Airport '89: Simulation of Airport Scheduling

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Summary

Our goal is to determine the order to select aircraft for takeoff at an airport that has a limited number of departure slots in each interval of time.

Our model assigns to a pool of waiting flights all aircraft that have "pushed back" (indicated readiness to take off). Aircraft are selected for takeoff from this pool on the basis of priorities that are adjusted on a minute-to-minute basis. The model allows for great flexibility in determining priorities, based on scheduled and actual pushback times, number of passengers, plane size, and scheduled flight connections.

A number of prioritization schemes are simulated and compared to a simple first-come-first-served scheme, in terms of three different specific criteria based on traveler and airline satisfaction. Finally, the model as a whole is evaluated, and suggestions for modification and implementation are made.

1. Restatement of the Problem

Our task is to develop a queueing model to determine takeoff priority from an air traffic controller's perspective. The controller will have access to computer data about each plane, including the following items:

- the time scheduled for *pushback*, that is, the time when the plane is scheduled to taxi away from the terminal and enter the queue waiting for clearance to take off;

- the actual time when pushback occurs;

- the number of passengers on board the plane;
- the number of passengers who must make a connection at the next stop;
- the time that a passenger can be delayed at this end and still make the connection; and finally,
- the scheduled time of arrival.

A certain number of planes can take off from our airport in any given minute. If the number of pushed-back aircraft in the queue is less than or equal to this number, no decision must be made. If, however, the number in the queue is too large, a model for prioritizing the airplanes is needed. The criterion for this model is to be the maximization of both customer satisfaction and airline satisfaction.

2. Assumptions

We make a few simplifying assumptions, which we believe are reasonable in the light of the actual demands of an airport queueing situation. Among our assumptions are the following:

1. The number of passengers on a plane can range from a minimum of 50 to a maximum of 400, which is the capacity of the largest model aircraft our airport can accommodate. Further, the capacity of a plane is its actual number of passengers, rounded up to the nearest 50, within the limits of 100 to 400 specified by the problem. In other words, we are relying on the airlines to assign the most economical aircraft to each flight.

2. The airport has a capacity for a specific number of planes to take off per minute. This capacity depends on the number and configuration of runways and may vary with weather and other conditions.

3. For simplicity, in-flight times are definite (i.e., delays cannot be compensated for by faster flying). The in-flight time also includes the time from takeoff clearance to leaving the runway, and this delay will be essentially constant for all aircraft. The reported departure time is in

fact the time when the plane is given clearance to leave the queue for a runway.

4. A passenger who misses a connection can take the next flight to the final destination. We also assume that there are flights connecting most cities an average of every 4 hr, so the passenger will be 4 hr late to the final destination.

5. For simplicity, no flight has passengers who must make two or more different connections. Only one connecting time per flight is considered. Adjustments could be made in the model to account for further possibilities.

6. We define *customer satisfaction* as the total number of minutes a passenger is late to the destination. We assume that it does not matter to the customer whether the delay was spent waiting in the terminal or in the plane on the runway. Thus each flight is assigned a total number of passenger-minutes of lateness, depending on both how late it is and the number of passengers on board. When a connection is missed, all passengers missing a connection are deemed an extra 4 hr late.

7. The time allowances in our database for connecting flights are preadjusted for the necessary transfer times. This assumption seems as reasonable as building such an allowance into our model. We also assume that if a passenger arrives without enough time allowance, the connection will not be made; that is, there is no opportunity to make up time by motoring or hurdling through the terminal.

8. We do not adjust customer satisfaction for the nearness of missing a connection (i.e., an allowance for stress and worry). We do, however, assess those actual minutes that passengers are late to a connecting city, even if they make their connecting flights (and thus their final destinations) on time. We cannot know what a passenger might have planned during a scheduled layover, such as a meal or a quick meeting with friends. This allowance also compensates to some degree for aggravation and dissatisfaction of customers who have close calls.

9. Customer satisfaction is affected by the deviation from the mean waiting time. That is, overall customer satisfaction is

greater if all customers have similar delays than if most customers have slightly shorter delays but a few have extremely long delays. An alternative measure of customer satisfaction is computed to include this consideration.

10. Satisfaction, from the airlines'—as opposed to the passengers'—perspective, is defined in terms not of total delay but in time actually in the queue. Thus, if an aircraft is late in pushing back, the airline—not the model—is responsible. Delay times for determining airline satisfaction are therefore computed from *actual* pushback time rather than *scheduled* pushback time. We assume that actual pushback will never precede scheduled pushback. Also, it is reasonable that airlines are more concerned, from an economic perspective, with the size of the aircraft delayed than with the actual number of passengers on board; so aircraft size is substituted for number of passengers in computing airline satisfaction.

3. Analysis of the Problem

Our task is to design a model to determine the order in which aircraft ready for takeoff are granted access to a limited number of runways. The problem is similar to general queuing problems in computer science (ordering processing of jobs), operations research (allocation of production when demand exceeds capacity), and a great many other real-world domains.

We characterize the list of waiting aircraft as a *pool*, to which aircraft may be added or removed according to various criteria, rather than as a queue in the formal sense (which implies some notion of ordering dependent on time of entry). The pool is dynamic, in size and in composition. Each minute, a set number (the airport's capacity) of planes are removed by taking off; and at the same time, new planes are added.

Logically, a plane should not be added to the pool until it is capable of taking off immediately. Thus the act of "pushing back," or informing ground control that it is ready to leave the terminal, is conceptualized as equivalent to being added to the pool. Actual pushback, as opposed to scheduled pushback, must occur for the plane to be added to the pool.

Once the pool at a given minute is determined, two cases are possible. If the number of aircraft in the pool is less than or equal to the capacity of the airport to support takeoffs in a single minute (the *takeoff capacity*), all the aircraft are cleared for takeoff, and a prioritizing model is not necessary. If, however, there are more aircraft, a priority must somehow be assigned to each. Once priorities are assigned, a number (equal to the takeoff capacity) of aircraft in the pool with the highest priorities are selected for takeoff. The size of the pool is reduced by the takeoff capacity; but more aircraft may push back and enter the queue in the next minute, whereupon priorities must be recomputed for all aircraft in the pool, selections made, and the process repeated.

We consider methods for assigning priorities, with the goals of the model as the major consideration: the satisfaction of both the travelers and the airlines. We suggest two alternative definitions of passenger satisfaction. The basic definition of *passenger satisfaction* is simply total passenger-minutes of delay. To compute this measure, the number of passengers on an aircraft is multiplied by the total minutes that flight was delayed, with an additional 240 min added for each passenger who missed a connecting flight.

The *alternative definition of customer satisfaction* deals with the desire to keep the variation in delays between passengers at a minimum, by weighting longer delays more heavily. The basic number of passenger-minutes is computed as above; then, if the delay for a particular flight was greater than average, the passenger minutes for each flight are multiplied by the ratio of its delay to the average delay. For example, if the average aircraft is delayed 10 min, but one particular aircraft is delayed by 30, the ratio is 3, so each minute of delay is given a weight of 3. Thus 90 passenger-minutes of delay would be recorded for each traveler.

The rationale for this alternative definition is to penalize the model if planes with only a very few passengers have extremely long delays because they are repeatedly passed over by aircraft with larger passenger loads. Since some airlines specialize in small commuter planes with only a few passengers, this criterion could help to ensure the satisfaction of these airlines as well.

Airline satisfaction is determined by multiplying aircraft *capacity* (*not* actual number of passengers) by time in the pool (time from *actual* pushback to clearance for takeoff). There is no penalty for missed connections. We believe that especially long delays are a primary aspect of airline dissatisfaction, so we adjust the resulting figure by multiplying by the ratio of the experienced delay to the average delay, as we did in the alternative measure of customer satisfaction.

A good model will allow any number of schemes to be used to prioritize the planes in the waiting pool. Different schemes could place more emphasis on one measure of model success or another, depending on the purposes of the model's user. We have deemed it prudent not to prioritize or combine the three different measures of model success in any way, but rather to present the effects on all three of different priority-assigning schemes.

4. Model Design and Testing

The heart of our model is a Fortran program on a DEC VAX 8600, which executes the model as outlined above. The program accepts input from a file of scheduled flights. For each flight, the following information is included:

- the flight's scheduled pushback time,.
- the number of passengers on board,
- the time allowed for a connection to be made,
- the number of passengers who must make that connection,
- the scheduled time of arrival at the destination.

The actual pushback time is also included, but the program is designed (imitating reality) so that this information cannot be acted upon until after the pushback occurs. This piece of information is the only one that would not be known in advance in a real-life situation.

To test our model, we used a database of 1100 flights scheduled for pushback, generated according to a uniform distribution over a 4 hr period. Actual pushback was anywhere from 0 to 60 min after scheduled pushback, but was weighted toward shorter delays, so that 75% of flights pushed back within 15 min of the scheduled time. The number of passengers on a plane was uniform random between 50 and 400, and the number who had to make a connection was a uniform random proportion, between 0 and 0.75, of the total. The time allotted to make the connection was uniform random between 30 and 120 min, and the scheduled arrival time was uniform random between 75 and 135 min after pushback.

The program begins at time 0 with no planes in the pool. Planes are added as they push back and removed at a specified rate of takeoffs per minute. When all aircraft in the database have pushed back (after 4 hr, for our test data), the program continues until all flights have been assigned to runways.

The model allows varying the rate of takeoffs per minute, so it can be applied to different airports or adjusted for severe weather conditions. We considered 3, 4, and 5 takeoffs per minute. With our 1100-flight, 4-hour database, 5 takeoffs per minute corresponds to the airport operating slightly below capacity, as would be ideal under most circumstances; 4, to slightly above capacity, such as during peak hours of the day; and 3, to greatly above capacity, such as during a severe blizzard on a major holiday!

The program consists of a loop that is repeated every minute from the beginning of operation until the last plane has taken off. During each minute, the composition of the pool is determined by finding all aircraft that have pushed back but have not yet been assigned to a runway. A subroutine then assigns a priority, according to the designated method, to each plane in the pool.

The flexibility of the model lies in its ability to select any one of several subroutines and to create new ones for new schemes. After priorities are assigned, the appropriate number (3, 4, or 5, for our database) of aircraft with the highest priorities are selected for takeoff and removed from the pool. If several flights have equal priority (which is likely to occur if simpler schemes are used, such as first-come-first-served), the program takes those with the lowest flight number. This practice is reasonable, because ties are unlikely in real life, where pushback times would vary by seconds, and because the flight numbers are assigned at random within the program anyway.

When all flights have taken off, the program reports on the three criteria of success: total passenger-minutes of delay; weighted passenger-minutes of delay; and number of minutes per aircraft seat spent in the queue (airline satisfaction criterion).

5. Schemes for Priorities

The program was first executed using the *first-come-first-served* method of assigning priorities, described in the original problem.

The second scheme, *the passenger-minutes-late scheme*, defines priority simply as the product of the number of passengers on a plane and the minutes that it was currently late, based on its scheduled pushback time. No allowance is made for connections or for actual pushback time.

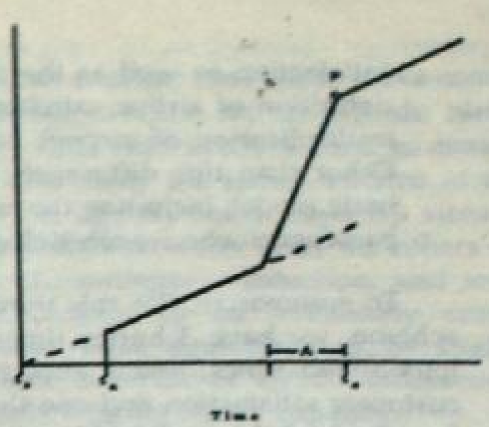
With a third scheme, our primary prioritizing system, we begin to introduce greater complexity, in an attempt to meet the demands of our various criteria. This scheme, the *multiparametric prioritizing scheme*, determines a flight's priority as a function of time according to a sequence of considerations (see **Figure 1**).

In the first minutes after the plane pushes back (enters the pool), its priority is determined as in the simple second scheme, by multiplying the time elapsed since scheduled pushback by the number of passengers on the plane. Thus, the flight's priority increases at a gradual rate the longer it waits in the pool.

However, as the time nears when some passengers may miss a connection, the priority begins to increase more rapidly. The point toward which the priority is increasing (point P in Figure 1) is the number of passenger-minutes of delay when the flight must leave in order for the connection to be made (t_C) plus a correction of 240 passenger-minutes for each passenger who must make the connection. The priority continues to increase along this line until time t_C is reached. Then the priority reverts to increasing at the rate at which it did in the early stages of the aircraft's wait, exactly the rate at which the customers' satisfaction is decreasing (passenger-minutes are increasing). Thus, the priority returned by this scheme is a measure of the amount of customer dissatisfaction that will occur if the plane does not take off at the given time.

Within the basic outline of this scheme, there are a number of parameters that can be varied:

1. *Buffer time*. The interval before t_C when the steeper increase in priority begins (length A in Figure 1) can be varied, in order to determine how far ahead of time imminent missed connections should be taken into consideration. We expected that the busier the airport, the greater this buffer time must be. We tested three settings of this parameter. The first was $A = 1$ min, or simply not taking a scheduled connection into account until it is absolutely imminent. The other settings we used were 5 min and 10 min buffer times.



t_s : scheduled pushback time
t_a : actual pushback time
t_c : time by which flight must leave to make connection

Figure 1. Basic multiparametric prioritizing scheme.

2. *Passenger size increment.* We allow the user to adjust the passenger size by incrementing it by the same constant for each plane. This option is included in an effort to reduce the variability in waiting times between passengers (weighted definition of customer satisfaction). Otherwise, a plane with very few passengers might never build up a high enough priority to get off the ground. We tested the model with increments of 0 and 250. Thus, with 0 increment, a plane with 400 passengers is a whole order of magnitude greater in passenger size than one with 50; with an increment of 250, their adjusted values are 300 and 650 respectively, and no plane will ever have a much more than twice the adjusted passenger size of any other.

3. *Look-ahead times.* The model allows the user to calculate priorities based not only on the current minute but on an aggregate of the current and a given number of future minutes. The priorities that will exist at each of these times are computed and simply added to obtain the final priority. In our test of the model, we set this parameter to 0 min (priority based only on current conditions), 4 min, and 10 min. This variation was designed to ensure even better that planes with connections take off in time to make them.

4. *Including airline satisfaction.* Finally, we allow the basic model to be altered to take into consideration the airlines'

satisfaction as well as the travelers'. Consistent with our definition of airline satisfaction, priorities are based on a multiplication of aircraft capacity and time in the pool. Other than this difference, the model is the same as the basic model, including the ramping up of priority for those passengers who are scheduled to make a connection.

To summarize: For this third scheme, the multiparametric scheme, we have 3 buffer times, 2 passenger-size weights, 3 look-ahead times, and 2 subschemes, one oriented solely to customer satisfaction and one that includes airline satisfaction, for a $3 \times 2 \times 3 \times 2$ model and a total of 36 cases.

Together with the first two schemes described above, the standard first-come-first-served scheme and the simple passenger-minutes-late scheme, we have a grand total of 38 cases. Each was used to determine flight priorities for the exact same database of 1100 flights. Each was combined with each of the 3-, 4-, and 5-takeoff-per-minute conditions as well, making a total of 114 executions of the program. A number of other parameter settings were investigated as well, but only those that appeared most interesting are reported.

6. Results and Discussion

Our computations yielded a great deal of data. Each of the 114 program executions can be evaluated in terms of three different success criteria, so a great many comparisons between schemes can be made. We summarize these results and direct attention to noteworthy effects and trends. [EDITOR'S NOTE: For space reasons, an appendix of 7 intricate tables is omitted].

First, in the slightly-below-capacity (5-takeoffs-per-minute) condition, there is no real difference, across all schemes and cases, in terms of the first passenger satisfaction criterion. For the alternative passenger satisfaction criterion, slightly worse than the rest are first-come-first-served and the variations of the multiparametric model that include airline satisfaction. (In terms of airline satisfaction, these two perform appreciably *better* than the rest, as expected.)

6.1. Effects of Airport Condition

For the other two airport conditions (slightly above capacity and greatly above capacity) first-come-first-served (which does not consider time left to make connections) and the multiparametric scheme set to include airline satisfaction (which *does* take into account time to make a connection) performe‹ essentially the same ‹n terms of all three criteria, just ‹ for the slightly-below-capacity situation. These two schemes tended to be worse than the others in terms of both definitions ‹f passenger satisfaction, and worse in terms of airline sati‹faction in an extremely congested airport. However, they were equivalent to, or slightly better than, other schemes in terms of airline satisfaction in an airport operating only slightly above capacity.

The simple passenger-minutes-late scheme resembled the multiparametric scheme.

6.2. Effects of Parameters

We now examine the effects of varying the parameters of the multiparametric model.

Buffer time. Varying the buffer time did not appear to have any impact on any of the three criteria (except for an extremely congested airport with priority set toward airline satisfaction, which was significantly worse than other cases).

Passenger size increment. Adding a constant to passenger sizes helps smaller flights, and the alternative passenger satisfaction criterion was formulated to detect small planes that are repeatedly passed over; so we would expect incrementing to help in terms of this criterion, but to be a hindrance in terms of the original passenger satisfaction criterion. The latter satisfaction was indeed considerably higher when incrementing was not used; but in the greatly congested airport, the alternative satisfaction was also higher, although the gap was somewhat smaller. Only in the less crowded airport was the desired effect seen, and then the differences may have been too small to be conclusive. In the slightly congested airport, incrementing passenger size caused more missed connections, but reduced by half the number of passengers late to their destinations by more than an hour. Overall, passenger size incrementing was some hindrance in overcrowded situations, and not overly beneficial otherwise.

Look-ahead times. In general, look-ahead times made no difference, although there was a slight trend for adjusted passenger satisfaction to increase with longer look-ahead times. Paradoxically, while our measures of satisfaction did not vary greatly with this parameter, significantly more passengers had to wait more than one hour when *greater* look-ahead times were used.

Airline satisfaction. When airline satisfaction was included, results resembled simple first-come-first-served queue. Other trends noted above, including differences dependent on passenger size incrementing, did not appear. Across different levels of airport congestion, we find some surprising results: When the airport is congested, the airlines' satisfaction is greater for the multiparametric method set for *passenger* satisfaction alone than when set to include airline satisfaction. Such is not the case for the slightly congested airport, however; in this case, the airlines' satisfaction is about the same as, or very slightly better than, when the airline satisfaction is included. Countering this fact, however, is that passenger satisfaction goes down significantly.

Interaction effects. A number of interesting interactions appeared between parameters. Measures of airline satisfaction tend to increase with increasing look-ahead times when passenger size is incremented, but decrease as look-ahead times increase when passenger size is not weighted.

The best setting of parameters in the multiparametric model seems to be a buffer time of 10 min, a look-ahead time of 4 min, and no passenger-size incrementing (especially in the more congested airport situations).

6.3. Recommendations

Incrementing the passenger size is ineffective—in fact, a hindrance in most cases, especially in high congestion.

In low congestion there is little difference among methods of assigning priorities. Therefore, scheme selection should be based on performance under congested conditions. In practice, it may be most feasible to use the least complicated method (first-come-first-served).

Finally, the multiparametric model set for just passenger satisfaction performs as well as or better than when set to include airline satisfaction. It also performs much better than the first two schemes, which do not take into account time left to make connections.

We conclude that the multiparametric model, set for passenger satisfaction, is the best of our methods for congested airports.

7. Suggested Modifications

Our model could be developed further. One enhancement would be a thorough statistical analysis of our data, to determine formally the strength and significance of the various effects we have reported.

Additional prioritization schemes could be investigated. One that we believe has some promise is similar to our multiparametric scheme but with the following variation: After a connection has been missed by a waiting flight, the flight's priority drops to the level it would be at had no adjustment for the connection been made. We assume that once a connection has been missed, the satisfaction of the passengers will be low anyway; so reducing this flight's priority might allow other flights with slightly lower priorities to make their connections, and the overall average delay per passenger could be less.

The results of computer analysis of this variation for a limited number of parameter combinations suggest a number of trends. As with other schemes, greater satisfaction was achieved when passenger size was not incremented. In selected cases, this method achieved slightly better passenger satisfaction than other schemes we tested; but overall, the other methods were superior.

8. Strengths and Weaknesses

The primary weakness of our effort is that the parameter settings are somewhat arbitrary, as is the very nature of the parameters we chose. Our model was able to assess the prioritization schemes we tested, in light of any given criteria; but better schemes may exist. However, it is not the particular schemes tested, but the method of implementing the priorities determined by the various schemes, which constitutes the heart of the model.

Another potential weakness is that for a majority of the prioritizing schemes examined, the need of passengers to make a connection is not considered until relatively soon before it may be too late. Our model may have a tendency to cause flights to wait until the last possible moment before taking off, and some passengers may be quite dissatisfied with nearly missing a connection.

The model has a few minor weaknesses as well. For example, the program is set up so that the number of flights that may leave the airport in a single minute must be an integer value. This shortcoming could be avoided through minor reworking of the model, by increasing the length of each discrete unit of time from one minute to the denominator of the non-integral flights-per-minute value. Also, as noted before, our model allows only one connecting flight per originating flight. The program could easily be modified to deal with additional connections. Finally, the inflexibility of our assumptions does not allow for certain natural variation, such as in time spent on the runway.

The greatest strength of our model is its flexibility. Not only were we able to test 114 variations in priority schemes in a short time; but any number of conceivable additional schemes could easily be incorporated into the model, tested, and compared.

In addition, its basic relation to queueing theory would allow our model to be applied to other conceptually related problems entirely outside the realm of air transportation.

Another important strength is our model's computation of not one but three different measures of success in terms of the criteria of passenger and airline satisfaction. We allow the model's users to set their own priorities in terms of these measures of success, and to pick and choose from among the several schemes we have examined and any others they may want to add. New criteria of success could be developed, or the three measures we treat could be differentially weighted.

The model is also valuable because it demonstrates that different schemes may be preferable at different times, depending upon how congested the airport is. In addition, the model is readily adaptable for use at any size airport.

Finally, the computer program we developed could be adapted, with only minor changes, to go beyond recommendation of specific schemes to actual implementation of those schemes. The program could be incorporated directly into the control tower information system; at any time, it could provide personnel with a list of planes designated for runway assignment. Of course, personnel could override these recommendations, in emergencies or other irregular situations.