lead aircraft in the bank, the size of the bank, the number of traffic samples, the range in Center arrival error, the airport configuration, and the airport acceptance rate. To determine the statistical performance of the FCFS algorithm and the priority algorithm, 500 traffic samples are generated for each designated bank. Each traffic sample comprises 108 jet and turboprop aircraft, 72 of which are

AAL or EGF flights. In this simulation the modeled airport configuration is south flow for DFW. Because the traffic model is limited to a single arrival rush period, and because of the manner in which a bank is defined, banks cannot be formed at or near the end of the arrival rush period. For example, if the bank length is specified as 20 and the designated lead aircraft is the 100th aircraft in the arrival rush, no bank will be formed because there are not enough aircraft following the lead aircraft to form a bank. Although we attempt to form banks across the entire range of the traffic rush period, this cannot be done for the reasons just outlined. The output of the fast-time simulation includes the average OD as well as histograms of the PSs for each bank of aircraft. Total delays and histograms of individual delays for all aircraft in the traffic rush are generated as well. Results can then be compared for the FCFS scheduling algorithm and the priority-scheduling algorithm.

Results and Discussion

The primary measure of the effectiveness of the priority-scheduling algorithm is the closeness of the match between the scheduled order of arrival and the preferred order of arrival. Figure 1 is a plot of the average order deviation for a bank size of 20, a range in Center arrival errors of ±5 min, and an AAR of 96 aircraft/h. For a designated bank whose lead aircraft has a nominal ETA_{FG} given on the x axis, a corresponding pair of ordinates shows the average OD for the bank using FCFS scheduling and priority scheduling. Figure 1 confirms that the priority-scheduling algorithm substantially reduces the average OD from that of the FCFS-scheduling algorithm. Note, however, that although the OD for each bank is less using the priority-scheduling algorithm, the OD is still nonzero for each bank. In other words, although the resulting bank order using priority scheduling matches much more closely the preferred order than does the FCFS order, the scheduled bank order does not precisely match the preferred order. Because the schedule must meet in-trail separation criteria at the runway threshold and the separation criteria are a function of both weight class and landing order, the preferred order of arrival is not always preserved at the runway.

Figure 1 shows the resulting OD for banks of aircraft beginning at different points in the arrival rush. The average order deviation for the FCFS algorithm first increases and then decreases as the ETA_{FG} of the lead aircraft in the bank increases. The change in average OD for the FCFS schedule is due to changing traffic density and mixture in the arrival rush. As the traffic density increases (ETA are more closely spaced), a given arrival error will cause larger position shifts within a bank and thus larger ODs. By the same token, the traffic mix impacts the OD because if non-AAL/EGF flights are interspersed among the bank aircraft, the aircraft comprising the bank will be spaced farther apart. Then, for a given arrival error, the OD for the bank will be smaller because the aircraft are not as closely spaced. The average OD for the priority-scheduling algorithm also varies with traffic density and mixture and is most effective in a region where some non-AAL/EGF aircraft are interspersed among the bank aircraft.

The effects of AAR, bank size, and Center arrival error on the success of the priority-scheduling algorithm are also examined. For the sake of brevity, no plots are shown, but important results are summarized here. Results show that for a given Center arrival error and bank size, the priority OD tends to decrease with decreasing AAR, meaning that the priority-scheduling algorithm is more effective for a more restrictive AAR. This is actually a characteristic of both the priority scheduler and the FCFS scheduler, and it can be shown that, for a lower AAR, either scheduler is better able to preserve the order in which the aircraft are scheduled. Lowering the AAR effectively reduces the airport capacity (because demand remains constant), requiring that the STAs be spaced farther apart. Because the STAs must be spaced farther apart, differences in crossing times or separation criteria are less likely to cause the resulting order to deviate from the order in which the aircraft are scheduled. Therefore, the resulting schedule for either algorithm will more closely match the sequence in which the aircraft are scheduled. Results also show that increasing the size of the bank of aircraft does not significantly impact the effectiveness of the scheduling algorithm. However, increasing the magnitude of the Center arrival error for a given bank size and AAR does lead to a decrease in the effectiveness of the priority-scheduling algorithm.

For purposes of illustration, Fig. 2 is a histogram of the position shifts for the bank whose lead aircraft has the earliest ETA_{FG} shown in Fig. 1. This histogram, along with the pair of corresponding OD values in Fig. 1, demonstrate the relationship between average OD and the closeness of the match between the scheduled bank order and the preferred arrival order. Priority scheduling reduces the spread of the position shifts for the designated bank of aircraft. In this case, aircraft belonging to the designated bank are scheduled in the preferred position (position shift = 0) approximately 60% of the time using priority scheduling. Using FCFS scheduling, bank aircraft are scheduled in the preferred position only about 25% of the time. The increase in the number of aircraft scheduled in the preferred position leads to a decrease in average OD for the bank.

The efficiency of the priority-scheduling algorithm is not measured in absolute terms, but is measured relative to the efficiency of the FCFS algorithm, which is considered to be a baseline. The change in average delay per aircraft when priority scheduling is used instead of FCFS scheduling can be measured as

$$\Delta_{\text{Delay}} = \left(\frac{\text{Delay}_{\text{Priority}} - \text{Delay}_{\text{FCFS}}}{\text{Delay}_{\text{FCFS}}} \right) \times 100\%$$

Figure 3 is a plot of the change in the average delay per aircraft for all aircraft in an arrival rush. For each designated arrival bank whose order deviation is shown in Fig. 1, a corresponding pair of points in Fig. 3 shows the change in average delay for the AAL/EGF aircraft in the arrival rush and for the non-AAL/EGF (others) aircraft in the arrival rush. Figure 3 shows that the change in delays due to priority scheduling varies with the position of the bank in the arrival rush and that the greatest delay increase occurs for a bank that starts near the beginning of the arrival rush. This is attributable to the changing traffic density and traffic mixture in the arrival rush and to all aircraft

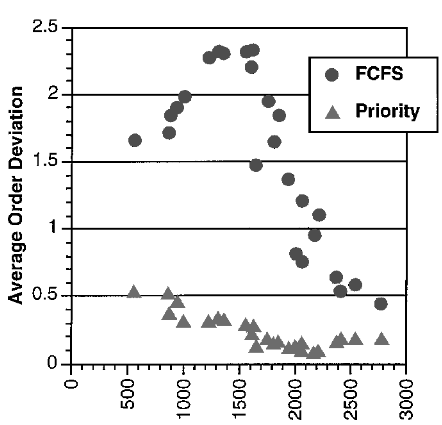

Fig. 1 Average order deviation (Center arrival error = ± 5 min).

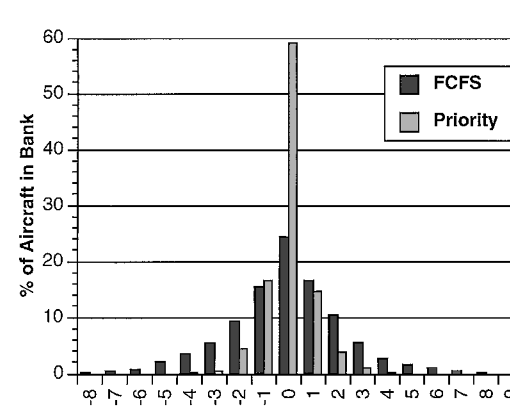

Fig. 2 Histogram of position shifts (Center arrival error = ± 5 min).

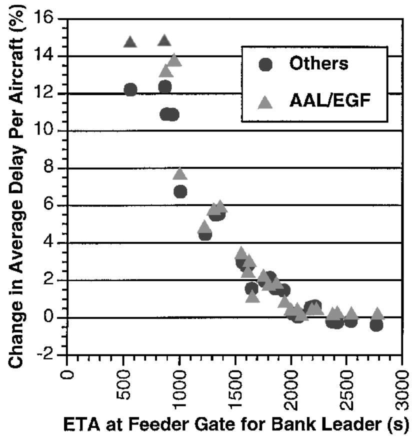

Fig. 3 Change in average delays per aircraft (Center arrival error = ± 5 min).

following the bank lead aircraft potentially being impacted by the reordering of the bank aircraft before scheduling. Because a larger number of aircraft may be impacted by the reordering, the aggregate increase in delays will be greater for a bank that begins earlier in the arrival rush. The average delay increase then diminishes as the ETA_{FG} of the lead bank aircraft increases, and priority scheduling in some instances actually results in a slight decrease in average delay per aircraft. The priority-scheduling algorithm has the smallest impact on scheduling efficiency in regions where arrivals are not closely spaced and banks have non-AAL/EGF flights interspersed among the bank aircraft.

A scheduling method that takes into account user preferences would ideally have no impact on scheduling efficiency when compared with FCFS scheduling. Figure 3 shows that for certain traffic conditions, the priority-scheduling method results in little or no decrease in scheduling efficiency; 18 of 25 banks scheduled had less than a 5% increase in average per aircraft delay. Although this simulation does not provide any information about the controller workload, it can be reasonably assumed that an increase in scheduled delays exceeding a certain threshold (when compared with FCFS scheduling) would be unacceptable to air traffic controllers because of the likely adverse effect on controller workload. Similarly, airlines would likely find an increase in scheduled delays exceeding a certain threshold (when compared with FCFS scheduling) to be unacceptable from the standpoint of increased cost. The amount of delay increase acceptable to controllers and airlines would have to be determined before a priority-scheduling method could be considered practicable. However, because the simulation results show that the priority-scheduling technique can in some instances equal the efficiency of the FCFS scheduler, the present simulation provides initial insight into the efficiency of priority scheduling and indicates that the technique warrants further investigation.

Any type of scheme that allows the introduction of user preferences into the arrival flow management process must ultimately be fair to all air carriers. In light of this, we are particularly interested in determining whether the priority scheduling of flights belonging to the airline whose flights are reordered disproportionately impacts the scheduled delays of aircraft belonging to other airlines. Examination of the delay increases for AAL/EGF flights in Fig. 3 shows that, for most of the banks, the delay increase for AAL/EGF flights in the arrival rush is greater than the delay increase for the non-AAL/EGF aircraft. In practice, an airline may be willing to accept increased delays on some flights if the early arrival of other flights can be achieved through reordering. Reordering only the aircraft belonging to the designated bank and scheduling all other aircraft according to an FCFS sequence minimizes the impact of reordering on both aircraft belonging to other airlines and on overall scheduling efficiency.

The effects of AAR, bank size, and Center arrival error on the change in scheduled delays are also examined. For a given bank size and Center arrival error, when priority scheduling is used instead of FCFS scheduling, the change in average delay per aircraft tends to increase as AAR is increased. Results are similar to those seen in Fig. 3 with the greatest change in delay occurring for banks that begin early in the arrival rush and the change in delays decreasing for banks that are positioned later in the arrival rush. Increasing the magnitude of the Center arrival error for a given bank size and AAR substantially increases the change in delays for banks of aircraft arriving early in the rush period, while not significantly impacting the change in delay for banks arriving later in the traffic period. Finally, results show that the change in delays due to priority scheduling is largely unaffected by an increase or decrease in the size of the arrival bank.

Conclusions

This paper investigates a method of scheduling a bank of arrival aircraft according to a preferred order of arrival instead of according to an FCFS sequence based on ETA at the runway. Fast-time simulation is used to evaluate the performance of the priority-scheduling method in terms of the algorithm's ability to produce a preferred order of arrival and in terms of its ability to minimize delays (scheduling efficiency). The output of the simulation is used to compare the performance of the priority-scheduling technique and the current CTAS FCFS scheduling technique. Although the determination of the operational feasibility of the priority-scheduling technique is beyond the scope of this paper, examination of scheduling efficiency is a crucial step in the determination of the operational viability of any CTAS-derived scheduling technique. Results show that compared with the FCFS algorithm, the priority-scheduling algorithm, for certain traffic conditions, produces a schedule that more closely matches a preferred order of arrival while nearly equaling the efficiency of the FCFS schedule, indicating that the method certainly warrants further investigation.

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