AN OPTIMIZATION MODEL FOR THE EXPANSION OF AN AIRPORT NETWORK

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ABSTRACT

Air transport has been growing at a fast pace for several decades. This has led to severe airport congestion problems everywhere in the world and, particularly, in the largest airports. In the short term, these problems can be dealt with through demand management measures. However, in the long run, they will be difficult to address without building new airports and/or expanding the capacity of existing airports. In this article, we introduce an optimization model aimed at helping air transport authorities in making these types of decisions. The model assists in determining the expansion actions to apply to a network of airports, while complying with a given budget. The objective is to maximize the total revenue passenger kilometers traveled within the airport network, taking into account the capacity of the airports and the impact of travel costs upon demand. The type of results that can be obtained through the application of the model is illustrated for a small size network.

Keywords: Airports, Capacity Expansion, Air Transportation, Optimization Model.

INTRODUCTION

Air traffic has grown at an average annual rate of more than 4.0 percent over the last three decades, giving an important contribution to the development of the world economy (Ishutkina and Hansman, 2009). In recent years, the growth rate has been clearly above average. Between 2003 and 2007, passenger traffic increased from 1.7 to 2.3 billion, that is, almost 6.0 percent per year on average (ATAG, 2008). Cargo traffic has also increased, but at the smaller rate of 3.5 percent.

The increase in air traffic has not been matched by an adequate expansion of airport infrastructure, and has been accompanied with the multiplication of airport congestion episodes. The number of delayed flights has been augmenting every year. For example, in the United States, and despite the increase of scheduled travel times, the percentage of late arrivals grew from 16.5 to 25.3 between 2003 and 2007 (BTS, 2009). The equivalent figures for Europe are 19.9 and 22.7, respectively (AEA, 2009). The incidence of flight delays is especially important in some of the largest airports (over 40 percent of late arrivals at JFK, Heathrow, Newark, etc.).

Airport congestion problems can be and are being dealt with at various levels (air transportation authorities, airports, airlines) and in many different forms (Hamzawi 1992, Forsyth 2007). In the short-term, demand management measures such as slot allocation systems and de-peaking practices can play an important role (Fan and Odoni, 2002). However, in the long term, air traffic can only keep growing at significant rates if the capacity of existing airports is expanded and/or new airports are built.

In this paper, we present an optimization model for assisting air transportation authorities in their strategic decisions regarding the expansion of the airport network of a country or a community of countries willing to coordinate their actions in respect to this type of infrastructure. The model determines in a comprehensive manner the best expansion actions to implement for each airport (or multi-airport system), while complying with a given budget. Expansion actions consist of increasing the number or changing the location of runways at existing airports, and of improving terminal buildings and apron areas. The objective is to maximize the total revenue passenger kilometers (RPK) traveled within the airport network, taking into account the capacity of the airports and the impact of travel costs upon demand.

We are well aware of the fact that the decision processes regarding the expansion of airports are extremely complex (see Mozdzanowska, 2008 for details about the USA). They involve a wide variety of stakeholders – including airport administrations, local governments, and non-governmental organizations – capable of influencing decisions to some extent, but the final choices are to be made by air transportation authorities (and, ultimately, by state or federal governments). These choices are expected (required) by the public to be the best possible, but they are too complex to be made and explained without appropriate decision-aid tools. The model presented in this paper is, in our opinion, an example of such tools.

The paper is organized as follows. We start with a brief overview of the literature on airport capacity expansion and related fields. Afterward, we present the optimization model developed to address airport network expansion problems and describe the heuristic algorithm used to deal with it. The type of results that can be expected from the application of the model is then illustrated for a small-size airport network. Next, we provide information on model solving issues. In the final section, we summarize the model and indicate directions for future research.

LITERATURE OVERVIEW

There is a significant body of literature dedicated to airport capacity expansion. This literature focus mainly on two broad subjects: airport expansion economics and airport site selection. The key contributions to the former subject are surveyed in Cohen and Coughlin (2003). They primarily consist of general, theoretical principles to be taken into account when making decisions on the expansion of individual airports. The airport site selection problems dealt with in the literature usually involve the comparison of alternative locations for building a new airport in a given region. Two types of techniques are typically used for this purpose – cost-benefit analysis (see e.g. Cohen 1997, and Jorge and De Rus 2004) and multi-criteria analysis (see e.g. Paelinck 1977, Min 1994, Min et al. 1997, and Vreeker et al. 2002).

In contrast, the literature dealing with airport expansion and/or location problems at the network level is extremely meager. This is especially true for the optimization-based literature. Indeed, to our best knowledge, Saatcioglu (1982) is the only article published in leading journals where an optimization model is applied to help determine the best locations and capacities for a set of airports. However, it is a simplistic, p-median model which does not capture the specificities of airport networks. Ferrar (1974) and Janic (2003) are two other articles where optimization models are applied to airport networks, but they focus on the utilization of existing airport capacity rather than on capacity expansion.

The lack of specific literature on optimization-based airport network expansion is partly compensated with the abundance of literature on related, well-established subjects, and particularly on the following three areas: facility location (Daskin 1955, ReVelle and Eiselt 2005), capacity expansion (Luss 1982, Van Mieghem 2003), and network design (Yang and Bell 1998). The work carried out within these areas with regard to hub location models (Campbell et al. 2002), multi-region capacity expansion models (Fong and Srinivasan 1981), location-routing models (Min et al. 1998), and combined facility location/network design models (Melkote and Daskin 2001), is especially relevant for the study of airport network expansion problems. But it does not properly address the full set of features that characterize these problems.

OPTIMIZATION MODEL

The model developed to represent the problem faced by air transportation authorities when making decisions regarding the long-term expansion of an airport network applies to a given set of airports (or multi-airport systems), $\boldsymbol{N} = \{1, \ldots, N\}$, of known initial (declared) capacities, $s_j > 0$, $j \in \boldsymbol{N}$.

The set of possible expansion actions applicable to airport j is $\boldsymbol{M}_j$. The capacity increase in airport j associated with expansion action m is g_{jm}. Therefore, assuming that at most one action will be applied to an airport within the period under consideration, the future capacity of airport j, z_j, is given by:

$$z_j = s_j + \sum_{m \in \mathbf{M}_j} g_{jm} \, y_{jm}, \forall j \in \mathbf{N} \tag{1}$$

$$\sum_{m \in \mathbf{M}_j} y_{jm} \leq 1, \forall j \in \mathbf{N} \tag{2}$$

where y_{jm} is a binary variable equal to one if action m is applied to airport j and equal to zero otherwise.

The expenditure associated with the application of action m to airport j is e_{jm}. The total expenditure must comply with the budget available for expansion actions, b. Therefore,

$$\sum_{j \in \mathbf{N}} \sum_{m \in \mathbf{M}_j} e_{jm} \, y_{jm} \leq b \tag{3}$$

The (future) capacity of airport j must be able to accommodate the traffic flow in the airport, w_j. That is,

$$z_j \geq w_j, \forall j \in \mathbf{N} \tag{4}$$

The traffic flow in airport j is obtained by adding the flows u_l for each flight leg l with endpoint at airport j, which, in turn, are obtained by adding the flows v_{jkr} on each possible flight route r between airports j and k where flight leg l is included. That is,

$$w_j = \sum_{l \in \mathbf{L}_j} u_l, \forall j \in \mathbf{N} \tag{5}$$

$$u_l = \sum_{j \in \mathbf{N}} \sum_{k \in \mathbf{N}} \sum_{r \in \mathbf{R}_l} v_{jkr}, \forall l \in \mathbf{L} \tag{6}$$

where $\boldsymbol{L}_j$ is the set of flight legs with endpoint at airport j and $\boldsymbol{R}_l$ is the set of flight routes that include flight leg l.

A flight leg will not exist unless there is a minimum level of traffic flow, u_{min}, to make it economically viable. That is,

$$u_l \geq u_{\min}, \forall l \in \mathbf{L} \tag{7}$$

The traffic flow on each route r connecting airports j and k is related with the total traffic flow between the airports, q_{jk}, and the travel costs paid by the passengers for each route, c_{jkr}, according to the following multinomial logit model (Ortúzar and Willumsen, 2001):

$$v_{jkr} = \frac{e^{-\gamma c_{jkr}}}{\sum_{p \in \mathbf{R}_{jk}} e^{-\gamma c_{jkp}}} \, q_{jk}, \; \forall j, k \in \mathbf{N}, r \in \mathbf{R}_{jk} \tag{8}$$

where $\boldsymbol{R}_{jk}$ is the set of routes connecting airports j and k, and γ is a calibration parameter.

The traffic flow between airports j and k depends on the size (mass) of the regions served by the airports, p_j and p_k, on the average air travel cost between the airports, c_{jk}, and on the competition from other modes connecting the regions where the airports are located, according to the following gravity-type demand function (Ortúzar and Willumsen, 2001):

$$q_{jk} = \alpha \left(p_j p_k\right)^{\mu} \phi_{jk}{}^{\varphi} c_{jk}{}^{-\beta}, \forall j, k \in \mathbf{N} \tag{9}$$

where ϕ_{jk} is a modal split factor that reflects the competition from other modes, and α, μ, φ, and β are statistical calibration parameters.

A possible, simple form for the modal split factor is:

$$\phi_{jk} = \begin{cases} 0 \Leftarrow d_{jk} \leq d_{jk_{\min}} \\ \dfrac{d_{jk} - d_{jk_{\min}}}{d_{jk_{\max}} - d_{jk_{\min}}} \Leftarrow d_{jk_{\max}} < d_{jk} < d_{jk_{\max}}, \forall j,k \in \mathbf{N} \\ 1 \Leftarrow d_{jk} \geq d_{jk_{\max}} \end{cases} \tag{10}$$

where $d_{jk_{\min}}$ is the distance between the regions of airports *j* and *k* above which some traffic is by air, and $d_{jk_{\max}}$ is the distance below which some traffic is by land.

The average air travel cost between airports *j* and *k* is given by

$$c_{jk} = \frac{\sum_{r \in \mathbf{R}_{jk}} c_{jkr} \, v_{jkr}}{q_{jk}}, \forall j,k \in \mathbf{N} \tag{11}$$

The air travel costs paid by passengers consist of ticket fares and time costs. Ticket fares are assumed to reflect the unit costs incurred by efficient airlines with fuel, crews, management, aircraft depreciation and maintenance, and airport charges, plus a “fair” profit. This assumption is consistent with the principle that, in the long term, under air space liberalization policies, inefficient airlines will be eliminated and efficient airlines will keep increasing the flights they offer until “unfair” profits are cancelled out. The ticket fare paid for a flight tends to increase with travel distance and, because of economies of scale, tends to decrease with traffic flow. Airport charges are assumed to reflect airport costs plus a “fair” profit, and may include congestion taxes. Airport costs tend to increase with the occupancy rate at airports (at least, above a given level of this rate), because congestion will make airport operations more expensive. Congestion taxes are levied by air transportation authorities to regulate the utilization of airports (in their absence, airports and/or airlines would be able to make “unfair” profits). The time cost of a trip is the value of the time spent on the flight (or flights) included in that trip and at airports (origin, destination, and possible hubs). The time spent on flights is approximately proportional to travel distance. A fraction of the time spent at airports is occupied with check-in, transfer, or baggage retrieval, in the origin, hub, or destination airport, respectively, and can be considered to have a fixed cost. The other fraction is occupied with waiting. The cost of waiting time tends to decrease with traffic flow, because flights can become more frequent as traffic flow increases, and tends to increase with the occupancy rate at the airports, because of congestion delays. Therefore, the air travel costs for each route *r* between airports *j* and *k* can be represented with the following general function:

$$c_{jkr} = \sum_{l \in \mathbf{L}_{jkr}} C_1(d_l, u_l) + \sum_{n \in \mathbf{N}_{jkr}} C_2\left(\frac{w_n}{z_n}\right) + f_n + x_n, \forall j,k \in \mathbf{N}, r \in \mathbf{R}_{jk}$$

with

$$\partial C_1 / \partial d_l > 0, \ \partial C_1 / \partial u_l < 0, \text{ and } dC_2 \Big/ d\frac{w_n}{z_n} > 0 \tag{12}$$

where d_l is the length of flight leg l, f_n is the fixed cost for the check-in, transfer, or baggage retrieval operations at airport n, w_n/z_n is the occupancy rate of airport n, w_n is the congestion tax for airport n, L_{jkr}, is the set of legs included in route r, and N_{jkr} is the set of airports included in route r.

The objective is to maximize the total RPK made within the airport network ("maximize demand coverage"). That is,

$$\max \sum_{j\in \mathbf{N}} \sum_{k\in \mathbf{N}} \sum_{r\in \mathbf{R}_{jk}} d_{jkr}\, v_{jkr} \tag{13}$$

where d_{jkr} is the distance between airports j and k through route r.

Expressions (1)-(13) define the model developed to represent the airport network expansion problems faced by air transportation authorities. It is a complex mixed-integer nonlinear optimization model. This kind of model is, in principle, extremely difficult (if not impossible) to solve to exact optimality, and has to be handled through heuristic algorithms even for moderate size real-world applications.

HEURISTIC ALGORITHM

For solving the complex model presented in the previous section we developed the following heuristic algorithm:

1. Set Iteration = 0
2. Set congestion taxes (x_j) equal to zero 0 (in expressions 12)
3. Calculate air travel costs (c_{jkr}) assuming $C_1(d_l,u_l) = C_1(d_l,0)$ and $C_2(w_j/z_j) = 0$ in expressions 12
4. Calculate the traffic flow for each pair of airports through the application of the travel demand model (9) and split traffic across possible routes using the multinomial logit model (8), using the current air travel costs
5. In consecutive iterations, using the successive average method (Ortúzar and Willumsen, 2001):

   (1) update air travel costs according to the flows on flight legs and the occupancy rate of airports

   (2) update the traffic flow for each pair of airports and split traffic across possible routes according to the new travel costs

   until convergence (that is, until the flows on the legs are the same in consecutive iterations, except for a small tolerance).

6. If the capacities of some airports are exceeded (i.e., if expressions 4 are not verified), determine through an iterative procedure the congestion taxes to apply in order to eliminate excess demand at airports. Return to 3.

7. If the minimum traffic flows on some flight legs are not attained (i.e., if expressions 7 are not verified), eliminate the flight leg with the lowest traffic flow and all flight routes where that leg is included. Return to 2.

8. Calculate the total RPK traveled within the airport network.

9. If Iteration > 0 or the total RPK traveled within the airport network increased in relation to the previous iteration then

   (1) set Iteration = Iteration + 1

   (2) determine through an iterative procedure the expansion action to apply in the airport network, checking whether the budget is not exceeded. Return to 2.

else stop.

The algorithm involves two (inner) iterative procedures in each (outer) iteration, one to determine the congestion taxes to apply and the other to establish the expansion actions to perform. In the current implementation, the former are calculated by successively increasing the congestion tax applied to the airport with the smallest positive excess demand of a given, small amount, until excess demand is eliminated from all airports. The latter are calculated according to a greedy, add plus interchange search approach. First, for all airports where congestion delays are observed, the one-level feasible expansion actions that allow the best improvement in the total RPK traveled in the network are successively applied, until no further RPK improvement is possible. Then, one-level feasible expansion actions are successively interchanged between airports, once again until no further RPK improvement is possible.

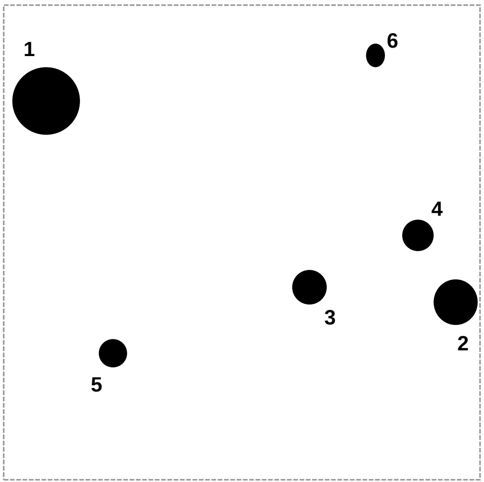
APPLICATION EXAMPLE

The type of results that can be obtained through the application of the optimization model will be illustrated for dataset #1 of the set of random instances generated to test the heuristic algorithm introduced in the previous section, considering a region with six population centers, each one served by an airport. The airports of the three largest centers are hubs. The initial capacity of the airports was determined by solving the optimization model without budget constraints, which means that it satisfies demand while maximizing the total RPK traveled within the network. It is therefore an equilibrium configuration that will tend to remain unchanged if nothing else changes (demand, costs, etc.). The application consists in determining the modifications that should be carried out in the airport network if the sizes of all population centers of the region increase by 25 percent. The modifications are calculated as a function of the budget allocated to airport expansion actions. Below we provide detailed information on the data used to run the model and on the results obtained through its application.

Data

The population centers served by the airports are randomly distributed over a square-shaped region with 4,000 × 4,000 km^2 (Figure 1). The sizes of the centers are equal to their populations, which were randomly determined to follow the Zipf rank-size rule considering the maximum population of 6 million for the largest center.

The airports have six possible layouts (multi-airport systems have not been considered). The possible airport layouts and the corresponding capacities are listed on Table 1. The airport expansion costs, which are the same for all airports, are shown on Table 2. The air travel demand function and the route choice logit model are defined by the parameters given in Table 3.



Population center	Population (10^6)
1	5.15
2	2.15
3	1.34
4	0.99
5	0.80
6	0.58

Figure 1: Location and size of population centers

Table 1: Airport Layouts and Capacities

Airport Layout	Capacity (10^3 pax/day)
1 - Single runway	40
2 - Two close parallel runways	60
3 - Two medium spaced parallel runways	70
4 - Two independent parallel runways	80
5 - Three runways (two close runways plus one)	100
6 - Four runways (two pairs of close parallel runways)	120

Table 2: Airport Expansion Costs

Initial airport layout	Costs (10^8 \$)					
	Final airport layout					
	1	2	3	4	5	6
1	-	6	8	9	12	14
2	-	-	5	6	9	11
3	-	-	-	4	7	9
4	-	-	-	-	6	8
5	-	-	-	-	-	5

Table 3: Demand Function and Logit Model Parameters

α	μ	$d_{\min}$ (km)	$d_{\max}$ (km)	φ	β	γ
2×10^{-5}	1.0	200	1000	1	0.5	0.025

The air travel costs per passenger are calculated with the following expressions:

$$C_1(d,u) = \begin{cases} \left(1 - \dfrac{0.5}{20000} \times u\right) \times 0.05 \times d \Leftarrow u < 20000 \\[2ex] 0.025 \times d \Leftarrow u \geq 20000 \end{cases} \tag{14}$$

$$C_2\left(w/z\right) = \begin{cases} 0 \Leftarrow w/z \leq 0.8 \\[2ex] 200 \times w/z - 160 \Leftarrow w/z > 0.8 \end{cases} \tag{15}$$

$f = 20$

where C_1, C_2, and f are expressed in \$, d in km, and u, w, and z in pax/day.

The minimum traffic flow required to justify the existence of a flight leg is $u_{\min}$ = 500 pax/day.

The initial airport network consists of one airport with two close parallel runways in Center 3, and single runway airports in all other population centers (Figure 2). Despite the high occupancy rates observed in Airport 3 (70%) and, especially, in Airport 1 (78%), they do not experience congestion delays (according to expression 18 delays only occur when the occupancy rate exceeds 80%). The total RPK traveled within the network is 247.5×10^3 pax×km/day. Trips are made predominantly (66%) through non-stop flights. In particular, the airports of the three largest centers are connected between them and with the airports of the smaller centers, 4, 5, and 6, by non-stop flights. However, approximately 69% of the trips between Centers 1 and 2 are made through Airport 3 (the reason is because the traffic on flight leg 1-2 is much smaller than the traffic on flight legs 1-3 and 3-2, which makes non-stop flights clearly more expensive). The three smaller centers are not connected through non-stop flights because they do not generate traffic enough for this to happen.

Results

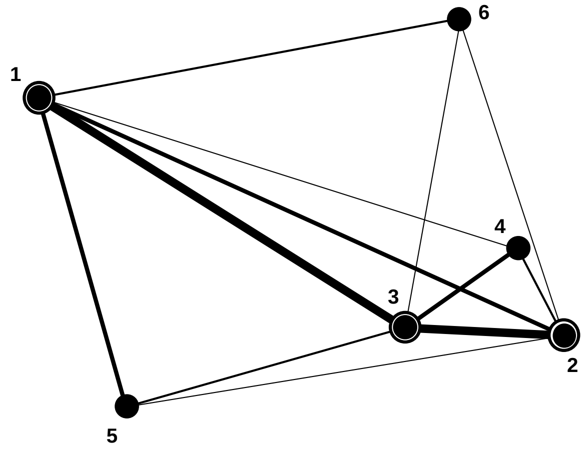
If the sizes of all population centers increase by 25% and the airport network remains unchanged (b=0), the three largest airports would start to suffer congestion delays (Figure 3). The delays would be especially important in Airport 1 (0.99 hours on average) and Airport 3 (0.57 hours). In the former, it would be necessary to apply a congestion tax of 50$ to regulate the utilization of the airport. The total RPK traveled within the network would rise to 332.3×10^3 pax×km/day (+34.3%). The percentage of non-stop flights would also rise, from 66.0 to 68.6%, in part because the congestion delays in the hub airports would divert some traffic to non-stop flights. Another reason is because there would be traffic enough between Center 4 and Centers 5 and 6 to make non-stop flights economically viable.

In order to eliminate any congestion problems while maximizing the RPK traveled within the network, the layouts of Airports 1, 2, and 3 should be transformed into “two medium spaced parallel runways”, “two close parallel runways”, and “three runways”, respectively (Figure 4). The capacity of these airports would therefore increase from 40 to 70, 40 to 60, and 60 to 100×10^3 pax/day. Since the expenditure involved in these transformations is, respectively, 8, 6, and 9×10^8\$, a budget of 23×10^8\$ should be allocated to airport expansion actions. After the implementation of these actions, the total RPK traveled within the network would grow to 399.8 pax×km/day (+61.5%). The role of Airport 3 as a hub would be reinforced (29.8% of the flights would stop there), contributing to the slight relative decrease of non-stop flights that would take place.

If only 12×10^8\$ could be made available to airport expansion actions, only Airports 1 and 2 would be improved, the former to Layout 2 instead of the more expensive Layout 3 (Figure 5). The total RPK traveled within the network would reach 384.8 pax×km/day (+55.5%). This means that approximately 90% of the possible RPK gains can be made with only a little more than 50% of the budget needed to completely eliminate congestion problems in the airport network. The congestion delays would disappear at Airport 2 and decrease considerably at Airport 1 (0.07 instead of 0.99 hours). In contrast, they would increase at Airport 3 (0.67 instead of 0.57 hours), making the hubbing role of this airport clearly less important (only 23.4% of the flights would stop there instead of 29.8%).

MODEL SOLVING

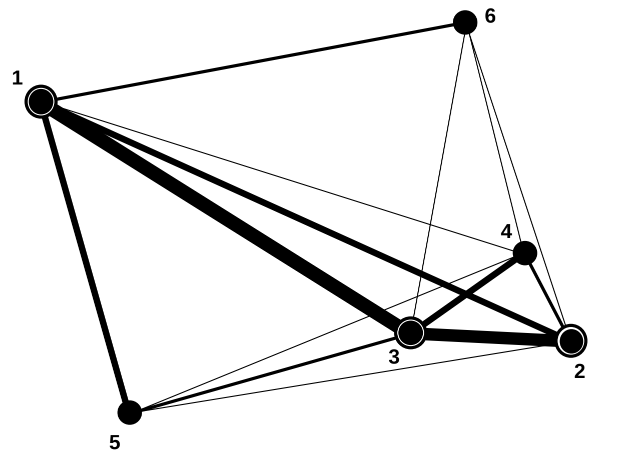
The set of experiments made up to now to assess the quality of the solutions provided by our heuristic algorithm and the effort required to compute them is still very limited. For the moment, the experiments focused on 6-airport instances like the one dealt with in the previous section, and also in 10- and 20-airport instances. Many 6-airport instances were solved, and the algorithm always provided the same solution as complete enumeration – that is, the global optimum solution. The average time required to find the solution on a Pentium IV 2.40GHz PC with 512 MB of RAM was about 10 seconds. For the 10-airport instances, solutions looked fine (but we did not confirm whether they are indeed optimum or not because complete enumeration would take a very long time), taking approximately one minute to calculate. The 20-airport instances entailed a computation time of 30 minutes to 3 hours, making it clear that the computation effort increases sharply with instance size. This basically means that the algorithm seems to be capable of finding good (possibly optimum) solutions to the model, but must be strongly improved before being applicable to the real-world networks we want to analyze in the future – e.g., the 50-largest airports of the European Union.



Airport	Capacity (10^3 pax/day)	Arrivals/ Departures (10^3 pax/day)	Occupancy rate (%)	Congestion delay (hours)	Congestion tax ($/pax)
1	40	31.15	78	0.00	0.00
2	40	23.21	58	0.00	0.00
3	60	41.72	70	0.00	0.00
4	40	9.09	23	0.00	0.00
5	40	8.31	21	0.00	0.00
6	40	5.85	15	0.00	0.00

Traffic flows (10^3 pax/day)					
Origin	Destination	Non-stop	Hub		
			1	2	3
1	2	3.30	-	-	7.26
1	3	7.83	-	0.23	-
1	4	1.67	-	0.46	2.54
1	5	3.96	-	0.01	0.44
1	6	2.43	-	0.04	0.41
2	3	4.24	0.02	-	-
2	4	1.25	0.00	-	0.20
2	5	0.82	0.03	-	0.79
2	6	0.99	0.00	-	0.28
3	4	1.23	0.00	0.49	-
3	5	1.03	0.07	0.07	-
3	6	0.63	0.03	0.14	-
4	5	0.00	0.02	0.20	0.48
4	6	0.00	0.00	0.30	0.21
5	6	0.00	0.09	0.05	0.22
Total		58.75	0.57	4.03	25.69
%		65.99	0.64	4.52	28.85

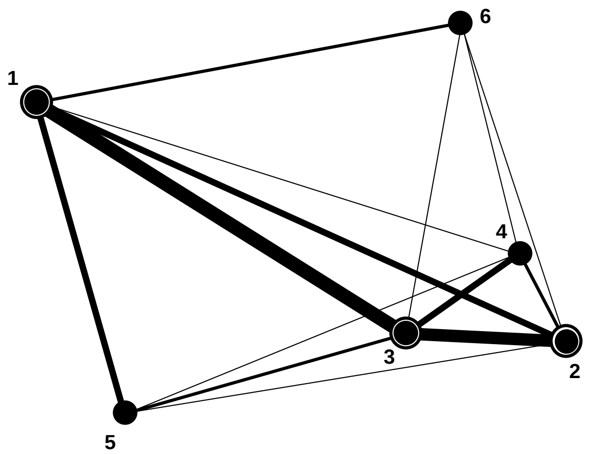
Figure 2: Initial airport network and traffic flows



Airport	Capacity (10^3 pax/day)	Arrivals/ Departures (10^3 pax/day)	Occupancy rate (%)	Congestion delay (hours)	Congestion tax ($/pax)
1	40	39.96	100	0.99	50.00
2	40	32.80	82	0.10	0.00
3	60	54.85	91	0.57	0.00
4	40	13.23	33	0.00	0.00
5	40	11.77	29	0.00	0.00
6	40	8.62	22	0.00	0.00

Traffic flows (10^3 pax/day)					
Origin	Destination	Non-stop	Hub		
			1	2	3
1	2	4.67	-	-	9.40
1	3	9.59	-	0.33	-
1	4	2.35	-	0.71	3.19
1	5	5.13	-	0.02	0.53
1	6	3.27	-	0.06	0.50
2	3	6.45	0.00	-	-
2	4	1.95	0.00	-	0.30
2	5	1.34	0.00	-	1.22
2	6	1.58	0.00	-	0.42
3	4	1.79	0.00	0.81	-
3	5	1.66	0.02	0.12	-
3	6	0.97	0.00	0.25	-
4	5	0.58	0.00	0.19	0.37
4	6	0.78	0.00	0.13	0.08
5	6	0.00	0.04	0.12	0.41
Total		84.23	0.20	5.46	32.84
%		68.63	0.16	4.45	26.76

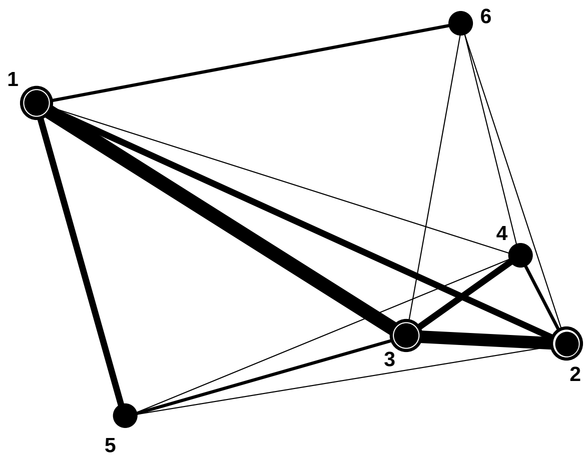
Figure 3: Future airport network and traffic flows for b = 0



Airport	Capacity (10^3 pax/day)	Arrivals/ Departures (10^3 pax/day)	Occupancy rate (%)	Congestion delay (hours)	Congestion tax ($/pax)
1	70	50.26	72	0.00	0.00
2	60	37.3	62	0.00	0.00
3	100	68.62	69	0.00	0.00
4	40	14.63	37	0.00	0.00
5	40	13.24	33	0.00	0.00
6	40	9.38	23	0.00	0.00

Traffic flows (10^3 pax/day)					
Origin	Destination	Non-stop	Hub		
			1	2	3
1	2	4.94	-	-	12.30
1	3	12.44	-	0.50	-
1	4	2.34	-	0.82	4.32
1	5	6.23	-	0.02	0.79
1	6	3.75	-	0.08	0.71
2	3	7.03	0.03	-	-
2	4	1.87	0.00	-	0.40
2	5	1.13	0.05	-	1.43
2	6	1.46	0.01	-	0.53
3	4	1.87	0.01	0.88	-
3	5	1.58	0.15	0.12	-
3	6	0.94	0.06	0.26	-
4	5	0.50	0.02	0.17	0.45
4	6	0.75	0.00	0.13	0.10
5	6	0.00	0.17	0.07	0.34
Total		93.67	1.02	6.11	42.75
%		65.25	0.71	4.26	29.78

Figure 4: Future airport network and traffic flows for b = 23×108 $



Airport	Capacity (10^3 pax/day)	Arrivals/ Departures (10^3 pax/day)	Occupancy rate (%)	Congestion delay (hours)	Congestion tax ($/pax)
1	60	48.88	81	0.07	0.00
2	60	37.27	62	0.00	0.00
3	60	56.34	94	0.69	0.00
4	40	14.22	36	0.00	0.00
5	40	13.06	33	0.00	0.00
6	40	9.31	23	0.00	0.00

Traffic flows (10^3 pax/day)					
Origin	Destination	Non-stop	Hub		
			1	2	3
1	2	7.42	-	-	9.33
1	3	11.50	-	0.62	-
1	4	2.72	-	1.25	3.28
1	5	6.47	-	0.04	0.55
1	6	3.92	-	0.11	0.51
2	3	6.36	0.04	-	-
2	4	2.00	0.00	-	0.28
2	5	1.35	0.08	-	1.12
2	6	1.60	0.02	-	0.39
3	4	1.73	0.01	0.83	-
3	5	1.49	0.14	0.12	-
3	6	0.90	0.06	0.25	-
4	5	0.57	0.03	0.20	0.34
4	6	0.78	0.00	0.14	0.07
5	6	0.00	0.20	0.09	0.28
Total		97.60	1.16	7.28	32.30
%		70.55	0.84	5.26	23.35

Figure 5: Future airport network and traffic flows for b = 12×108 $

CONCLUSION

In this paper we presented an optimization model for assisting air transportation authorities in the determination of the best expansion actions to implement in an airport network, while complying with a given budget. The model maximizes the total revenue passenger kilometers

(RPK) traveled within the airport network, taking into account the capacity of the airports and the impact of travel costs upon demand. As illustrated for a small-size network, the model can be of great practical utility. However, many relevant real-world applications will only be possible to address if the heuristic algorithm developed to solve the model is clearly improved.

With regard to the near future, our main efforts will certainly be directed towards the enhancement of the heuristic algorithm. But we also want to augment the model with a number of new, important features. In particular, we plan to consider the construction of new airports in addition to the expansion of the existing ones. Moreover, we plan to replace the objective of maximizing the total RPK traveled within the airport network, which currently underlies the model, with an objective more relevant from the economic standpoint – the maximization of social welfare (consumers' surplus). Finally, we plan to address three types of issues that air transportation authorities have to care about: equity issues; robustness issues; and flexibility issues. Indeed, the solutions to airport network expansion problems must consider the needs of regions located far away from heavily populated areas (equity), must perform well enough even under adverse conditions (robustness), and must be capable of incorporating changes as new information becomes available (flexibility).

An optimization model with all these features that could be solved within reasonable computation effort would undoubtedly be a very important tool for assisting air transportation authorities at making the best decisions with regard to the expansion of airport networks.

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