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Capacity Planning Based on Scenario Tree and Passenger Motion Equation (IKIA and MIA)

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Abstract

Demand for air travel has increased in quantity and quality, like pre-flight services and communications systems, necessitating more serious attention to air terminal capacity planning. Capacity planning, especially when uncertainty exists about future levels of passenger demand is also considered, becomes even more complex. The problem of random, multistage and nonlinear modeling must be adapted to include a multi-commodity network flow structure which shows the flow of passengers at terminals. In this paper a capacity planning approach is utilized based on the concepts of scenario tree and motion equations of passengers, and implemented for passenger terminals of the two major International Airports (IKIA & MIA) in Tehran, Iran. Results of mathematical programming model for these case studies indicate that increasing the capacity of the passenger terminal in IKIA can increase the productivity of the existing space and the whole airport which is also very economical. At MIA, it would be necessary to increase the effective width of corridors and to increase number of processing stations.

Keywords: airport passenger terminal, capacity planning, Multistage Stochastic Programming, Imam Khomeini International Airport, Mehrabad International Airport

1. **Introduction**

The nature of air transportation is different from other modes of transportation, e.g. airports may be considered the most important component since they tend to be the bottleneck of the system. Major bottlenecks are at airport passenger terminals since the total capacity of the system depends on the maximum volume of passengers who can use the airport. Considering the increasing demand for air travel, passenger terminals need to satisfy this demand, otherwise these terminals will serve as bottlenecks reducing the capacity of the airport meaning that the rest of the airport facilities will not be fully utilized.

One way to increase capacity is to increase the number of passenger terminals [1]. However acquiring land on which to build a new terminal often is not possible due to high costs. Building also increases the number of programmable terminals without necessarily promoting optimal operation. The airport passenger terminal plays a vital role in planning different features such as passenger volume, location and number of output gates, hallways and corridors and emergency exits. Efficient use of airport capacity was analyzed by Fernandes & Pacheco [2], considering passenger demand, and the time required to develop capacity to maintain high standards of service that passengers need.

One main objective in the analysis of airport terminal capacity is to minimize passenger delay. Therefore, an essential component of the capacity planning model is to accurately estimate the time it takes for passengers to traverse passageways and delay times at processing stations. It is also important to reduce delays and costs resulting from reductions in waiting time of flights and to lower travel duration [1].

A stochastic version of the general network design problem has been studied by Riis & Andersen [3] and Andrade et al. [4] within the context of telecommunication network design. In these studies, two-stage stochastic programming models with linear costs are described. Riis & Andersen extend this approach to the multi-period case, using a two-stage model [3]. Another two-stage stochastic model based on the Steiner tree problem is described by Gupta et al., where a linear programming rounding approximation algorithm is proposed as a solution procedure[5].

Most efforts to solve such problems have been problem-specific since there are no practical general purpose algorithms for multistage stochastic integer programming problems. The problem-specific efforts are based on decomposition procedures through column generation [6, 7]. The deterministic equivalent of a stochastic integer problem can be solved by branch and bound methods [4], however for most problem formulations, this multistage structure leads to a large number of integer variables, leaving the problem extremely difficult to solve.

In this paper, a passenger terminal capacity planning based on scenario tree and motion equation of passengers is applied: a multistage stochastic integer programming model for the capacity planning problem for airport terminals is addressed. We calculate walking and waiting (processing) delays separately and develop delay time approximates for each of the two case studies (namely Terminal 1 of Imam Khomeini International Airport- IKIA- and Terminal 2 of Mehrabad International Airport- MIA): the origin and destination of processes are considered in the calculation of the total time, which includes passenger walking time. Efficient use of existing terminals will determine the bottleneck capacity of airports in coordination with the various facilities for passengers.

2. Research Methodology

To consider all delays at the terminal, problem formulation and mathematical modeling in this research is decomposed into two phases: the first includes the time that passengers are moving (walking) between different stations (processing or service stations) within the passenger terminal; and the second includes the time that passengers are waiting at these stations to receive service. Characteristics and behavior of passengers at terminals, including waiting halls, private rooms, processing stations, and servicing, are also taken into account as design components.

If aviation industry forecasts [1, 3] over the coming decades are realized, worldwide RPK will grow at an average rate of approximately five percent per annum over the next 20 years, resulting in about 8 percent increase per year in passengers [8]. Based on these figures, flight schedules over one year were used to estimate passenger arrival rates in this research. Solak et al. determined three approximations to represent the shape of a peak to estimate the maximum queue length. In this paper, we calculate walking and processing delays separately and develop delay time approximates for each of the two areas under study. Validity of the time functions are then analyzed by comparing them with simulation results based on the actual airport, terminal number 1 of IKIA and terminal number 2 of MIA. Walking time is calculated using equation 1 [1]:

$$S = -0.34\phi + 1.34 \qquad (1)$$

where, ϕ is the density of passengers (passenger per square meters) and S is the average walking speed of passengers (meter per second).

Maximum delay estimation at the process stations (as a function of flow and capacity) assuming a deterministic approximation with varying arrival rates and constant process rates based on fluid approximations was suggested by Newell [9].

Simulation with Arena is an effective tool for assessing the delay time functions in processing stations [6]. Considering a multi-commodity flow network, different types of passengers correspond to different commodities. Using this model, several objective functions can be considered. For example, the model could minimize the worst case scenario of the maximum total time spent in the system by a passenger who is routed through the network regardless of the route. Another objective could be to minimize the maximum delay at each passageway and processing station. We assumed that the passenger flow during peak demand periods is distributed optimally among alternate routes within the airport terminal as described by the system equilibrium concept of Wardrop [10].

A scenario tree is a viable way of taking the underlying dynamic stochastic data over time and discretizing it to solve a problem. Each stage in a scenario tree denotes the stage of time when new information is available to the decision maker. The stages might include a number of periods in the planning horizon, not necessarily corresponding to time periods [1] The scenario tree of this research (Fig 1) has three stages, each with two passenger types that enter or exit the terminals, while it has four combinations of passenger demand in future: low-low, low-high, high-low, and high-high. Three epochs, each 5 years long, are considered to have a forecast for next 15 years. Moreover, each arc in this tree has its specific probability, indicating the probability that each node and arc may occur. Table 1 shows LL, HL, LH and HH probability for the three stages, based on which:

Lowest probability is associated with LL scenario. Probability changing rate is equal to 5 percent for LL scenario. Strongest scenario is HH which also increase during the 3 stages [11].

Software packages MatLab 7.12.0 and Rockwell Arena 13.5 were used for simulation purposes. In the second phase, all the formulas obtained from the first (optimization problem) were fed into Lingo 8.5 software package to solve the problem. For validation of the simulation process, (surveys of) actual passengers at different stations in the passenger terminals were used.

Table 1: Probabilities in the Scenario Tree of the Research [11]

Pen	***LL***	***LH***	***HH***	***HL***
1	0.150	0.200	0.400	0.250
2	0.092	0.018	0.575	0.150
3	0.057	0.140	0.650	0.153

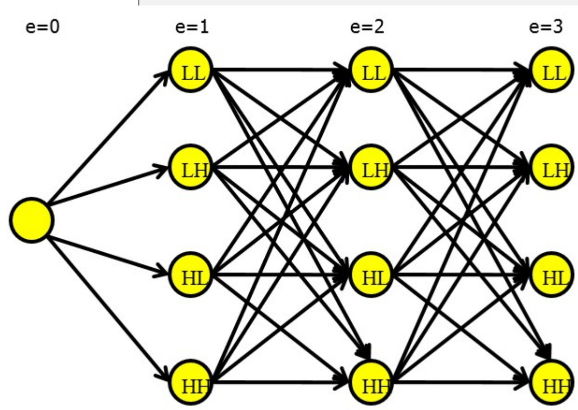

Fig.1: Scenario Tree scheme for IKIA and MIA airports [11]

The research integer model is based on the model presented by Solak et al. (2009) and modified according to the problem size for the specific case studies. The mathematical programming problem is to minimize the objective function (z) presented in equation 2 [1].

$$\text{minimize } z = \sum_{n \in T} \sum_{l \in A_p} p_n f_{nl} t^{\rho}_{nl}(.) + \sum_{n \in T} \sum_{l \in A_w} p_n f_{nl} t^{\omega}_{nl}(.) \qquad (2)$$

$$\text{s.t.} \quad \sum_{j \in V:(i,j)\in A} x^k_{n,ij} - \sum_{j \in V:(i,j)\in A} x^k_{n,ji} = 0 \quad \forall\ n,k, \forall\ i \notin \{O^k \cup D^k \cup R\} \qquad (3)$$

$$\sum_{j \in V:(i,j)\in A} x^k_{n,ij} = d^k_{in} \qquad \forall\ n,k, \forall\ i \in O^k \qquad (4)$$

$$\sum_{j\in V:(i,j)\in A} x^k_{n,ji} = \sum_{i'\in O^k} d^k \quad \forall n, \forall k\in K_d, \forall i\in D^k \tag{5}$$

$$\sum_{j\in V:(i,j)\in A} x^k_{n,ji} = \sum_{i'\in O^k} d^k \quad \forall n, \forall k\in K_d, \forall i\in D^k \tag{6}$$

$$\sum_{j\in V:(i,j)\in A} x^k_{n,ji} = \sum_{i'\in R^k} \sum_{j'\in V:(i,j)\in A} x^k_{n,i'j'} \quad \forall n, \forall k\in K_p, \forall i\in D^k \tag{7}$$

$$\sum_{j\in V:(i,j)\in A} x^k_{n,ji} = \sum_{i'\in R^k} \sum_{j'\in V:(i,j)\in A} x^k_{n,i'j'} \quad \forall n, \forall k\in K_p, \forall i\in D^k \tag{8}$$

$$\sum_{j\in V:(i,j)\in A} x^k_{n,ij} - u_{n,i'i} \frac{\sum_{j\in O^k} d^k_{jn}}{\sum_{k'\in K_{i'i}} \sim \sum_{j\in O^{k'}} d^{k'}_{jn}} = 0 \quad \forall n, \forall (i',i)\in A_p, \forall k\in \tag{9}$$

$$u^0_l + \sum_{m\in P(n), m\neq n} \varepsilon_{ml} = u_{nl} \quad \forall n, \forall l\in A_p \tag{10}$$

$$u_{nl} - f_{nl} \leqslant 0 \quad \forall n, \forall l\in A_p \tag{11}$$

$$(1-c_{nl}) f_{nl} - u_{nl} \leqslant 0 \quad \forall n, \forall l\in A_p \tag{12}$$

$$Q(x^k_{nl}, u_{nl}, f_{nl}, \varepsilon_{nl}) \leqslant 0 \quad \forall n,k,l \tag{13}$$

$$x^k_{nl}, u_{nl}, f_{nl}, \varepsilon_{nl}, u^0_l, w^0_l \geqslant 0 \quad \forall n,k,l \tag{14}$$

$$V_{nl} \in \{0,1\} \quad \forall n\in N, n\neq 0, \forall l \tag{15}$$

Network node balance (or flow conservation) constraints are represented by constraints 3 to 7. Constraints 8 and 9 indicate overall capacity of the network. Constraint Number 10 shows that flow in nodes and arcs is dependent on time. Constraints 11 and 12 providing for conditions under which the capacity of processing stations is between the average and maximum flow. Constraint 13 shows a vector that provides additional constraints on the network. Constraints 14 and 15 show the decision variables of the problem.

3. Research Case Studies

The empirical case of this research includes two of the main airports in Tehran, capital city of Iran: namely Terminal 1 of Imam Khomeini International Airport (IKIA) and Terminal 2 of Mehrabad International Airport (MIA). These most congested terminals are selected due to their large number of flights and since access to technical information and flight schedules for these airports were also available. Data for the years 2010 and 2011 are used regarding these airports and their passengers and based on them, predictions for the next 5 and 20 years are conducted [11].

3.1. IKIA passenger terminal No. 1

Based on passenger distribution at IKIA passenger terminal No. 1 (Figure 2) for peak hour traffic for the first hundred peak hours of the year, the busiest time of the year with 3125 passengers is on 7th of April from 03:45 to 04:45 hours. The thirtieth and fortieth busiest time happen on 27th of March (with 2116 passengers) from 04:35 to 05:35 hours, and on 3rd of May (with 2027 passengers) from 03:45 to 04:45 hours, respectively. This terminal will also be busy for 144 hours in April, 23 hours in June, 21 hours in March and in August, and 10 hours in May and September (Table 2) [11].

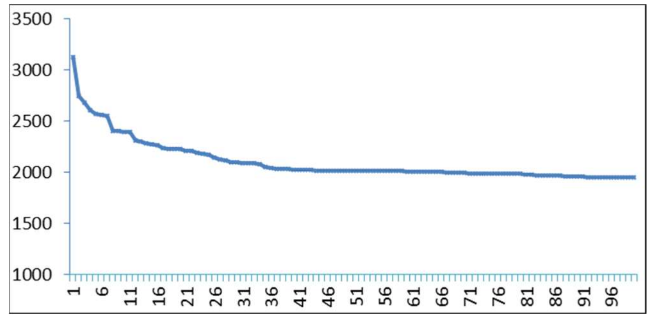

Fig.2: Passenger Distribution at IKIA Passenger Terminal (V-axis: Passenger number, H-Axis:1st 100 peak hours)

Departure peak hour of this terminal for 100 peak hours indicates that the busiest hour of the year (with 1964 passengers) is on 27th of March from 04:35 to 05:35 hours. The thirtieth and fortieth busiest time is on 22 August (with 1481 passengers) from 06:20 to 07:20 hours, and on 26th of March (with 1447 passengers) from 07:55 to 08:55 hours, respectively. The same measures for Arriving passengers of this terminal are 2698 passengers, on 7th of April from 03:35 to 04:35 hours. The thirtieth and fortieth busiest time occur on 30th of March (with 1534 passengers), and on 31st of September (with 1470 passengers), respectively (Table 2) [11].

Table 2: Probabilities in the Scenario Tree of the Research [11]

	type	*1st*		*30th*		*40th*	
		BTP	DBTP	BTP	DBTP	BTP	DBTP
IKIA	T	3125	Apr 7	2116	Mar 27	2027	May 3
	D	1964	Mar 27	1481	Aug 22	1447	Mar 26
	A	2698	Apr 7	1534	Mar 30	1470	Sep 31
MIA	T	2779	Dec 4	2134	Jan 22	2097	Dec 30
	D	1983	Mar 14	1659	Jun 17	1624	Mar 10
	A	1883	Mar 22	1434	Mar 21	1416	Jul 9

Where T=Total, D=Departure, A=Arrival, BTP is "Busiest Time Passengers"; DBTP is "Date of Busiest Time Passengers".

3.2. MIA passenger terminal No. 2

MIA has six passenger terminals, one of which (number 2) has an area of 20330 square meters with 32 check-in counters. The busiest time of the year with 2779 passengers is between 12:45 and 13:45 hours on 4th of December (Figure 3). With 2134 passengers, the thirtieth hour occurs on 22 January between 12:25 and 13:25 hours. The fortieth hour with 2097 passengers occurs on 30 December between 13:15 and 14:15 hours. The busiest times of this terminal include 141 hours in December, 37 hours in January, 10 hours in February, 7 hours in October and 4 hours in March and August [11].

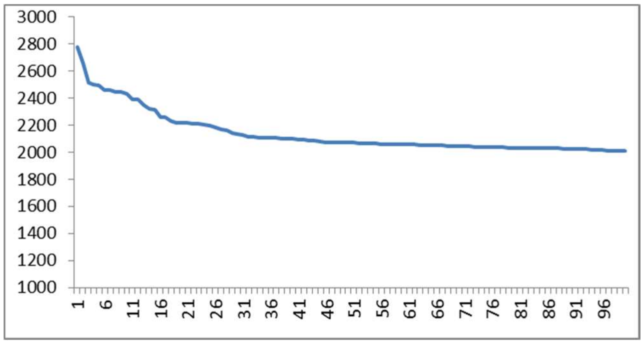

Fig.3: Passenger Distribution at MIA Passenger Terminal (V-axis: Passenger number, H-Axis:1st 100 peak hours)

From Table 2, it can be observed that the busiest time of the year for departure at MIA with 1983 passengers occurs on 14th of March between 6:35 and 7:35 hours. The thirtieth peak hour with 1659 passengers occurs on 17th of June between 5:55 and 6:55 pm. There were 1624 passengers at fortieth peak hour on 10th of March between 6:15 and 7:15.

Rush hours of this terminal arrival are rather uniform with a gentle slope. The busiest time of year, with 1883 passengers on 22nd of March occurs between the hours of 22:55 and 23:55. The thirtieth and fortieth with 1434 and 1416 passengers, respectively, occur on 21st of March between 8:00 and 9:00 hours and on 9th of July between 23:30 and 00:30 (Table 2).

3.3. Other characteristics of IKIA & MIA

As another input set of parameters of the planning problem, each airport special characteristics and properties including facilities, area, and number of gates as well as length and width of corridors need to be considered. Table 3 presents these characteristics for IKIA and MIA as applied in model estimation. Some other observations specific to these terminals are: gates at IKIA are located in such a way that at peak hours (large aircrafts), they cannot work at full capacity; and in MIA Terminal No.2, there is no passport control because it operates for only domestic flights [7].

Table 3: Passenger Terminal Facilities for IKIA and MIA

Type of facilities	*IKIA counters*		*MIA counters*	
	Total	Active	Total	Active
Check – in	64	23	32	32
Passport	32	26	8	8
Police	4	3	2	2
Gate	14	14	14	14
Baggage	9	9	5	5

4. Model Results

For estimation of passenger arrival equations to each terminal, simulation was adopted for higher precision. Using Arena software package, we studied passenger arrival rates and estimated the arrival equations as presented in Table 4. The best fit for these equations was observed to have Beta distribution [11]. There is, naturally, a difference (although not very large) between the estimated equations as expected, due to e.g. different number of passengers and different nature of these terminals.

Table 4: Passenger Terminal Facilities for IKIA and MIA

	MIA	IKIA
Expression	*1.24 + 0.6 * BETA(4.08, 1.55)*	*1.08 + 0.84 * BETA(4.85, 1.7)*
Square Error	*0.036698*	*0.068477*
	Chi-Square Test Results	
Number of intervals	*38*	*37*
Degrees of freedom	*35*	*34*
Test Statistic	*438000*	*1210000*
p-value	*< 0.005*	*< 0.005*

Model calibration results for delay function at IKIA and MIA based on Solak et al. method are shown in Table 5 for different functions [1]. It can be observed that the half-elliptical function (equation 16) and the parabolic function (equation 17) are the more proper delay functions for IKIA for MIA, respectively:

$$t_E^{\rho} = \frac{T_0 \pi}{4cuf}(f-u)^{3/2}\sqrt{u-(1-2c)f} \qquad (16)$$

$$t_p^{\rho} = \frac{2T_0(f-u)^{3/2}}{3u\sqrt{cf}} \qquad (17)$$

$$c = 1 - \frac{\bar{f}}{f} \qquad (18)$$

where, f is the arrival rate, T_0 is the time when the arrival rate drops below the average arrival rate, c is a constant, u is the area between capacity and triangular arrival rate curve, t_p is the maximum time spent for the parabolic approximation of peak at process station, and t_e is the maximum delay in half-elliptical approximation.

Table 5: Passenger Terminal Facilities for IKIA and MIA

Airport	*Simulation*	*Triangular*	*Parabolic*	*Half elliptical*
IKIA	*8.9746*	*6.3584*	*7.9465*	*8.5938*
MIA	*44.6798*	*28.7566*	*45.3736*	*69.9909*

For arriving passengers, a double node represents the origin. In the first test model, only unidirectional flow was assumed, however by approximating delay times using the speed density relation (1), bidirectional flow was integrated into the larger model. It was assumed here that density is based on flow in both directions. The lengths of the passageways were measured directly. For each customer type, a triangular curve was assumed for arrival rate (demand) at the initial processing and the downstream stations [7]. Details of delay time estimation were applied from Saffarzadeh & Braaksma's research [2]. All other parameters were determined based on forecasts and actual measured peak demand levels at IKIA and MIA. Up to three stages were studied with the multistage models. LINGO software was used to perform the standard branch and bound procedure. Computations were performed on a PC with an Intel Pentium 4 2.4 GHz processor and 4 GB of internal memory. A relative tolerance of 0.0001 was used, while a time limit of 3600 s (one hour) was imposed on the number of iterations.

The standard branch and bound did not produce an optimal solution within the one-hour time limit for problems on the small network. However, the time for the branch and bound procedure increases with increasing problem size and number of nodes for two airports. In all instances the standard branch and bound performs well. We can conclude that the standard branch and bound performed well under all scenarios, including those where in-flow rates were the highest. The reason is the size of the problem that made it different from Solak et al.'s problem condition. Actual 15 year traffic forecasts at IKIA and MIA were the basis for the demand levels in the test models.

5. Conclusions and Recommendations

In this paper, by focusing on air terminal capacity planning, a multi-period stochastic planning problem under uncertainty was addressed. Based on the concepts of scenario tree and motion equations of passengers, passenger terminals of the two major International Airports (IKIA: Imam Khomeini International Airport & MIA: Mehrabad International Airport) in Tehran, Iran were considered as the case studies. Mathematical programming models for IKIA and MIA case studies include 157278 and 119023 variables and 19064 and 14021constrains, respectively (for horizons of 5, 10 and 15 years). Nonlinear (MINLP) planning problems were solved by branch and bound method using LINGO software package. Results indicate that increasing the capacity of the passenger terminal in IKIA can increase the productivity of the existing space and the whole airport which is also very economical. Potential current capacity of IKIA can be used for emergency capacity (for the next 5 years). However, IKIA also needs to expand its terminal in the next 10 years at Check-In areas and gates.

At MIA, different parts of the process and walking stations need to be expanded: It would be necessary to increase the effective width of corridors and to increase number of processing stations (expanding its gates and security checks). This terminal was observed to operate 89% of its nominal capacity during peak hours, resulting in a level of service of F. Development of MIA terminal after the first 5-year period would be possible only in certain directions of motion. Thus, managers should consider other facilities near this terminal.

Overall, empirical results for the IKIA and MIA problems (with various numbers of stages) suggest that the proposed model can be applied as a powerful tool for capacity planning at airport terminals. The question is whether there is a relationship between the optimal expansion decisions and the expected future demand at a given decision point. In summary, our recommendations and suggestions for further research are:

1- Behavior analysis can be used for a more detailed consideration of the processing stations. Image and video processing would be an effective tool in this regard.

2- For a more realistic situation for a terminal, both air field and land field should be considered in the analysis. Thus, we suggest a study on airfields of these two major airports of Iran.

3- It is recommended that further research take into account the costs to develop various scenarios, and thus extending the model to an economical optimal as well.

4- Although expansion will increase delay of walking and transfer of passengers between stations in the airport, facilities such as electrical vehicle, pedestrian conveyor and arc shape stations can be useful. Moreover, level of service will increase, too.

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