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# Stochastic Planning Approach in Airport Passenger Terminals

Hesam. Shabani Verki
Department of Highway and Transportation, Science and Research Branch, Islamic Azad University, Tehran, Iran
Email:hesam.shabani@gmail.com

Amir Reza. Mamdoohi and Mahmoud. Saffarzadeh
Tarbiat Modarres University, Tehran, Iran
Email:{armamdoohi, saffar_m}@modares.ac.ir

***Abstract*—Motivated by the challenges encountered in airport passenger terminal planning, we study a multistage stochastic programming model based on a multi commodity flow network representation of the whole airport terminal. As delays in passageways and processing stations of airport terminal different uncertain natures, they are modeled separately and then integrated. In this study, we consider the airport terminal capacity planning problem as a whole. In this regard, we first derive time functions to approximate maximum delays in passageways and processing stations of an airport terminal. Demand uncertainty is considered as a dynamic stochastic data process during the planning horizon which is modeled as a scenario tree. Based on available data for the Imam Khomeini International Airport like passenger demands, a multi-stage stochastic programming model is proposed which is full recourse for demand scenarios. Numerical results indicate that the solution to the multi-stage model is far superior to the optimal solution to the mean-value deterministic and the three-stage stochastic models.**

***Index Terms*—Passenger terminal design, airport planning, capacity expansion, multistage stochastic programming**

## I. INTRODUCTION

Passengers and airlines have long recognized airports as important points of origin, destination, and transit points for air travel. Applying the well-known systematic analysis, airport systems can be dissected into airside and landside components, based on the various activities involved in each. Facilities for landside activities such as check-in, security check, waiting areas, boarding, and baggage claim are housed in the airport passenger terminal.

Planning the APT is a key area of airport management. Plans must be made despite the uncertainties in environmental and system issues such as passenger demand and expansion budgets. One method that is used for airport terminal planning is mathematical programming. However, traditional mathematical programming models are deterministic. Given the potential uncertainties to be considered in airport terminal planning, this method may result in unsatisfactory airport plans.

The goal of this work is to address the problem of planning for an airport terminal environment that is multi-period and multi-commodity where at the same time, alternative choices for expansion depend on several different kinds of scenarios.

Consideration must be given to passengers' non-homogenous and random habits, the type of airport terminal (national or international) as well as how the flights are scheduled. Therefore, the volumes of passengers needing to be handled at each step of the process are random variables. Moreover, planning for the future is equally challenging given the uncertainty of passenger demands.

The APT problem we are studying includes functions to account for develop time in order to approximate maximum delay times in passageways and passenger processing stations. Using developed time functions, optimal capacities are calculated using a stochastic programming model based on a multi-commodity flow network representation of the entire airport terminal. Optimal capacities represent the highest levels of service possible. It should be noted that the developed time functions are valid for other flow networks as well. The model yields outputs of the optimal capacity levels at the processing stations and passageways of the terminal for multiple planning periods and the optimal expansion decisions with optional recourse possibilities due to the uncertainty of demand.

Capacity problems at airport terminals are discussed in the literature in several studies. Hamzawi (1992) emphasizes the need for a solution to congestion caused by lack of capacity.[1] He argued that if no remedial actions are taken, it could lead to an eventual breakdown of the functioning of the airport system. In practice, the most common remedial actions taken are costly expansion projects, since during initial construction; there are generally limited resources available amidst great uncertainty regarding the future demand. However, it is extremely important to minimize the need for expansion along with the costs associated with the initial design and future expansion projects. Significant, long-lasting

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increases in airport terminal capacity can only be achieved by building new terminals that are designed to be expandable at their conception. Worldwide, upwards of 20 new airports may need to be built in the next twenty years. Given the historically uncertain demand for air transportation, there is a definite need for new terminal designs that are efficient and flexible enough to accommodate the wide range of possible demand scenarios.

The focus of the capacity problem in most studies is the optimum design of airport terminals. Such studies are usually based on short-term demand forecasts and the corresponding passenger flows within the terminal to formulate a single period approach. Using this concept, Saffarzadeh and Braaksma (2000) developed a resource utilization model in which the cost of over-sizing or under-sizing the terminal facilities is minimized.[2] McCullough and Roberts (1979) present a capacity analysis model based on the study of movements within the terminal during discrete time intervals.[3] Mc. Kelvey (1989), on the other hand, analyzes passenger processing times under different capacity levels by taking a multi-channel queuing system approach.[4]

Although queuing models can be used for passenger flow analysis, the high variability in the number of arrivals and departures during a typical day make a steady state assumption invalid for airport terminals. Steady state results for queuing systems in these cases are therefore inapplicable. Transient studies, on the other hand, are generally intractable due to the complexity of flow in an airport terminal. Most studies, therefore, attempt to model this random and complex flow process through the use of simulations.

Required capacity levels are simulated in these studies to make operations more efficient. For example, Jim and Chang (1998) use a simulation model that evaluates several terminal designs as alternatives. None of the existing models address the airport terminal capacity problem from a holistic perspective, however. The main reason they have not attempted this approach is because of the difficulty of modeling passenger flow with transient demand patterns within a complex terminal structure. Moreover, models never take into account expandability of the system. [5]

Solak (2009) presents an algorithm for optimizing airport terminal capacity planning for the Hartsfield-Jackson Atlanta International airport. This paper will improve this algorithm and apply it to the Imam Khomeini International Airport (IKIA) in Iran with the objective of focusing on passenger flow in airport terminals. To do so, closed form time functions are derived to approximate the maximum delay that might be experienced in queuing networks when the transient studies are intractable and without the existence of a steady state.

Additionally, a network model for an airport terminal that takes a holistic approach is developed that can be used to model similar complex flow networks. A stochastic capacity expansion problem can be formulated based on this network model leading to an efficient solution to the problem. The resolution is also expected to lead to improvements in the analysis of other capacity expansion problems described in literature. The uncertain demand can be assumed to evolve as a discrete time stochastic process with finite support during the planning process. This information structure can then be interpreted as a scenario tree. Each stage in the demand scenario tree corresponds to a particular cluster of time periods. Demand during the periods at each stage can be assumed to have a stationary behavior.

## II. APPROXIMATION OF MAXIMUM PEAK PERIOD DELAY

The 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 approximate the time it takes for passengers to traverse passageways and delay times at processing stations as a function of capacity and flow rates.

Demand cannot be neglected in this analysis. Because of its special stochastic and transient nature, it is the most important detail to be considered. Estimations of demand can be based on direct observational data or on simulated models. In this paper, we calculate walking and processing delays separately and develop delay time approximations for each of the two areas. The validity of the time functions are then analyzed by comparing them with simulation results based on the actual airport, IKIA.

## III. MAXIMUM DELAY IN PASSAGEWAYS

Travel time functions for pedestrians have been studied in some countries. The information is presented in Table I.

These references are very helpful for the locations listed, but do not include study in Iran. We therefore selected the average of this table as our input data in calculating the formula. Utilizing this assumption, the mean speed for passageway travel by passengers is 1.345 m/s with a standard deviation is 0.328.

$$S = -0.328\phi + 1.345 \qquad (1)$$

## IV. APPROXIMATION OF MAXIMUM DELAY IN PROCESSING STATION

Congestion at airport terminal processing stations, such as security checkpoints and check-in counters, is more important than travel time down passageways. Congestion at these points can cause massive delays and long queues to form. In this portion of the paper, we develop a mechanism to estimate the maximum delay at the processing stations in APT’s. The formula is a function of flow and capacity. Towards this goal, we consider a deterministic approximation with varying arrival rates over time yet constant process rates. This approach is based on fluid approximations suggested by Newell (1982). [6]

Using flight schedules over one year to estimate passenger arrival rates into the terminal, these rates can be plotted against time. Fig. 1 shows an example. For design purposes, the highest peak in this graph is used in peak demand analysis. A peak represents a period during which the arrival rate remains above the average arrival rate. Solak determined three approximations to represent the shape of a peak. These approximations can be used to estimate the maximum queue length.

$$t^{\omega} = \frac{LW}{-0.000181 f + 1.345 w} \qquad (2)$$

TABLE I. THE MEAN SPEED STUDY AROUND THE WORLD

| **Source** | **Mean Speed (m/s)** | **Standard Deviation (m/s)** | **Location** |
|---|---|---|---|
| CROW | 1.4 | 0.215 | Netherland |
| Daamen | 1.41 | | Netherland |
| Daly et al | 1.47 | | United Kingdom |
| FHWA | 1.2 | | United States |
| Fruin | 1.4 | 0.15 | United States |
| Hankin and Wright | 1.6 | | United Kingdom |
| Henderson | 1.44 | 0.23 | Australia |
| Hoel | 1.5 | 0.2 | United States |
| Institute of Transportation Engineers | 1.2 | | United States |
| Knoflacher | 1.45 | | Austria |
| Koushki | 1.08 | | Saudi-Arabia |
| Lam et al | 1.19 | 0.26 | Hong Kong |
| Morral et al | 1.25 | | Sri Lanka |
| Navin and Wheeler | 1.4 | | Canada |
| O'Flaherty and Parkinson | 1.32 | 1 | United States |
| Older | 1.3 | 0.3 | United Kingdom |
| Pauls | 1.25 | | United States |
| Roddin | 1.6 | | United States |
| Sarkar and Janarhan | 1.46 | 0.63 | India |
| Sleight | 1.37 | | United States |
| Tanariboon et al | 1.23 | | Singapore |
| Tanariboon and Guyano | 1.22 | | Thailand |
| Tregenza | 1.31 | 0.3 | United Kingdom |
| Virkel and Elayadath | 1.22 | | United States |
| Young | 1.38 | 0.27 | United States |

A triangular, based on a linear approximation, parabolic or half-elliptical approximation as shown in Fig. 1.is used depending on the sharpness of the peak. Wirasinghe and Bandara (1990) use similar approximations when estimating airport gate position. When the peak cannot be represented with either of these shapes, other approximations or exact functions can be substituted.

## V. VALIDATION OF APPROXIMATION

The accuracy of the developed approximations were validated by comparing the analytical values with results obtained from simulation software. Rockwell Arena was used for this purpose. Various capacity/flow levels are shown in Table II.

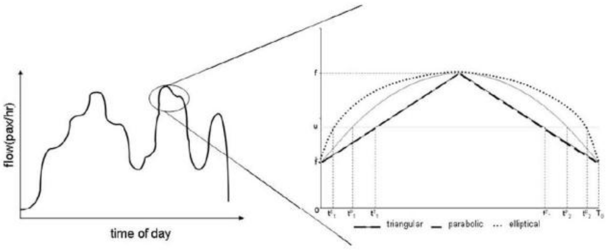

Figure 1. Highest peak is identified and approximated by a triangular, parabolic or half-elliptical function.(Solak-2009) [5]

Table II confirms that approximations for triangular peaks are accurate for all flow-capacity ratios and appear to include only a slight under-estimation. A similar observation can be made when comparing the estimates of maximum delay with simulation results for a parabolic peak demand curve. In this case, the approximations again appear to be accurate.

For validation purposes, in addition to simulation analyses, the approximations were also compared to observed statistics at IKIA. Information from the IKIA Master Plan (2010) was used for the approximation of passageway delays. In this document, results of a concourse circulation and level of service analysis are discussed for the five concourses at IKIA. The Master Plan (2010) also describes the results of a peak period time study for two of these concourses, complete with walking time observations. Under the peak flow rates of 3214 passengers/hour and 2108 passengers/hour, the maximum walking times in two different 166-feet long passageways with effective widths of 22.5 feet were recorded as 46.72 s and 41.60 s respectively. The corresponding approximations based on formula (2) for these two cases are 126.41 s and 125.53 s, which are very close to the actual observations.

Data from processing stations was obtained from observation and from passenger-completed forms in order to approximate the queuing delay. The results obtained for the security checkpoints were a maximum delay of 17.2 minutes during a near-triangular peak demand level of 3847 passengers/hour based on observed data. The average processing capacity of the security checkpoints were calculated as 2374 passengers/hour. Calculating the delay, the triangular peak delay is estimated as 16.28 min, thus confirming the closeness of the approximation.

## VI. THE MULTI STAGE STOCHASTIC PROGRAMMING

The design of a decision model should be such as to allow the user to adopt a policy decision that can respond to events as they unfold, especially when time and uncertainty play a significant role in the problem. The exact form the decision takes on depends to a large extent on the assumptions used by the decision maker regarding the information that is available, when it becomes available, and what adjustments to the decision or recourse can be taken, if any, once the decision is made. Several authors (Kall and Wallace, 1994; Birge, and Louveux 1997; Kall and Mayer, 2005) suggest a multistage stochastic programming (MSP) approach should be taken to address multi-period optimization models with dynamic stochastic data. In MSP, much emphasis is placed on the decision to be made today. MSP also considers the present resources, future uncertainties, and possible recourse actions that may be taken in the future. A scenario tree with an objective function chosen to represent the risk associated with the sequence of decisions to be made can be used to represent uncertainty. The entire problem can then be solved as a large scale linear or quadradic program. In the subsequent sections of this paper, we first review the characteristics of scenario trees. We then provide a general formulation for multi-stage stochastic programming. The network that is described here is similar to a multi-commodity flow network. In this case, 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 (1952).[5]

Literature is filled with the use of stochastic programming approaches when it comes to solving capacity planning problems (Eppen et al., 1989, Berman et al., 1994, Swaminathan, 2000, Riis and Andersen, 2004, Ahmed et al., 2003, Barahona et al., 2005). Except for Ahmedet al. (2003), all of these studies use a linear approach or two-stage integer stochastic models to solve the problems. In this study, we propose a multistage stochastic integer programming model with nonlinear costs for the capacity planning problem at airport terminals.[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 (Lulli and Sen, 2004; Shiina and Birge, 2004). The deterministic equivalent of a stochastic integer problem can be solved by branch and bound methods. However, for most problem formulations, this multistage structure leads to a large number of integer variables, leaving the problem extremely difficult to solve. LINGO software, which we used to test the problem, could not find a solution for this very reason; because of the large number of variables and limitations.

For airport terminal capacity planning, on the other hand, since the planning periods are usually 4–5 years long and passenger demand forecasts exist for 15–20 years into the future, the number of stages is limited. With the number of discrete variables not as large, the deterministic equivalent solution of the proposed stochastic model can be solved in a reasonable amount of time. Regardless of the method chosen to solve the problem, the efficiency of the process is highly important.

In the following section, we used a branch and bound algorithm. This solution is significantly more efficient than the standard branch and bound procedures used by general purpose mixed integer nonlinear programming (MINLP) solvers in the LINGO software. The branch and bound algorithm relies on the implementation of an effective upper bounding heuristic at each node of the branch and bound tree. As a main reference for our work, we used definitions from Solak (2009).

TABLE II. COMPARISON OF ANALYTICAL AND SIMULATION RESULT

| **Capacity/Flow** | **Triangular peak** | | **Parabolic peak** | |
|---|---|---|---|---|
| | ***Avg. Max. Delay in Simulation.*** | ***Approx.*** | ***Avg. Max. Delay in Simulation.*** | ***Approx*** |
| 0.5 | 30.3 | 30 | 40.5 | 40 |
| 0.55 | 22.6 | 21.3 | 34.24 | 30.14 |
| 0.6 | 16.37 | 16.28 | 28.17 | 24.45 |
| 0.65 | 10.93 | 11.16 | 21.95 | 18.12 |
| 0.7 | 8.24 | 8.12 | 15.22 | 13.68 |
| 0.75 | 5.53 | 5.24 | 11.87 | 9.63 |
| 0.8 | 4.38 | 3.67 | 9.98 | 6.15 |
| 0.85 | 2.73 | 1.83 | 4.15 | 3.47 |
| 0.9 | 1.23 | 0.92 | 2.37 | 1.39 |
| 0.95 | 1.24 | 0.71 | 1.59 | 0.77 |
| 1 | 0.73 | 0 | 0.89 | 0 |

## VII. COMPUTATIONAL RESULT

The simplified network representation of an airport terminal and the larger network were used to conduct computational studies. IKIA was used as a sample of the arrival passengers' configuration. The larger network contains 41 passageway arcs and 22 processing arcs, with several simplifications of actual passenger flow. Six terminal points were assumed for the departing passengers. The completion of security screening was depicted as a double destination node. For arriving passengers, a double node indicated the origin.

For arriving passengers, a double node represents the origin. In the first test model, only unidirectional flow was assumed between arcs. However, by approximating the delay times using the speed density relation (1), bidirectional flow was integrated into the larger model. The assumption was made here that density is based on flow in both directions. The lengths of the passageways were measured directly. For each customer type, an arrival rate curve similar to Fig. 1 was assumed. A triangular shape was assumed for the demand curves in the initial processing and the downstream stations. Details from Saffarzadeh's boom were used to estimate processing delay times. All other parameters were determined based on forecasts and actual measured peak demand levels at Imam Khomeini International Airport. 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 Pentium4 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 was imposed on the computations.

The first column of the table lists the number of edges in the test problem networks. Column two shows the number of nodes in the scenario tree. The standard branch and bound process did not produce an optimal solution within the one hour time limit for problems on the small network. However, the time for the heuristic branch and bound procedure increases with increasing problem size and number of nodes. In all instances the improved branch and bound process performs better than the standard solution. According to the results, we can conclude that the developed upper bound heurtistic performed well under all scenarios, including those where in-flow rates were the highest. Actual 10 year traffic forecasts at IKIA were the basis for the demand levels in the test models.

Overall, results for the IKIA problems with various numbers of stages suggest that the proposed model is an innovative and powerful tool for use in 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. Results show there that there is a definite relationship between decisions and expansions. We found that the passenger terminal needs to be expanded within the next decade.

TABLE III. RESULTS FROM STANDARD B&B AND HEURISTIC B&B

| **jEj** | **jTj** | **Standard B&B** | **CPUs** | **Gap (%)** | **B&B based on heuristic according to Solak algorithm** | | |
|---|---|---|---|---|---|---|---|
| | | ***Nodes*** | | | ***Nodes*** | ***CPUs*** | ***Gap (%)*** |
| 9 | 4 | 2 | 0.03 | – | 0 | 0.03 | – |
| 9 | 13 | 24 | 2.75 | – | 2 | 0.19 | – |
| 9 | 40 | 4468 | 3600 | – | 47 | 20.47 | – |
| 9 | 121 | 1873 | 3600 | – | 56 | 412.3 | – |
| 44 | 4 | 4 | 0.09 | – | 0 | 0.09 | – |
| 44 | 13 | 68 | 9.3 | – | 4 | 3.14 | – |
| 44 | 40 | 387 | 1223 | – | 24 | 278.9 | – |
| 44 | 121 | 672 | 3600 | – | 47 | 1430 | – |

## VIII. CONCLUSION

In this paper, we addressed a multi-period stochastic planning problem under uncertainty in passenger demands and behavior. We used multi-stage stochastic model to address the problem and we presented the computational results using LINGO software as well.

Moreover, the calibration of used functions, for IKIA is presented. Calibrated functions were used in NLP problem solved by Branch and Bound method.

Finally, we found that IKIA passenger terminal can solve by standard Branch and Bound solver in LINGO software. So, the model is applicable for IKIA.

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**Hesam. Shabani Verki** was born in Qazvin, Iran in 1985. He is student of Highway and Transportation Engineering in Science and Research Branch, Islamic Azad University of Tehran. He received his B.S. in Civil-Engineering, Imam Khomeini International University, Qazvin, Iran, 2009 and High School Diploma in Mathematics and Physics, Shahid Babaee High School, Exceptional Talents School Organization, Qazvin, Iran, 2003. He was Secretary of Faculty board, First conference of “ The Role of Universities and Industries in Developing Highway and Transportation “, IKIU, 2007. Secretary of Faculty Board, First traffic safety week as “Traffic Culture Week with Pedestrian Approach”, Qazvin municipality, 2012. Traffic safety, transportation planning as well as ITS are his major fields of interests.

**Amir Reza Mamdoohi** was born in Tehran, Iran in 1965. He received his PhD in Transportation Planning and Engineering from Sharif University of Technology, Tehran, Iran, in 2005. His major field of study includes Transportation Planning and Modeling and Transportation Demand Management. He is currently an assistant professor of Civil and Environmental Engineering Faculty at Tarbiat Modares University.

**Mahmoud Saffarzadeh** was born in Kerman, Iran in 1963. He received his PhD in Transportation Engineering from Carleton University, Canada, in 1995. His major field of study includes Air Transportation and Traffic Engineering. He is currently a full professor of Civil and Environmental Engineering Faculty at Tarbiat Modares University.