Cost Minimization of Providing a Wheelchair Escort Service

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Summary

Epsilon Airlines provides a wheelchair escort service to passengers who require aid. We use an optimized earliest-due-date-first (EDD) algorithm to minimize the overall cost. Our algorithm is broad enough to accommodate various airport concourses, flight schedules, and flight delays. In addition, it allows for wheelchair escorts to perform other tasks beneficial to the airline, such as provide information at a kiosk, to help reduce the overall cost. Moreover, it creates schedules for each employee.

A naive strategy would be to employ the minimum number of escorts to guarantee that all passengers reach their gates on time. We show that this strategy is not optimal but can be improved by assigning different numbers of escorts to shifts based on expected traffic. For example, if Delta Airlines were to utilize the naive strategy at Atlanta International Airport, the cost would be over \$5 million/yr, whereas our strategy reduces this cost to under \$4 million/yr. A similar reduction in cost could be expected for Epsilon Airlines.

Assumptions

- The original problem can be adequately modeled with a numerical simulation that uses a discrete time step Δt and discrete length step Δd, provided that Δt, Δd are small compared to actual dimensions.
- The layout of the airport concourse(s) is known, along with positions of gates. The concourse(s) can be on one or two levels.

The UMAP Journal 27 (3) (2006) 387–398.

- There is a kiosk or information desk in the concourse that can communicate with escorts, for example, by using walkie-talkies.
- The movement of escorts is constrained to a rectangular lattice.
- The escort transports a wheelchair passenger *(WP)* from an incoming flight gate to a connecting flight gate.
- The number of WPs on a flight is small compared to the total number of passengers on the flight [Backman et al. 2004]. This assumption allows for tracking individual passengers rather than flights.
- Most WPs are known to the airline in advance, but some arrive unexpectedly.
- Both incoming flights and connecting flights can be delayed.
- When escorting a WP, the wheelchair and the escort stay together.
- An unoccupied escort performs another job (such as providing information at the information desk) [Backman et al. 2004].
- The goal is to minimize the cost of escorting WPs.

Approach

Our objective is to provide cost-minimizing staffing and inventory recommendations, as well as an algorithm to generate optimal schedules for wheelchair escorts.

We model the geometry of the airport and simulate arriving and departing WPs according to a fixed schedule. We add unscheduled WP arrivals and allow for random unscheduled flight delays. We set out rules to govern the behavior of an escort at each time step throughout their shift. These rules are comparisons between choices that the escort can make; the algorithm predicts which choice will result in the least cost to the airline, based on an objective cost function.

Formulating the Optimization Criteria

The costs of operating an escort service are associated with:

- flight delays due to WPs arriving late to connecting flights;
- WPs having to wait for service (i.e., long-term decrease in ticket sales as a result of damage to airline reputation);
- employing escorts;

- depreciation, maintenance, and storage of wheelchairs; and
- reassigning idle employees to alternative tasks (a "negative cost").

We adopt the following notation, where the length of one time step Δt in the simulation is 1 min:

$$
\begin{aligned}
w &= \text{number of escorts on the shift} \\
T &= \text{length of a single shift (min)} \\
K &= \text{wage of a worker (\$/min)} \\
W_0 &= \text{costs associated with wheelchairs} \\
\omega(t) &= \text{number of escorts employed at an alternative job at time } t. \\
\psi(t_{\text{fd}}) &= \text{number of flights delayed } t_{fd} \text{ min} \\
c_\psi(t_{\text{fd}}) &= \text{cost associated with delaying a flight by } t_{\text{fd}} \text{ min (\$)} \\
\phi(t_{\text{pw}}) &= \text{number of WPs made to wait } t_{\text{pw}} \text{ min for an escort.} \\
c_\phi(t_{\text{pw}}) &= \text{cost associated with having a passenger wait } t_{\text{pw}} \text{ min (\$)}
\end{aligned}
$$

Quantities are measured at discrete points in time (at each minute). We can now mathematically express the costs listed above:

$$\text{Flight Delay Cost} = \sum_{t_{\text{fd}}=1}^{\infty} \psi(t_{\text{fd}})\, c_\psi(t_{\text{fd}}), \tag{1}$$

$$\text{Passenger Waiting Cost} = \sum_{t_{\text{pw}}=1}^{\infty} \phi(t_{\text{pw}})\, c_\phi(t_{\text{pw}}), \tag{2}$$

$$\text{Employment Cost} = wKT, \tag{3}$$

$$\text{Wheelchair Cost} = W_0. \tag{4}$$

Note that W_0 depends only on the airport and the number and type of wheelchairs, so is constant with respect to the number of escorts on a particular shift, which can be varied.

Multitasking Employees

A key feature of our model is that we allow employees to take on a secondary task. This task can be any other job the escort can perform when not actively assisting a WP, such as providing information at a kiosk. This cuts down on inefficiency associated with low volume points during a shift.

Guided by microeconomic theory, we assume that the extra benefit to the airline from adding a worker to perform a task is inversely proportional to the number of workers already contributing to that task [Wikipedia 2006a]. Mathematically, this implies that the benefit from n employees performing a certain task is approximately proportional to $\ln(n+1)$. Since the airline would have to hire another worker to perform this secondary task if no escorts were available, the benefit to the airline from a single employee working a secondary job should equal the employee's wage. This implies that the net negative cost for a single shift is

$$\frac{-K}{\ln 2}\sum_{t=0}^{T}\ln\big(\omega(t)+1\big). \tag{5}$$

Assumptions About Waiting Costs

We assume that the average total cost associated with delaying a flight is \$44/min, and the average total cost associated with delaying a single passenger is approximately \$0.25/min [Federal Aviation Administration 2000]. Since the marginal cost of waiting an additional minute independent of the total delay, it follows that

$$c_\varphi\left(t_{\text{pw}}\right)=0.25t_{\text{pw}}, \qquad c_\psi\left(t_{\text{fd}}\right)=44t_{\text{fd}}.$$

Since the expression $\psi(t_{\text{fd}})t_{fd}$ is the sum of the delay times of all planes delayed exactly t_{fd} minutes, the aggregate flight delay time is

$$T_{\text{fd}}=\sum_{t_{\text{fd}}=1}^{\infty}\psi(t_{\text{fd}})t_{\text{fd}}.$$

Similarly, the aggregate passenger wait time is

$$T_{\text{pw}}=\sum_{t_{\text{pw}}=1}^{\infty}\phi(t_{\text{pw}})t_{\text{pw}}.$$

These gives alternative expressions for the costs defined in **(1)** and **(2)**,

$$\text{Flight Delay Cost}=44T_{\text{fd}}, \qquad \text{Passenger Waiting Cost}=0.25T_{\text{pw}}.$$

The Cost Function for a Shift

Combining the results in **(1)–(5)**, the total cost is

$$C=44T_{\text{fd}}+0.25T_{\text{pw}}+wKT+W_0-\frac{K}{\ln 2}\sum_{t=0}^{T}\ln\big(\omega(t)+1\big).$$

The Cost Function for the Year

The objective is to minimize cost not only on a day-to-day basis, but also over the entire year. We assume that each of the 1,095 8-hour shifts during a year fall into one of the three following categories of air traffic:

- Light: These are the shifts from 4 P.M. to 12 A.M. and from 12 A.M. to 8 A.M. on days of the year in the bottom 90% (329 days) of air traffic days. These shifts comprise 60% (657) of all 1095 shifts during the year. We estimate that mean traffic on these days is approximately one-half of total mean traffic.
- Heavy: We define these shifts as the top 10% 8-hour shifts by air traffic (top 110 shifts). We estimate that these shifts have a mean traffic 2.5 times total mean traffic.
- Medium: Those shifts not falling under the above two definitions (328 remaining shifts). We estimate that these shifts have a mean traffic 1.5 times total mean traffic.

The cost function for the year is a weighted sum of the cost functions for each type of day, which we denote as C_l, C_m, C_h for light, medium, and heavy traffic days:

$$C_{\text{annual}} = 657C_l + 328C_m + 110C_h. \tag{6}$$

Algorithm Implementation

We implement an algorithm that dynamically assigns escorts. The overall behavior is depicted in the flow chart on page 392. The algorithm is divided into six main parts.

Input

The algorithm requires the layout of the concourse(s) and the flight schedule of known WPs. The layout of the concourse(s) includes the positions of the information kiosk, the arrival and departure gates, and an elevator if the concourse has two floors. The flight schedule includes the incoming and connecting flight gates and times.

Main Simulation Loop

In each time step the algorithm queues WPs, assigns escorts, and moves escorts to their optimum destinations.

Queueing WPs

The first task of the algorithm is to consider the possibility of the arrival of an unexpected WP. The average number of unexpected arrivals is taken to be a fixed percentage of the number of expected WPs, which can be specified in the algorithm; we take it to be 5%.

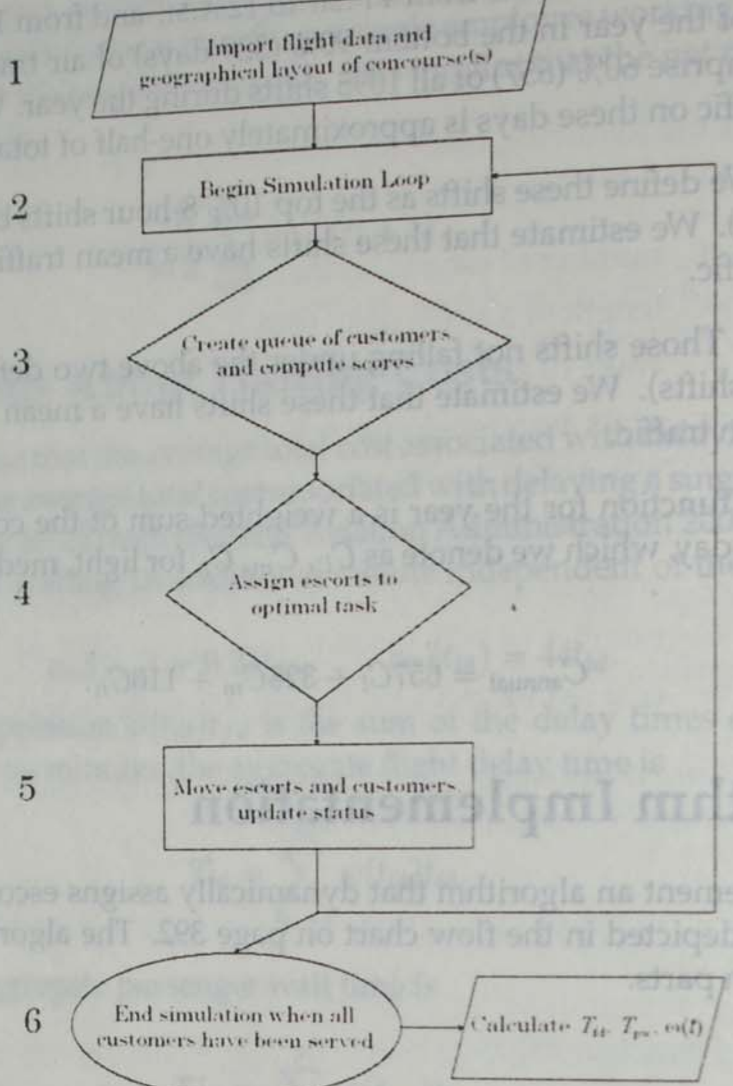

Figure 1. Flow chart outlining the algorithm used in the numerical simulations. The output of the simulation gives the aggregate flight delay time T_{fd}, the aggregate passenger waiting time T_{pw}, and $\omega(t)$, the number of escorts employed in an alternative job at time t.

Each WP (previously known or new) is assigned a score, the amount of time before their connecting flight departs. The algorithm then reorders the queue, inserting newly-known WPs who have not yet been assigned an escort. WPs with a lower score are served first. This score function reduces the total flight delay time t_{fd} as much as possible, since this is the most costly delay for the airline.

Escort Assignment

The nearest available escort is assigned to the WP at the head of the queue using the "city block" distance $|\Delta x| + |\Delta y|$ instead of the Euclidean distance $\sqrt{(\Delta x)^2 + (\Delta y)^2}$.

An escort assigned to a WP may be able to return to (or remain at) the information kiosk and perform an alternative job for some time before picking up the assigned WP.

Motion and Status of Escorts

After the assignment of escorts, escorts who are not at their destination are moved toward it. In each time step Δt, an escort can move one lattice distance Δd. This defines a natural speed, $\Delta d/\Delta t$. We take $\Delta t = 1$ min and the speed of escorts to be 2.5 feet/second (reasonable, considering that a concourse may have obstacles including other passengers). It follows that $\Delta d = 150$ ft.

When an escort reaches the incoming or connecting gate for a WP, the escort's status is updated accordingly.

However, when an escort reaches the incoming flight gate of a WP, the WP may not have arrived yet. We denote the probability of a flight being delayed by p_{delay}; in fact, $p_{\text{delay}} \approx 0.29$ [Mueller and Chatterji 2002]. For delayed flights, we take the length of the delay to be distributed exponentially [Wikipedia 2006b].

Output

The main simulation loop continues until all WPs on the input flight schedule have been escorted to connecting flights. Once this condition is met, the algorithm outputs the aggregate WP waiting time T_{pw}, aggregate flight delay time T_{fd} caused by a WP not arriving for their connecting flight on time, and $\omega(t)$, the number of escorts employed in an alternative task at time t.

Case Studies

We did case studies of Delta Airlines concourses in three airports; O'Hare International Airport (Chicago, IL), John F. Kennedy International Airport (New York, NY), and Atlanta International Airport (Atlanta, GA).

We take the wage of an escort to be $K = \$3.50$/h, an average of the \$7/h paid by some airlines and \$0 paid to volunteers.

In each case study, we generated a simulated schedule of passengers over an 8-h shift that approximates the actual frequency of incoming and connecting Delta Airlines flights in each airport [City of Chicago 2005; Schumacher 1999]. Using the mean time interval between arrivals and departures, the airline's number of terminals, and the number of planned passengers from airline flight and concourse data, we modeled the number of expected WP arrivals per interval as a Poisson process. Unexpected WPs are not included in this schedule, but are accounted for in the simulation. Also, passengers are assumed to connect to Delta Airlines flights, which allows for analysis of the Delta Airlines concourse in isolation.

For each airport, we obtained satellite images of the concourse(s) from Google Earth in order to find distances between gates and kiosks. We found gate information at Delta Airlines' Website [2006]. We translated this information into a grid layout of the concourse, to serve as input to the simulation. Gates much less than the lattice spacing ($\Delta d = 150$ ft) apart are assigned a common point on this grid. For the JFK concourse, a point was also assigned for an elevator; this concourse has arrivals and departures on different floors, so every route from an arrival gate to a departure gate includes a trip on the elevator (assumed to take one time step $\Delta t = 1$ min).

JFK International Airport

For a medium-size two-concourse airport terminal, we consider the Delta Airlines concourses at JFK International Airport, with 20 gates. The low, medium, and high traffic flows are 10, 30, and 50 incoming flights per 8-h period [Delta Airlines 2006]. Even though the JFK concourses are larger than those at O'Hare, many fewer Delta Airlines planes fly into JFK than into O'Hare. The predicted cost of numbers of escorts for these 8-h shifts are shown in **Figure 2**. The costs for small numbers of escorts are astronomically high because of the cost of delayed planes and missed flights, since there are too few escorts for the demand.

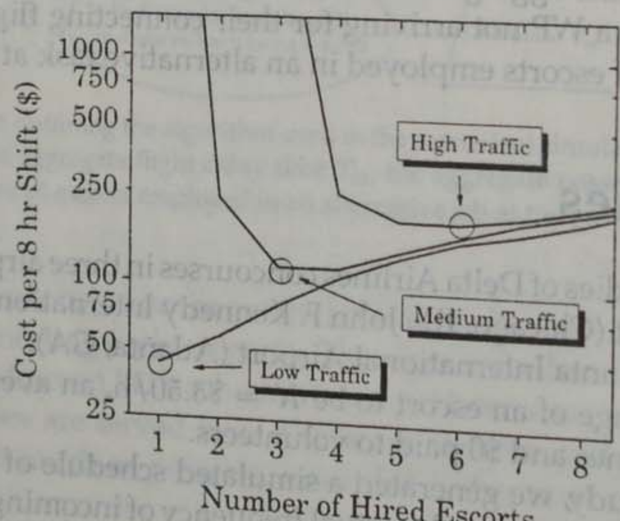

Figure 2. Simulated cost curves under low, medium, and high traffic flow in 2005 for the Delta Airlines JFK International Airport concourses.

The least-cost numbers of escorts for each traffic flow rate are 1, 3, and 6, at costs \$40, \$115, and \$190 per shift. From **(6)**, the minimum total annual cost of escorts is \$121,000.

O'Hare International Airport

The Delta Airlines concourse at O'Hare International Airport has only five main gate areas. The low, medium, and high traffic flows are 43, 129, and 215 incoming flights per 8-h period [Delta Airlines 2006]. The predicted cost of numbers of escorts for these 8-h shifts are shown in **Figure 3**.

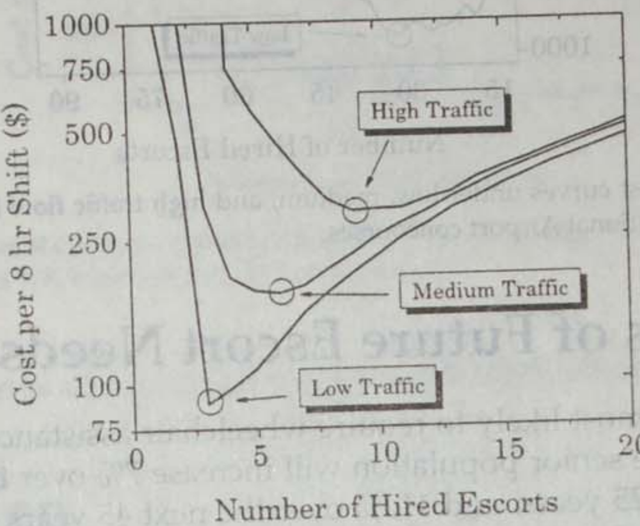

Figure 3. Simulated cost curves under low, medium, and high traffic flow in 2005 for the Delta Airlines Chicago O'Hare concourse.

The least-cost numbers of escorts for each traffic flow rate are 3, 6, and 9, at costs $90, $180, and $300 per shift. From **(6)**, the minimum total annual cost of escorts is $152,000.

Atlanta International Airport

Delta Airlines has its headquarters in Atlanta, with a large four-concourse terminal with 20 main gate areas. Even though JFK has the same number of gates, the gates in Atlanta are spread much farther apart and handle much more traffic. The low, medium, and high traffic flows are 107, 321, and 535 incoming flights per 8-h period [Delta Airlines 2006] The predicted cost of numbers of escorts for these 8-h shifts are shown in **Figure 4**.

The least-cost numbers of escorts are 32, 40, and 70, at costs of $1,180, $3,880, and $6,430 per shift. From **(6)**, the minimum total annual cost is $3,977,000. This figure is much larger than for O'Hare or JFK because the concourses at Atlanta are roughly four times as large and handle between three and ten times the traffic of the other airports. The main component of the cost for Atlanta is the cost of flight delays. To compensate for the larger concourses, we set the average time between connecting flights in Atlanta to 75 min (in agreement with actual flight schedules), as opposed to 45 min for the other airports.

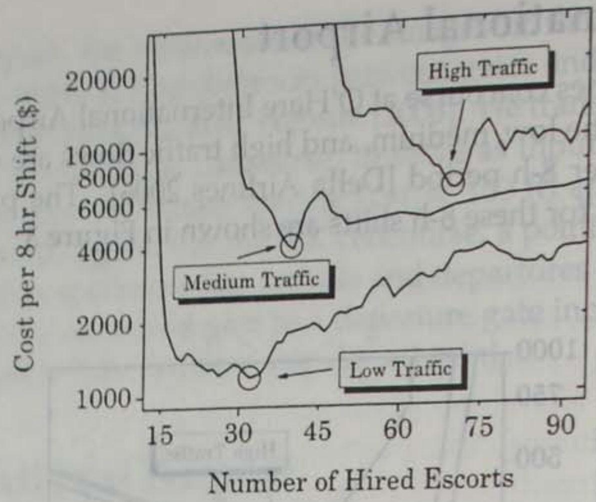

Figure 4. Simulated cost curves under low, medium, and high traffic flow in 2005 for the Delta Airlines Atlanta International Airport concourses.

Predictions of Future Escort Needs

Those who are most likely to require wheelchair assistance at airports are senior citizens. The senior population will increase 7% over the next 5 years, 87% over the next 25 years, and 112% over the next 45 years [Department of Health and Human Services 2006]. Assuming that flying patterns for this age group remain unchanged, and that the layout of airports does not significantly change, our algorithm can predict the change in cost to the airline. The number of flight arrivals to the JFK Delta concourse under medium traffic will increase from 50 to about 100 over the next 30 years. Using our simulation, we find that the optimal number of escorts will increase from 6 to 9, with a corresponding increase $600 per 8-h shift. These results are depicted in **Figure 5**, with predictions of costs also for low traffic and high traffic.

Model Strengths and Weaknesses

- The simplicity of the model makes it very versatile. Parameters such as the layout, the speed of WP and escort, costs, and other parameters can be specified with minimal modifications to the algorithm.
- Simulation times are quite small for even the busiest airport.
- The lattice and the use of a "city block" distance is more natural and realistic for the interior of buildings.
- The algorithm is simple and intuitive, making it easy to communicate and justify.

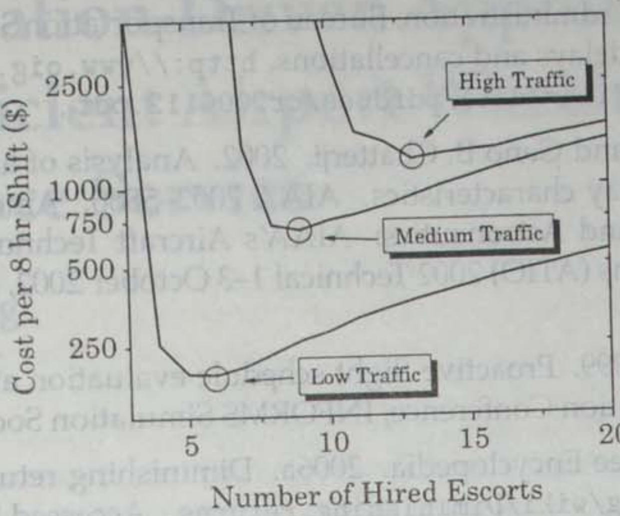

Figure 5. Simulated cost curves under predicted future low, medium, and high traffic flows in 2036 for the Delta Airlines JFK International Airport concourses.

- The algorithm is also practical, outputting a schedule for each escort.

Conclusion

We have presented a systematic study of how to administer a wheelchair escort service at the least cost to an airline. Our algorithm can predict the costs under different concourse layouts, flight schedules, arrival of unexpected WPs, flight delays, and reallocation of escorts to a secondary task to reduce cost. We applied our approach and presented results for case studies of Delta Airlines terminals in Chicago, New York, and Atlanta.

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