Operational Research for Wheelchair Service Provided by Epsilon Airlines

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1   Introduction

For many people, air travel is the safest, easiest, and quickest means of long distance travel. Wheelchair handicapped citizens, however, can encounter hardship when traveling by air, because of the need to travel quickly between gates in order to make connecting flights despite their impairments. Airlines provide escorts and wheelchairs to passengers transferring between flights if they request wheelchair assistance. There are two favorable features of this service. Firstly, it makes traversing large airport terminals easier for people with walking disabilities. Secondly, it cuts down on departure delay, the largest cost related to passengers, because wheelchairs would aid passengers in moving at a faster speed than they normally would.

   As a consultant group, it is our task to predict and minimize the cost of implementing such a wheelchair service in an airport. In minimizing cost, we determine a policy for scheduling escorts and managing wheelchairs in the short term and long term.

1.1   Mathematical approach- Operational Research

The closest mathematics applicable to our problem is Operational Research. Operations Research is:

> the attack of modern science on complex problems arising in the direction and management of large systems of men, machines, materials, and money... [by developing] a scientific model of the system, incorporating measurements of factors such as chance and risk, in order to predict and compare the outcomes of alternative decisions, strategies, and controls. The purpose is to help management to determine its policy and actions scientifically [ref].

   Even though operations research is well defined, it is heavily dependent on the system being worked with. There are common tools to deal with purely linear systems or dynamic systems, but they only give example based strategies [4]. Unfortunately, we were unable to find a previously developed system that was analogous to an airport. Thus, we developed our airport system from scratch, but develop a strategy to solve the problem using operation research as inspiration.

1.2   Strategy

Before we start optimizing cost, we have to model the airport system. This involves three separate components:

- Elements that contribute to total monetary cost

- Physical airport layout

- Wheelchair passenger distributions throughout the airport with respect to time

After these are done being modeled, we can start analyzing the cost equation. This will be a complicated equation that will have many dependent factors. We will analyze these dependencies and impose conditions, defined by the airport system, with the hope that some may be simplified with little effect on accuracy. We will then start developing approximate solutions to estimate the total cost, and develop policies minimizing this cost.

1.3   Requirements of a good model

A good model should meet these requirements:

1. It has an optimal cost in terms of number of escorts, number of wheelchairs, and policy for managing them.

2. It produces a policy that is easy to follow by escorts.

3. Its cost will be stable in extreme scenarios.

4. It is easy to implement and provides tangible long term improvement.

2   Cost

- **Key Point:** Having identified the components of the cost, we can develop an expression for the total monetary cost of airline wheelchair operations – the quantity which we want to develop a policy to minimize.

There are five distinct monetary costs that determines the necessary budget for the wheelchair service. The costs are:

- Wheelchairs repair and replacement

- Renting storage rooms for wheelchairs

- Liability of unstored wheelchairs

- Employment of escorts for disabled passengers

- Delay in aircraft departure due to lateness of passengers with wheelchairs

In order to define cost, we have to have some sense of what our airport is going to be. As will explain in the next section, we model the airport as a graph $G(V, L)$ where V is the set of vertexes representing gates in an airport and L is the set of lines connecting gates, representing hallways in a concourse. The geometry of the resulting graph models accurately the concourses in an airport. At any particular time, on any particular vertex, there will be a certain number of preoccupied escorts, unoccupied escorts, available wheelchairs, unavailable wheelchairs, amount of storage, and scheduled and unscheduled passengers in need of wheelchair assistance.

2.1   Elements of Cost

To model these costs, we look at:

- E, the total number of escorts at the airport at some time

- W, the total number of wheelchairs at the airport

- w, the amount of wheelchairs not in storage

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- S, number of storage rooms

- D_p, The amount of delay per passenger

- k_1 the cost of a single escort per unit time

- k_2, the cost of repairing and maintaining wheelchairs per unit time

- k_3, the cost of a single storage room per unit of time

- k_4, the cost of unstored wheelchairs due to liability per unit time

- k_5, the cost of delay per unit time

2.2 Total Cost Equation

The total cost over a set period of time, C, to implement wheelchair service to passengers is given by the sum of the individual costs over the same period of time:

$$C = k_1 E + k_2 W + k_3 w + k_4 S + \sum_{p \in P} (k_5 D_p).$$

(P is the set of all passengers)
The rest of this paper's goal minimize C over the span of the whole day.

3 Airport

- **Key Point:** Our model of airport operations gives us the distances and travel times needed to calculate the movement component of the total cost.

We model the airport based solely on its physical features. We can define four general structures any airport has: Each airport has some number of terminals, each terminal has some configuration of concourses, and each concourse is comprised of gates that lie on the perimeter of the structure. The only relevant features are the gates, the paths between gates, and the location of wheelchair storage facilities.

3.1 Terminals

Let us first analyze terminals. By looking at various international airports (Chicago O'Hare , Seattle-Tacoma, Miami, Frankfurt, Pittsburgh, and Denver) we see that they accommodate a wide variety of airlines.

International airports, which are always large, usually have three terminals. Each terminal serves mixed international and domestic flights. Domestic airports have only one terminal (Albuquerque Airport, Spokane Airport).

3.2   Concourses and Five Modeled Configurations

First, we note by analyzing the above mentioned airports, that a single airline company controls certain gates. These gates tend to be clustered. In some instances, a single airline controls an entire concourse (Miami International, for example), in which case it is called a hub. However, most airlines only control only a few gates in a concourse. We consider both situations: Airlines with few gates (on the order of 4 or 5), and many (on the order of 20).

Now, let us focus on the possible arrangements of concourses in a terminal. An airport terminal is divided into four categories: pier, satellite, semicircular, and mobile lounge terminals. Most airports use some combination of pier and satellite configurations: Chicago O'Hare, (Pier and Satellite), Seattle-Tacoma (Pier and Satellite), Miami (Pier), Frankfurt (Pier), Pittsburgh (Satellite), and Denver (Satellite), for examples. The other categories are less popular, and thus not considered in this model.

To get a variety of airports, we model airports with various configurations of terminals with different numbers of total concourses.

- One Concourse

    - Single satellite with gates on one side

- Two Concourses

    - Pier configuration of a branching concourse with gates all around

    - Satellite configuration with gates along one side of one satellite and all around the other.

- Four Concourses

    - Pier Configuration with four branches

    - Satellite Configuration with four parallel satellites

3.3   Distances Between Gates

The distance between neighboring gates is fixed by the minimum separation between parked airplines, so it is directly related to wingspan. For simplicity, we assume all airplanes are the same size and use the average wingspan of several common aircraft at international airports. Also, at each airport discussed above, each concourse has roughly the same number of gates (close to 20). This allows us to approximate the length of the concourse and approximate the distance an escort will need to travel to get from one gate to another.

Table 1.

Airplane	Wingspan (meters)	Capacity		Airplane	Wingspan (meters)	Capacity
757-200	38	228		L1011-1	47	350
757-300	38	289		DC10-10	50	375
767-200	48	285		777-200	61	420
767-300	48	325		747-100	60	505

The average wingspan of these aircraft is slightly below 50 meters. Thus we take the average gate separation to be 50 meters.

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3.4　Airport Size and Configuration Affect on Cost

The reason we are modeling the physical airport is to get distances escorts will need to travel in order to get a passenger from their arrival gate to their departure gate. This will give us an idea of how many escorts are needed in order to get every passenger to their gate in a reasonable amount of time. A reasonable amount of time will be defined later. We can use distance to each gate to decide where to put wheelchair storage (the ideal location will minimize the average amount of time needed to reach any gate in a single concourse).

3.5　Epsilon Airline Location

Since Epsilon Airlines only services their own customers, we know which gates escorts need to be near in order to receive passengers. What is unknown, however, is where the departure gates are. Without any specific information to the contrary, we assume that any gate in a terminal has the same probability. We do not include gates outside of the terminal of arrival.

　　We make the assumption that Epsilon Airlines controls the gates on the end of a concourse. This is so that the average distance to a gate is the largest possible value, and thus we deliberately overestimate the average time it takes for an escort to get to any gate in the terminal.

3.6　Escort Walking Distances for Modeled Airport Configurations

Using distances between gates for five different airport configurations, and the average speed of a walker (1.3 meters a second), we compute the average time it takes to traverse the terminal (from arrival gate to departure gate). We get the following results:

Table 2.

Configuration	Time		Configuration	Time
Single concourse	5 min.		Four pier Concourse	15 min
Two Pier Concourse	10 min.		Four satellite Concourse	20 min
Two satellite Concourse	15 min			

4　Passengers

- **Key Point:** Knowing the expected number of disabled passengers and the pattern of flight arrivals and departures throughout the day, along with what we know about the airport already, we can determine the delay component of the total cost.

　　Here we model the distribution passengers that arrive at the Epsilon Airlines gates throughout the day at an airport. This will give us how busy the escort service will be- which will help us in estimating the number of wheelchairs required and the number of escorts required at any given point in the day.

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4.1 Percentage of transferring passengers that require wheelchair assistance

We assume the distribution of passengers in need of assistance is proportional to ratio of wheelchair disabled individuals to the whole population, suppose airline passengers are no more or less likely to be wheelchair disabled than any other people. The current population of America is estimated to be 300 million people, and the estimated number of people that require wheelchairs is estimated to be 1.6 million [ref's]. This indicates that 0.53% percent of American aircraft passengers require wheelchair assistance. We assume this percentage is fixed for the global population.

Out of these .53% passengers, 1/3 of them will transfer. Thus, 0.18% of all transferring passengers will wheelchair assistance.

4.2 Predicted vs. Unpredicted Passengers requiring wheelchairs

There are two types of passengers we model that require wheelchairs: passengers that request wheelchair assistance well in advance, and passengers that request assistance a few minutes before reaching the arrival gate. From the view of escorts, these passengers are predicted and unpredicted, respectively. We have no estimate as to the average ratio of the two. Therefore, later in the paper, we will consider both extremes: all predicted, and all unpredicted.

4.3 Departure Delay Cost

Departure delay is the biggest factor in cost, but it is also a hard value to calculate. It is possible to find reliable immediate monetary loss estimates, but including long-term elements, like service record and reliability, are much harder to estimate. The most reliable estimate for the total monetary loss states that it costs approx. 1€ ($1.20) per minute for the first fifteen minutes, and then 84 € ($100.10) per minute for any time after fifteen minutes [ref].

4.4 Distribution of Transition Time Lengths

Inherent to the flight arrival and departure times, there is a distribution to how long passengers have to wait for an aircraft. The timeframe each passenger has to get to their gate restricts service times of escorts since a late arrival of a passenger delays the departure time of an aircraft.

4.5 Busyness of gates throughout the day

We use activity levels at check-in desks for each day of the week (Figure XXXXX) to approximate the distribution for the overall activity level of the airport, and therefore the frequency of passenger arrival.

This has a couple notable features that we will use. We see that the airports receives most traffic between the early morning and the late evening. During this time, there is an unsteady decline in passengers.

Now we estimate the maximum number of passengers that require assistance in an hour. We assume that a flight, with an average of 450 passengers (from table 1), arrives and departs

within the smallest period in our distribution of transition times, which is 30 minutes, and immediately after departure, another plane arrives, creating the largest volume of passengers possible that arrive at a gate. In section 4.1 we determined the percentage of passengers that require wheelchair assistance (0.18%). Thus, out of the 450 passengers on a flight, we expect there to be 450*.0018=0.8 passengers that require assistance per half hour, or 1.6 passengers per hour. This computation was for one gate. To get total passengers requiring assistance for all gates controlled by an airline, we multiply by the amount of gates they control. So, if the airport is not a hub for this airline, we expect that 4*1.6=6.4 passengers will require assistance per hour. If it is a hub, we expect 20*1.6= 32 passengers will require assistance per hour. All our other values have had time units of minutes, there we phrase our final result in those units also.

- At an airport where Epsilon Airlines does not have a hub, there are 0.11 passengers per minute arriving at peak times.

- At an airport where Epsilon Airlines has a hub, there are 0.53 passengers per minute that arrive at peak hours.

From figure XXXXXXXXX we know that the least busy period will be 1/2 as busy as the peak time. Therefore:

- At an airport where Epsilon Airlines does not have a hub, there are 0.06 passengers per minute arriving at off-peak times.

- At an airport where Epsilon Airlines has a hub, there are 0.27 passengers per minute that arrive at off-peak hours.

5   Wheelchairs

- **Key Point:** Most costs associated with wheelchairs don't depend on particular policy choices, so they can be safely excluded from cost calculations.

The number of wheelchairs required at a particular time depends on the number of escorts needed at a particular time. Since the number of wheelchairs remains constant throughout the day, we need to make sure there are enough for the entire day. Thus the minimum number of wheelchairs required will be close to the maximum number of escorts during peak hours. Otherwise, during peak hours the escorts without wheelchairs will be useless. As a consequence, the number of wheelchairs is always greater than or equal to the number of escorts.

5.1   Cost of Repairing and Replacing Wheelchairs

A closer look at the cost equation reveals that the number of wheelchairs affects only the repair and replacement cost of wheelchairs and the cost of liability for unstored wheelchairs. Notice that the frequency of repair and replacement for a wheelchair is only proportional to the use of the wheelchair, which is based solely on how many passengers request wheelchair service. So if there are only a few wheelchairs, they will be worn out faster, creating a

higher frequency for replacement. However, if there are many wheelchair, the wear on an individual wheelchair will be less, but the wheelchairs will not have to be replaced as often. So, it is easily argued that maintaining many wheelchairs cost the same as maintaining few wheelchairs when you average over a long period of time. Thus,

$$A = k_2 W$$

where A is a constant.

Now we give a reasonable value for A above. Searching the internet, we estimate that a cheap, but sturdy wheelchair costs around $300, such as the "Nova 307/309 Transport Wheelchair". We estimate that a single wheelchair will last one year before it is in need of repair, and that it can be repaired a maximum of three times. We estimate that it will cost $50 to repair one wheelchair, based on typical labor costs for repair services. Therefore, in a three year period, one wheelchair will cost around $450. This amounts to 5×10^{-5} dollars a minute for each wheelchair. Now we multiply by the average number of wheelchairs constantly in use to get total cost of wheelchairs per minute, which is approximately 6.4 passengers per hour, or 32 passengers per hour, (.11 passengers per minute and .53 passengers per minute respectively) from section . This eliminates one element of cost in our cost function when trying to find an optimal cost.

5.2   Cost of unstored Wheelchairs

The cost of unstored wheelchairs due to liability is the most intangible and unpredictable monetary value of all the factors that affect total cost. There is only one way we can see that unstored wheelchairs affect cost - lawsuits due to personal injury of passengers. However, we have nowhere to begin in estimating how much these law suits will cost much less the frequency of them. We can disregard this factor if we impose a policy that maximizes storage of wheelchairs when not in use.

6   Storage

6.1   Storage Room Cost

Another cost associated with wheelchairs is storage, which can also be simplified greatly. For a short-term policy we cannot control storage. However, for the long term, we can specify where storage should be created in order to decrease the size of unstored wheelchairs (if it will decrease total cost).

Here, we assume each storage room is a humble size of $6x4$ ft. Thus, given the wheelchair specified above, with dimensions (.75 w x 4 h x 1.5 d) ft^3 when folded, we can store two rows of wheelchairs on top of each other and two rows of wheelchairs next to each other on the ground, where each row contains 8 wheelchairs. Thus we can store an estimated $8 * 2 * 2 = 32$ wheelchairs in one storage room.

We also do not have any information on the price of using storage. In effect, the airline is renting this space from the airline in the same way a person rents an apartment. Therefore we assume, under the realization that we have no better approach, that the cost of renting this room is the same as renting an apartment. By looking at a variety of single room

apartments, we get an average of $400 a month. Thus, $k_4 = \$0.009$ per minute, where k_4 is defined in the the section titled "cost".

7 Escorts

- **Key Point:** We can now develop a simple policy for optimal allocation and movement of escorts to minimize total cost.

7.1 Quick Review of Accomplishments So Far

Up until this point we have been simplifying the cost equation as much as possible. In all, we have already modeled three of the five terms. Through argument, we have deduced that k_2W is a factor that we cannot change- it only depends on the amount of use of a wheelchair which happens to be uncontrollable. We have deduced a value of k_4 on a flaky (but reasonably so), analogy between using storage and renting apartments. We deduced that in order for k_4 to be nearly zero, we must impose a policy that minimizes the amount of unused, unstored wheelchairs. Thus, the amount of storage, S, will have to be adequate to store all the wheelchairs (Approx $32 * S >= W$). Finally, we have concluded that $W >= max(E)$.

7.2 Estimating Necessary Number of Escorts

In this section, we will get an estimate on the number of escorts required in order to minimize the cost between escort salary and departure delay cost. We will make arguments, based mostly on policy considerations that will give us a range of final costs.

Firstly, it is easy to estimate the salary, k_1, of a single escort. It will be in the vicinity of $8.00 and hour, or $.13 a minute.

The number of escorts that need to work will be proportional to both the distance the passengers need to travel and on the number of passengers that need wheelchair assistance. There will be a certain number of wheelchair users that will be registered ahead of schedule, but then there are going to be a certain number that will not be. The total number of these passengers will be directly proportional to how busy the airport is at that time. We have already computed that a busy schedule is where .11 passengers per flight arrive at an airport per minute if the airport is not a hub, and .53 passengers per flight if it is a hub.

7.2.1 First Approximation

Let us look at the most basic case to estimate the maximum number of escorts needed-which does not necessarily reflect most optimal cost. Consider the case where there are as many escorts as the amount of passengers that require assistance during the span of time it takes a single escort to escort a passenger across the airport. Therefore, no passenger will have to wait for assistance because there is an escort available to help (assuming an available escort is nearby). In this way, there will be absolutely no flight delay since the passenger is assumed to be able to get to the location on time if they do not have to wait (otherwise the scheduling would be unreasonable). This assumes that the distribution of escorts will be roughly constant throughout the distribution of gates Epsilon Airlines controls.

7.2.2 Effect of First Approximation on Cost in an airport withOUT an Epsilon Airlines hub

If the airport is not a hub for Epsilon Airlines, then satisfying the first approximation is absolutely arbitrary- just have all escorts and wheelchair near the four gates. Ideally, wheelchair storage will be within a minute or two walking distance way.

Now we compute the number of needed escorts for this approximation. The average walking time for an escort is either 5, 10, 15, or 20 minutes one way dependent on which configuration the terminal is in. We know the escort will have to make a round trip to get back to the Epsilon Airline gates. Thus the time a single escort is away will be double the numbers given above. We multiply this number by how many require help per minute(=.11). Thus the number of escorts needed during peak times is 1.1, 2.2, 3.3, and 4.4 respectively.

We are given that the number of wheelchairs must be greater than the number of escorts at peak time. Thus we need 2, 3, 4, and 5 wheelchairs. Each of these fits into a single storage room, thus there is not need for more than one room. Calculating cost for all three of these situations we get:

$$C_1 = .13(1.1) + .00032(2) + .009(1) + 0 = \$0.15 \text{per minute}$$

$$C_2 = .13(2.2) + .00032(3) + .009(1) + 0 = \$0.30 \text{per minute}$$

$$C_3 = .13(3.3) + .00032(4) + .009(1) + 0 = \$0.44 \text{per minute}$$

$$C_4 = .13(4.4) + .00032(5) + .009(1) + 0 = \$0.58 \text{per minute}$$

Now, the cost per minute for low number of passengers (0.06) gives the number escorts to be .60, 1.2, 1.8, and 2.4 respectively:

$$C_1 = .13(.60) + .00032(2) + .009(1) + 0 = \$0.087 \text{per minute}$$

$$C_2 = .13(1.2) + .00032(3) + .009(1) + 0 = \$0.17 \text{per minute}$$

$$C_3 = .13(1.8) + .00032(4) + .009(1) + 0 = \$0.24 \text{per minute}$$

$$C_4 = .13(2.4) + .00032(5) + .009(1) + 0 = \$0.32 \text{per minute}$$

Now, to a relatively good approximation, we can average the two costs for each configuration of airport and multiply by the operational hour of the day given by figure XXXXXXX (approx 15 hours a day), and then by how many days in a year to get the budget required for a year. The annual costs are:

$$C_1 = \$62,000$$

$$C_2 = \$120,000$$

$$C_3 = \$180,000$$

$$C_4 = \$240,000$$

7.2.3 Effect of First Approximation on Cost in an airport WITH an Epsilon Airlines hub

We the same method as above, except that we use a different value for peak passenger arrival rate and low passenger arrival rate (.53 and .27 respectively).

We get the following equations:

-Peak

$$C_1 = .13(5.3) + .00032(6) + .009(2) + 0 = \$0.71 \text{ per minute}$$

$$C_2 = .13(10.6) + .00032(11) + .009(2) + 0 = \$1.40 \text{ per minute}$$

$$C_3 = .13(15.9) + .00032(16) + .009(2) + 0 = \$2.09 \text{ per minute}$$

$$C_4 = .13(21.2) + .00032(22) + .009(2) + 0 = \$2.78 \text{ per minute}$$

-Low

$$C_1 = .13(2.7) + .00032(6) + .009(2) + 0 = \$0.37 \text{ per minute}$$

$$C_2 = .13(5.4) + .00032(11) + .009(2) + 0 = \$0.72 \text{ per minute}$$

$$C_3 = .13(8.1) + .00032(16) + .009(2) + 0 = \$1.08 \text{ per minute}$$

$$C_4 = .13(10.8) + .00032(22) + .009(2) + 0 = \$1.43 \text{ per minute}$$

This gives us a annual cost of:

$$C_1 = \$280,000$$

$$C_2 = \$560,000$$

$$C_3 = \$830,000$$

$$C_4 = \$1,100,000$$

7.2.4 Second Approximation- the most accurate and optimal cost

Just by looking at the costs, it is clear that the majority of the budget for the wheelchair service pays the salaries of the escorts. One easy argument can be made to show that this is not optimal: not every passenger needs to get to their gate without a waiting period since their flights do not necessarily leave right away. So, decreasing the number of escorts by a certain amount has no consequence, assuming that escorts attend to the most needy passengers first. However, there is no change in distribution of passengers.

Looking at the figure for transfer time, we see that only a rare amount of passengers have flights that leave within 50 minutes of there arrival time, and a majority of them leave after an hour or more the time they arrive at the airport. Since it takes an average of 10, 20, 30, and 40 minutes, depending on concourse configuration, for an escort to serve an individual, we can argue that the single concourse terminal has to only hire 10/50 of the original escorts, the two pier terminal can hire 20/50 of the original escorts, the two satellite and four pier terminals can higher 30/50 of the original escorts, and the four satellite terminal configuration airport need to higher 40/50 of the original escorts.

Thus, the annual costs for airports without a hub are:

$$C_1 = \$12,000$$

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$$C_2 = \$48,000$$
$$C_3 = \$110,000$$
$$C_4 = \$190,000$$

and with a hub:

$$C_1 = \$79,000$$
$$C_2 = \$220,000$$
$$C_3 = \$490,000$$
$$C_4 = \$870,000.$$

8 Conclusion

Since we do not know which terminal configuration this model is going to apply to, we conclude that the maximum cost for an airport with a hub is $870,000 and for an airport without a hub is $190,000 annually.

This is a relatively good model because it produces a policy that is easy to follow. Escorts simply evenly distribute themselves around gates that are controlled by Epsilon Airlines. If the airport is a hub for this airline, then the escorts distribute themselves around storage rooms so they quickly get wheelchairs from storage on que.

The model does have its share of problems. Many of the statistics were impossible to find, so they had to be approximated. In these cases, we had nothing to compare to verify the reasonableness of our assumptions. This exemplified by our estimate for the cost of a 6x4 ft^2 storage facility. If more information was provided to us by Epsilon Airlines, many of these problems could be remedied.

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