

Overview of Airport Terminal Simulation Models

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Airport terminal simulation models developed in academia, industry, and government are surveyed. An overview is presented of modeling and simulation including definitions, conceptual approaches to modeling, and types of simulation techniques and simulation languages used for airport landside simulation. Desirable technical properties of airport terminal simulation systems are discussed. Three simulation approaches considered most suitable to model airport terminals are reviewed and their use is discussed in detail.

Airports are currently facing many problems of varying complexity and importance. Although most of these problems are not new, the long-term neglect and lack of action to find valid solutions have exacerbated the current situation of aviation and airport systems. Major problems include inadequate capacity and deterioration of quality of service, difficulties of financial planning and funding of new major airport development, political and environmental considerations that affect airport development and other specific issues related to planning, design, and operation of airports. For airport terminals in particular, airport congestion, severe capacity shortages in the competitive deregulated environment, and airport security are major problems facing airport planners, designers, and managers (1). The status of airports is becoming a major concern, not only to airport operators who are struggling to accommodate passenger loads for which the designers did not plan, but also to federal, state, and local government officials, the airline industry, local communities, and the public at large.

Airport planners and managers need effective tools to assess the effects of these problems on airports. Techniques currently used for planning, design, and management of airport landside facilities appear inadequate to provide appropriate solutions. Nomographs, empirical data, and rule-of-thumb approaches are overly simplistic, based mostly on gross and generalized assumptions, and unlikely to achieve effective solutions to complex problems in such a dynamic environment as the airport terminal (2).

This paper reviews modeling and simulation from a transportation systems vantage point, presents an overview of the development of airport terminal simulations reported in the technical literature, and concludes with a discussion of state-of-the-art simulation and the future of simulation techniques in airport planning, design, and operation.

MODELS AND SIMULATION

It is important to differentiate between modeling and simulation. Models are generally thought of as an idealized rep-

resentation of reality, as some subject of inquiry that may be already in existence, or as a conceived idea awaiting execution (3,4). Because models are abstractions of an assumed real-world system that can identify pertinent relationships, models are used rather than the real system primarily because manipulating the real-world system would be costly or impossible. In most instances, models are constructed to be simpler than the real-world system because complex systems are difficult to implement and control.

To optimize the accuracy of the simplest possible model, the elements of the model are examined to determine their degree of representation of the real system. Finding the right variables and the correct relationships among them is the essence of good modeling. Although a large number of variables may be required to predict a phenomenon of the real system with perfect accuracy, only a small number of variables usually account for most of the real system. This rule is widely recognized and accepted in modeling—especially in regression. Nonetheless, the reliability of information obtained from a model eventually depends on the validity of the model in representing the assumed real-world system.

Simulation is one type of model. Iconic (physical), analogue, symbolic (abstract), and heuristic are other types of models. Simulations are models that use mathematical-logical representations of the real-world system to convert system descriptions, or input parameters, into output that describes some features of the system. Operations research scientists hold various interpretations of simulation. Taha (4) regards simulation as behavioral imitation of the real-world system over time and seeks to replicate real-world behavior by studying interactions among its components. Shannon (5) interprets simulation as a process of designing a model of real-world systems and conducting experiments to either understand the behavior of the system or evaluate various strategies to operate the system. Pritsker (6) considers simulation models as laboratory versions of systems on which experiments can be conducted as a first step in the design, analysis, and assessment of the performance of real-world systems. Inferences can then be drawn about the real system without the need to physically build, disturb, or destroy it.

Functional types of simulation models are

- Analytic queueing models—probabilistic models that use mathematical expressions derived from queueing theory;
- Accounting models—time-based and deterministic in nature that use predefined rules to describe the state of the system; and
- Time-dependent models—event-based and stochastic in nature that use dynamic equations with mathematical-logical

representations or Monte Carlo methods for fast-time reproduction of the state of the system.

In developing a simulation model, the first step should be to select a conceptual framework to describe the system to be modeled. Essentially, this involves defining a "world view" within which the real-world system's functional relationships are perceived and described (6). If a general-purpose computer language is used (e.g., FORTRAN), then defining the world view and organizing the system description are the modeler's responsibility. On the other hand, if a simulation language or package is used, then the world view is implicit in the simulation language.

Simulation basically employs one of two world views: discrete or continuous. In discrete-event simulation, the system can be described by changes of its state that occur at discrete times (event times); between these times, the state of the system remains unchanged. In continuous-event simulation, the behavior of the system is characterized by equations for a set of state variables whose dynamic behavior simulates the real-world system (the state of the system is represented by dependent variables that change continuously over time).

Discrete-event simulation is normally used for an airport terminal system because no set of equations can be derived to define the characteristics of the airport terminal and describe the nature of the systems operation.

Discrete-event simulation can be of three general types depending on the specific features of simulation. These are event-oriented, activity-oriented, and process-oriented simulations. Objects or basic units within the boundaries of a discrete system are called "entities." Each entity has various characteristics called "attributes." Attributes are characteristics common to those groups of entities that engage in different kinds of "activities" (sometimes called "transactions"). A "process" is a time-ordered sequence of events that may encompass several activities. The relation among an event, an activity, and a process is graphically presented in Figure 1. This representation of simulation is adhered to throughout this paper.

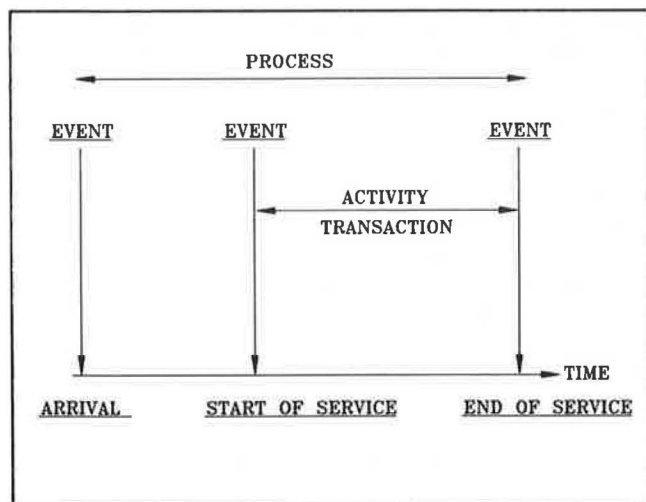


FIGURE 1 Conceptual diagram of service.

A simulation system, whether a language or computer package, could be one of these three general types, could be an object-oriented simulation, or could be a hybrid simulation. A brief description of each follows.

Event-Oriented Simulation

A system is modeled by defining changes occurring at event times and by determining events that can change the state of the system, and then by developing the logic associated with each event type. Simulation is run by executing the logic associated with each event in a time-ordered sequence. This category of simulation languages includes SIMSCRIPT, a FORTRAN-based language that uses English-like statements (7), and GASP, a language that uses a general-purpose computer language (e.g., FORTRAN or PL/I) structured as a conceptual framework with a short main program and supporting routines that are coded by the user in the same general-purpose language to provide event logic and perform different executive functions (8).

Activity-Oriented Simulation

Models are built by describing activities engaged in by entities of the real world and prescribing conditions that cause each activity to start or end. These conditions must be scanned continuously to ensure that each activity is accounted for. This orientation results in a rather cumbersome structure with inefficient computer handling. ECSL (9) is an example of this category; it is used mainly for industrial process control.

Process-Oriented Simulation

The real-world system is modeled by defining the flow of entities through the system on the basis of sequences of events that occur in a predefined pattern, the logic of which can be generalized and used in single statements. Because event logic is implicit and automatically contained in corresponding statements, process-oriented simulations combine features of both event- and activity-oriented approaches. This contributes to the simplicity and the relative ease of use of this approach. GPSS, Q-GERT, SIMPL/I, and SIMULA are process-oriented simulation languages. The most widely used is GPSS, a FORTRAN-based package in which a model is constructed by combining a set of standard "blocks" that maps the logical structure, or network, of the simulated real-world system. Each block is a short subroutine or GPSS macro that performs a particular function on entities and is represented graphically by a standard stylized figure and by a statement containing all parameters (attributes) of the function (10). Q-GERT employs an activity-on-branch network representation, in which entities flow through the network model defined by its nodes and branches that refer to processing time or delay (11).

Object-Oriented Simulation

Model development consists of a highly modular approach used mostly in artificial intelligence (AI) and expert systems

to provide simple, unifying programming and prevents extensive intertwined subroutine coding (12). The basic entities in object-oriented simulation are objects with attributes that have values, or object-attribute-value (OAV) triplets. Each object has rules and procedures associated with the OAV triplets. These objects have the capability to "communicate" with each other through "messages"; upon arrival of messages, OAV and rules and procedures process these messages and carry out their effects. This approach is believed to have great potential in simulation because it can considerably reduce the amount of programming and coding required for real-system representation.

Hybrid Simulation

Hybrid simulation systems incorporate the advantageous characteristics of the alternative simulation approaches in a unified modeling framework. SLAM, Simulation Language for Alternative Modeling, is a hybrid system that can operate in the discrete-event, network, and continuous-event simulation modes. These modes can also operate in the same model. SLAM adopts GPSS's block-statement approach, GASP's discrete-event simulation approach, and Q-GERT's philosophy of graphical representation of networks (6). SLAM is a FORTRAN-based package containing various subprograms, functions, and capabilities that support model development in the alternative modes. In SLAM's network mode, statement blocks call FORTRAN subprograms that model generic activities and transactions, and this can specify organizational structures for simulation model building.

DESIRED PROPERTIES OF SIMULATION

To build and run simulation models efficiently, the simulation system should possess certain minimum requirements for built-in capabilities and facilities (13). They are

1. Flexible methods of describing state changes during an event;
2. Techniques for scheduling events to occur relative to the independent variable time, or upon satisfaction of a set of logical relations of state variables;
3. Extended data structures such as lists and trees and capabilities for easily manipulating these structures;
4. Built-in capabilities for generating random variables and random functions (because many discrete models are stochastic processes);
5. General arithmetic capabilities and methods for gathering statistics and controlling experiments in the system;
6. Interfacing capabilities with other segments of the computer system (e.g., FORTRAN library and standard statistical packages); and
7. Debugging features.

Additional desirable capabilities that are becoming popular in simulation systems are

1. Graphics capabilities to display output of statistical analysis of experiments;

2. Real-time animated graphics of the simulated system, showing entities entering the system and going through different processes and components of the system before leaving the system;

3. A programming and editing capability to facilitate entering and manipulating data structures, programming, and coding; and

4. A "help" function to provide brief useful information on various features of the simulation system while it is in use.

AIRPORT LANDSIDE SIMULATION

As mentioned earlier, simulation is increasingly becoming an essential tool for planning, design, and management of airport landside facilities. Landside-related research started in the late 1960s to investigate the problem of severe congestion and delay in airport terminals resulting from the substantial growth in air travel and the introduction of wide-bodied jets. Researchers in airport landside considered using simulation because of its convenience, reliability, and efficiency in analysis, and its capability in describing detailed activities in a manageable fashion (14). Airport organizations worldwide credited simulation as the most promising method of analysis, because it can efficiently cope with the time-varying nature of demand and the stochastic nature of the air travel system (15).

Characteristics of simulation can vary depending on their features, specific approach in modeling particular situations, and the objective of using simulation in analysis in airport planning. Basic properties of simulation could be static versus dynamic, analytic versus numeric, deterministic versus stochastic, discrete versus continuous, or interactive versus closed. Low (16) treats simulation as a technique for developing artificial historic (synthesized) data for situations described by the airport planner.

Simulation is the preferred tool for airport capacity assessment. As shown in Figure 2, the central step in the process of landside capacity assessment, planning, and management is capacity and level-of-service evaluation (Steps 7 and 8) (2). In Steps 5 and 6, data on demand characteristics, operating conditions, and community factors are collected. Essentially, these steps will determine the level of detail of the simulation model as the analysis tool. In Steps 7 and 8 capacity and levels of service of the different components are evaluated, compared with the service volumes generated throughout operation. A balance should be struck between simplicity, speed, and ease of use of the model on the one hand and accuracy with more detailed representation of the facilities and services of interest, greater need for data, and cost on the other (3). Different functional levels of simulation can be defined by the purpose of the simulation, characteristics of the model, degree of simulation sophistication and detail in representing the real-world system and level of precision anticipated (17), and as follows:

- **LEVEL I:** The simplest and most basic level that considers only fixed peak-demand patterns at each part of the airport (e.g., design peak hour). Time variation and the stochastic element of the system are not taken into consideration.
- **LEVEL II:** Only time variation in average demand, not its stochastic nature, is explicitly considered. Such models do

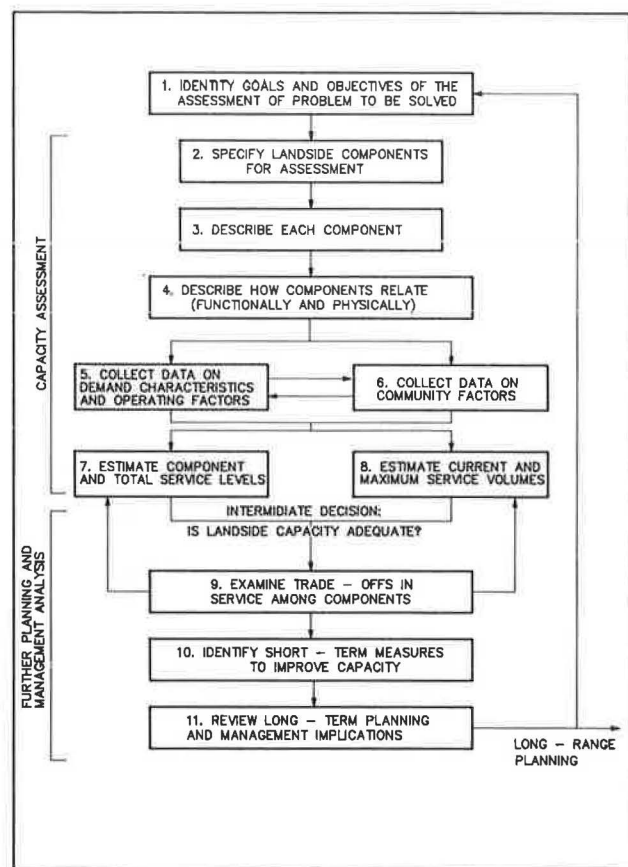


FIGURE 2 Landside capacity assessment, management, and planning (2).

not follow queueing theory, in which congestion and delays are incurred only when average demand rate at a particular time exceeds the maximum service rate (e.g., accounting-type models).

- **LEVEL III:** Probabilistic aspects of demand and the stochastic nature of service are explicitly considered. However, for this modeling level, assumptions of steady-state queueing analysis hold (e.g., queueing theory-based models).

- **LEVEL IV:** Demand arrival and service rates are both probabilistic and explicit functions of time. Calculations involve a high degree of mathematical complexity and can prove to be impractical for computer simulation (i.e., time-varying probabilistic queueing).

Typical of modeling, there is a trade-off between accuracy and cost-effectiveness. Although airport landside capacity can be measured only in terms of an airport's individual functional components, the analyses of individual components' capacities may fail to recognize important functional linkages within the airport landside (3).

It is convenient to group the airport terminal simulation models surveyed by the environment in which they were developed. Models are categorized as those developed by academia, industry, and government.

Academia-Developed Simulation

Universities pioneered research on airport congestion, initiating simulation approaches to solve this problem. The Massachusetts Institute of Technology (MIT) first drew attention to future problems facing air transportation in a workshop convened in 1967 (17). Other U.S. universities followed suit, mainly the Universities of California, Berkeley, and Texas at Austin.

At MIT, Odoni simulated processing facilities of the terminal using analytical queueing models, which were later used to model passenger delay in airports under steady-state queueing conditions (18). As part of the MIT research a simulation model of the terminal building (19) was developed as well as an approach to evaluate alternative terminal designs (20).

At Berkeley, Horonjeff (21) was the leader in modeling airport terminal facilities using deterministic queueing models. Work done at Berkeley included modeling of gate utilization (22–25), baggage claim facilities (26,27), movement in piers (28), processing of departing passengers (29,30), arriving passengers (31), passenger enplaning and deplaning (32), check-in counters (33), security (34), and departure lounges (35). This work, however, did not culminate in a complete and integral airport terminal simulation model.

At Austin, federally sponsored research analyzed terminal operations and evaluated systems' capacity (36). Airport access (37) and passenger flows in terminals (38) were modeled, and a simulation model (ACAP) was developed (39,40). ACAP is a Level II FORTRAN-based, accounting-type model. Its structure is composed of a main program and component modules that simulate individual facilities. The peculiar aspect of ACAP is that the modules' deterministic models are actually regression models derived from survey data collected in the airports studied. In essence, these models draw their predictive power only from the survey data from which they were derived. Hence, these models could not replicate operational conditions except where and when survey data hold. To overcome this shortcoming, the regression-derived, logic-core modules of ACAP were replaced by Monte Carlo models to simulate passenger processing on the basis of average service times of negative exponential distributions (41). This modification transformed ACAP from a Level II to Level III model. Unfortunately, the modified ACAP was not used in a practical application.

AIRSIM was developed in Florida. It is a GASP-based, event-oriented simulation model that dealt with flows of individual passengers and baggage according to flight schedules. The model was tested at the Miami International Airport (42).

Outside the United States, airport simulation studies were done in universities in the United Kingdom, Canada, Australia, Germany, and Denmark. At the University of Strathclyde, Scotland, a terminal simulation model (AIR-Q) was developed (43,44). Research conducted at the Loughborough University of Technology included analyzing behavior of passenger processing in airports (45), processing and service time distributions (46), and simulating individual terminal facilities using SLAM (42).

At Monash University, Australia, international terminal operations were simulated using GPSS and FORTRAN (47). In Denmark, Rallis (48) studied terminal operations, and a

simulation model was established for quantitative evaluation of basic alternative design strategies for terminal extensions of Copenhagen/Kastrup Airport (49). In Germany at the University of Dortmund, Baron developed a simulation model for terminal operations at Dusseldorf Airport (50,51). In Canada, airport modeling research was conducted at the Universities of Toronto (52) and Waterloo and at Carlton University (53) where the airport terminal building was modeled using PERT as sequences of essential functions to process passengers in airports (54,55).

Industry-Developed Simulations

Several consulting firms have established their own airport simulation models that are used in planning, design, and management of airport terminals inside and outside the United States. However, because these models are essentially proprietary, little has been published on their properties and features.

TAMS Consultants, Inc. developed a simulation model for the planning and design of Maiquetia International Airport, Caracas, Venezuela (TAMS, unpublished data, 1972)—a Level III, GPSS-based, time-oriented queueing landside simulation model. A previous version of this terminal simulation model was used to design the Greater Pittsburgh Airport (16). A model for gate selection and occupancy, as part of a comprehensive airfield simulation model, was developed and used for the planning and design of Dallas-Fort Worth Regional Airport (P. Sih, unpublished data, 1973).

Bechtel developed a similar model (Level III, GPSS-based, time-oriented queueing) capable of simulating terminals of up to 50 gates (B. Metais, unpublished data, 1974). The FAA later acquired this model and expanded and embellished it as ALSIM (15), as described later. A modified version of the Bechtel model was used to plan the international airports in Saudi Arabia. This model was demonstrated to the author in 1985. It is used at the International Airports Project in Jeddah, Saudi Arabia. The model is an interactive, GPSS-based model with FORTRAN subprograms.

Battelle (56) developed a Level II, FORTRAN-based, deterministic, accounting-type airport landside model that has fixed service times. This model is similar in its characteristics to ACAP.

Peat Marwick Mitchell & Company developed a time-based simulation model, which has been applied in assessing operations at several U.S. airports (2).

Another proprietary airport terminal simulation model, ATSIM, was developed by Aviation Simulations International (2). ATSIM has been used in the planning of Denver Stapleton International Airport.

Government-Developed Simulations

Government agencies actively support research and development of airport simulation models. In the United States, FAA's policy has been to sponsor research in this area. In Canada and the United Kingdom, similar organizations developed airport simulation models.

Some of the FAA-sponsored airport simulation models were ACAP (discussed earlier), the Airport Landside Model developed by H. H. Aerospace (17) (a Level III model that uses the analytical queueing approach of MIT), and ALSIM, which was acquired from Bechtel Corporation and was subsequently upgraded by the U.S. Department of Transportation Transportation Systems Center (15). ALSIM's properties and features are described in more detail in the next section.

The Port Authority of New York and New Jersey developed a simulation model to evaluate expansion plans for international arrivals at John F. Kennedy International Airport (57). It is GPSS based and uses the time-oriented queueing model approach.

The Canadian Air Transportation Administration developed the Calgary Model, a GPSS-based simulation using time-oriented queueing models (Canadian Air Transportation Administration, unpublished data, 1973). Recently, Transport Canada developed a terminal simulation model composed of three interactive modules for gate assignment (58), ground transportation, and passenger and baggage terminal flow. It has several attractive features, including graphics capability, good editing capabilities, and flight schedule simulator. The modules employ deterministic multichannel queueing models using FORTRAN IV with Monte Carlo sampling technique (59). This model will be discussed in detail in the next section.

The British Airport Authority (BAA) has developed an airport simulation model for gates and individual processing facilities in-house. General properties and features of this model are not known because nothing has been published about it. The author saw a demonstration of this model in 1982 at BAA's main offices in Gatwick. One attractive feature is the real-time animated graphics screen display that simulates passenger flow and processing. Passengers, shown as "blocks" with different colors identifying their attributes, move through the terminal. Predefined attributes determine exactly where each block will go and what processes are to be performed on it. This feature is similar to the one adopted in the TEXAS Model for modeling intersection traffic. This model considers the interaction among individually characterized driver-vehicle units as they operate in a predefined intersection environment. It provides real-time animated graphics simulation of the intersection together with all simulated data output and statistical analysis of the data (64).

DESCRIPTION OF SELECTED SIMULATION APPROACHES

The airport terminal can be modeled on two scales—macroscopic, as one integral system from groundside to airside; or microscopic, where individual facilities are considered separately (41). Each approach has its merits and shortcomings, and it is up to the airport planner to decide which scale to use. The microscopic view may fail to recognize the importance of functional interactions between individual facilities. On the other hand, adopting the macroscopic view may prove to be extremely laborious and costly because it is so data intensive. Of the airport terminal simulations it surveyed, TRB's Special Report on airport landside capacity (2) con-

sidered three simulation approaches. They are FAA's ALSIM, the Canadian Airport Planning Models, and SLAM.

Airport Landside Simulation Model (ALSIM)

ALSIM (15,65) is a macroscopic, probabilistic, discrete-event, fast-time computer simulation model capable of producing flow and congestion parameters and statistics on simulated facilities. The structure consists of main and auxiliary programs (written in GPSS-V, which creates transactions representing passenger and visitor processing and directs them through the model blocks that describe the simulated system), FORTRAN-based supporting subprograms (to provide flight schedule, airport configuration data, matrix manipulation, and assignment of facilities to GPSS-created transactions), and IBM/370 assembly language subprograms to provide linkages between GPSS-V and FORTRAN subprograms. (See Figure 3.)

Model input is grouped into four major categories: flight schedule, passenger characteristics, airport geometry, and facility information. (See Table 1.) The first two describe demand and the last two represent service characteristics of the system. ALSIM produces a statistical report for each facility encountered in a simulation. The report includes total number of persons served, maximum and average number of servers (agents) busy, occupancy, and flow of persons through the system. ALSIM assumptions are as follows:

- Passenger and visitor processing facilities are similar and independent of airport type,
- Random functions govern transfer flight selection and baggage delivery times,
- Service time distributions are independent of time and server workload,
- Single queue lines are used to represent multiserver queues at each facility,
- People proceed directly from one facility to another,
- Exogenous flight schedule provides the time-varying demand, and
- Arrival rates and operations of facilities are determined by the model itself.

Operationally, ALSIM can simulate a 100-gate airport during a busy 5-hr period involving 20,000 passengers on 165 flights. Such a simulation requires about 7 min of CPU time on an IBM/370 mainframe computer (with GPSS-V and FORTRAN IV compilers) and takes 570K bytes of core capacity.

Canadian Airport Planning Models

Transport Canada has developed a set of airport planning simulation models to assist planners and designers in assessing demand, capacity, and levels of service in airport terminal

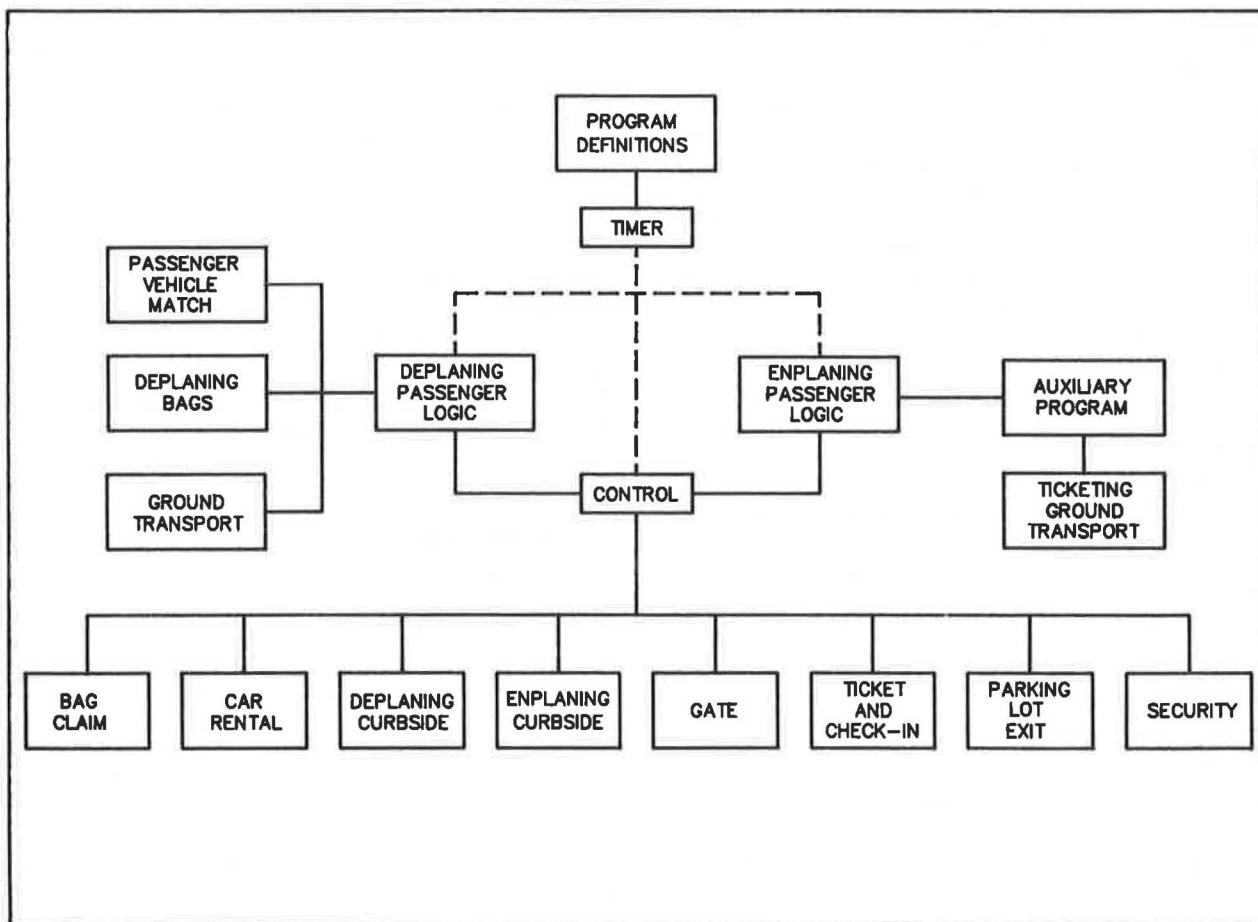


FIGURE 3 Airport landside simulation model program structure (15).

TABLE 1 ALSIM INPUT DATA (15)

1. FLIGHT SCHEDULE CHARACTERISTICS

Flight Number
 Airline
 Arrival / Departure Time
 Aircraft Type
 Domestic / International / Commuter
 Total Passengers
 Transferring Passengers
 Bag Claim Facility Identification Number

2. PASSENGER CHARACTERISTICS

Percent Preticketed
 Percent Using Express Check-in
 Passenger Routing on Landside
 Ground Transportation Modal Choice
 Passenger Group Size
 Well-Wishers Per Group
 Greeters Per Group
 Originating Passenger Times of Arrival Distribution
 Prior to Flight
 Arrival Distribution Greeters
 Arrival Distribution of Vehicles Meeting Passengers
 Distribution of Number of Bags Per Passenger
 Car Rental Agency Selection Distribution
 Percent of Well-Wishers or Greeters Proceeding to Gate
 Percent of Greeters Proceeding Inside Terminal

3. AIRPORT GEOMETRY CHARACTERISTICS

Point Number
 X-Y Coordinates
 Facility Type at Point
 Facility Number Within Type

4. FACILITY INFORMATION

Service Time Distributions
 Car/Taxi Loading and Unloading Times
 Number of Servers or Size of Facility
 Baggage Transport Times to Claim Area

and groundside facilities (Transport Canada, unpublished data, 1988). These models are interactive, interrelated, and mutually compatible separate models that run on an IBM-AT compatible microcomputer. They are structured in front and end segments programmed in BASIC/PASCAL and a middle segment, the simulator model, programmed in FORTRAN IV. These three models are the gate assignment model, air terminal passenger flow simulation model, and ground transportation simulation model.

Gate Assignment Model

This model is a deterministic multichannel queueing model, operating in 5-min intervals (58; G. Singh, unpublished data, 1988). Gates are assigned to flights in the schedule according to the assignment strategy specified by the user. Each flight is assigned in the order that they appear in the flight schedule. Required input consists of the flight schedule (up to 300 flights) created by a computer editor and the airport description. The

airport description input includes aircraft class by seating capacity, carrier preference (up to 30 carriers), gates (up to 100), service times in minutes of aircraft arriving at and departing from gates, gate conflict (up to 50) defining any intergate restrictions caused by aircraft or gate size incompatibility, and time equal to the aircraft push-out maneuvering time.

Simulation output includes a listing of the two-way passenger flow through each gate, a Gantt Chart assigning aircraft to gates, statistics on gate utilization and aircraft and passenger delays, and a step chart plotting the cumulative number of aircraft on gate in each 5-min interval over the simulation period or time span of the schedule.

Air Terminal Passenger Flow Model

The air terminal passenger flow model is an interactive event-oriented stochastic simulation model that simulates flow of passengers along predefined paths from curb to aircraft and vice versa (Transport Canada, unpublished data, 1988; F. Mangano, unpublished data, 1988). The model consists of three interactive segments: the airport terminal description data entry and edit module, the simulator module, and the statistics report generation module. Special data files are created using the data entry and editor module. Data required as input include the following:

1. Identification of carriers, sectors, terminal users, aircraft types, passenger types, and baggage claim;
2. Description of layout of air terminal building by identifying gates, links, processing facilities, separators and meeting areas, baggage dispensers, waiting, and holding rooms;
3. Arrival distribution tables;
4. Processing rate distributions;
5. Sequential lists of node numbers identifying paths used in the terminal;
6. Ratio tables of visitors to passengers by hour of day and by sector; and
7. Flight schedule that includes 17 different attributes for each flight.

The program processes terminal users through the building according to the information provided by the airport terminal description entry module. The simulation module is then activated. Each element of a flow path representing a part of the terminal building (node) is acted upon, assigned a next event time, and moved sequentially through its designated flow path. Each transaction is associated with 19 attributes that are used in the logical control of the transactions when simulation progresses as described by the airport description file. When a transaction enters a baggage area, a probabilistic match is performed based on passenger arrival rates, baggage arrival rates, and bag-to-passenger ratio. The statistical report generation module then accesses the output files created by the simulation module to print the output data specified by this module. Simulation output includes the following:

1. Cumulative number of users entered and exited, present count in facility, maximum accumulation of users, and time of maximum accumulation for each facility;
2. Summary of baggage device assignment statistics;

3. Queue statistics for each processor including total and maximum user queue time, number of users in queue, frequency distribution of queue times, and flight causing maximum congestion; and
4. Summary of delay statistics for each flight.

Ground Transportation Model

The ground transportation model is an interactive program developed to simulate the flow of vehicular traffic along access and egress road systems of the airport (Transport Canada, unpublished data, 1988; G. Singh, unpublished data, 1988). Movement of traffic on roads, parking lots, and curbs is simulated through a description of the road network, vehicular flow patterns and paths, and behavioral characteristics of the vehicles on the road system. The simulation approach applies the survey statistics and flow path information to each flight in the schedule, employee schedule, visitor schedule, and cargo schedule. Vehicle transactions are created as they move through the road link system. At each part of the system, transactions are acted upon, assigned a next event time, and moved through their prespecified paths. Statistics are gathered whenever a vehicle enters or exits an element in the road network.

Required data input consists of

1. Road link system and associated transit times;
2. Vehicular and user flow along the road link system;
3. Time distribution relating vehicle creation to flight arrival and departure times;
4. Visitor-to-passenger ratios, modal split, average vehicle occupancy by mode, curb processing distribution, and mass transit schedule and demand parameters;
5. Aircraft flight schedule; and
6. Arrival and departure schedules for employees, visitors, and cargo.

The model's output can provide information on any combination of the eight attributes (current node, next node, path, transportation mode, trip purpose, user type, sector, and flight number). Output statistics include time-interval occupancy counts for each link in the simulated network. Output includes the following information on each link: time, total number of vehicles entering and exiting the time interval (broken down into passenger, visitor, employee, and cargo vehicles and private cars, taxis, rental cars, and mass transit), present vehicle count at end of interval, and maximum vehicle count for time interval and time of its occurrence.

Alternative Simulation Method for Individual Facilities

SLAM was used to simulate individual processing facilities of the airport terminal (41). This is a microscopic approach to simulating terminal facilities in which input requirements are minimal. Each facility is modeled by writing a short program consisting of SLAM network-mode statements that best describe the operation of the facility. The major input is number of channels (servers), processing rate of each, service discipline, and arrival distribution of demand. A user function USERF(I)

(7) was used to simulate an aggregate stochastic arrival distribution on 20-min intervals, closely representing the arrival distribution for the facility actually observed (41). This SLAM function simulates any pattern of arrival distribution, an essential requirement that provides accurate simulation of operation and a realistic performance model. Using a randomly sampled arrival rate from a standard probability density function would have been erroneous and unrealistic.

As an example, the following model in SLAM network-mode statements was used to simulate the departure official controls (security and passport checks) (41):

```

NETWORK;
CREATE,USERF(1);
ASSIGN,ATRIB(1)=TNOW;
ASSIGN,XX(2)=XX(2)+1;
COLCT,XX(2),PAX ARRIVING;
SECK QUEUE(1);
ACT/2,EXPON(0.15,2),,PASP;
PASP COLCT,INT(1),TIME IN SECURITY,20/0/0.75;
ASSIGN,ATRIB(2)=TNOW;
QUEUE(2);
ACT/3,EXPON(0.12,3),,EXIT;
EXIT COLCT,INT(2),TIME IN PASSPORT,20/0/0.5;
TERM;
ENDNETWORK;
INIT,0,250;
MONTR,SUMRY,0,20;
FIN;

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All major input describing the operation at this facility is represented as parameters to SLAM statements in this example. For instance, CREATE USERF(1) will assign a prespecified (user-defined) arrival rate corresponding to the observed rate at the particular simulation time (TNOW). COLCT will record total number of arrivals in the time interval (20 min) to the first facility, security check (SECK). This arrival will be assigned to the security process queue [QUEUE(1)], where the security check takes place if the queue is empty. The statement ACT/2,EXPON(0.15,2),,PASP will perform a security check (ACTivity 2) for a time duration whose value is randomly selected from a negative exponential distribution with an average rate of 0.15 min per transaction before directing the entity (passenger) to the next facility, the passport check (PASP). The simulation time (TNOW) is changed to the current time after completion of security check. The entity (passenger) is now ready for passport check (ACTivity 3), which commences immediately if the queue [QUEUE(2)] is empty. The processing time for passport checks is randomly sampled from a negative exponential distribution with an average rate of 0.12 min per transaction, after which the entity EXITS. The statements (TERM) and (ENDNETWORK) mark the end of the model and termination of simulation, and the statement (MONTR) produces a summary report on all operations between initializing and terminating the simulation (in this case 250 min). This example is modeled using the SLAM network mode. SLAM's discrete-event mode could have been used as well. A user-written, FORTRAN program would replace the SLAM network statements.

Standard SLAM output includes statistics on processing operations at a facility at any desired time or time interval.

Statistics for the example are collected for TIME IN SECURITY and TIME IN PASSPORT. Such statistics as maxima, minima, averages, variation of queue length, queue time, server utilization, and number of entities in each facility can be gathered.

SLAM can also be used for the macroscopic simulation approach. Of course, the programming involved will be much more detailed with a more complex modeling structure than the example. The macroscopic approach was used to establish the performance models for individual facilities at varying service volumes and demand levels (41). Separate FORTRAN segments will be needed to relate various parts of the model and provide the means to input arrival distributions at the system boundaries.

SUMMARY

Airport terminal simulation models developed in academia, industry, and government were reviewed. An overview of modeling and simulation was presented. Definitions, terminology, conceptual approaches to modeling, types of simulation, and simulation languages used to model airport terminal systems were reviewed and discussed. To evaluate different simulation systems and set selection criteria, desirable technical properties of simulation systems were presented. Three simulation approaches to model the airport terminal were presented in detail and implementations of these approaches were discussed.

General conclusions are as follows:

1. Airport landside simulation is an effective tool that airport planners and managers can use to provide synthesized data to help plan individual facilities and the relationship between all facilities that compose the landside. The efficiency and reliability of landside simulation for planning and operational analysis depend on the particular application. Although it is ideally suited for planning purposes, namely, capacity and performance analyses of new or existing facilities, simulation may be less efficient for operational analysis of the system. This is because of extreme variations in system attributes caused by the probabilistic nature of system operations and the need to provide quantified level-of-service criteria for all components of the landside.
2. Airport landside simulations are data intensive and, depending on the specific features of the simulation and scale of application, generally require relatively high computer capabilities. However, most of the recently developed simulation systems can be operated on standard advanced technology microcomputers.
3. Desirable features for landside simulation include the ability to use standard microcomputers, flexible programming methods for simulating state changes and system representation, efficient programming and editing capabilities to facilitate manipulation of the data structures, and graphics capabilities to display output of statistical analyses and real-time animated graphics of the simulated system.
4. Airport landside simulation has advanced in stages over the past two decades using conventional computer simulation techniques to their maximum capabilities and either general purpose languages (e.g., FORTRAN) or simulation lan-

guages (e.g., GPSS). A different approach is apparently needed in the future to enhance the efficiency and reliability of simulation. Such enhancements include more efficient and flexible programming logic and structure, modular and interactive simulation, better real-world animation capabilities and graphics display, and more manageable data structure editing capabilities. It is believed that object-oriented programming has good potential for facilitating enhancements to airport landside simulations in the coming years.

REFERENCES

1. Airport Terminal Inquiry. *Progressive Architecture*, Vol. 3, March 1987, pp. 96-103.
2. *Special Report 215: Measuring Airport Landside Capacity*. TRB, National Research Council, Washington, D.C., 1987.
3. C. Churchman, R. Ackoff, and E. Arnoff. *Introduction to Operations Research*. John Wiley, New York, 1960.
4. H. Taha. *Operations Research—An Introduction*, 3rd ed. Macmillan, New York, 1981.
5. R. Shannon. *Systems Simulation: The Art and the Science*. Prentice-Hall, Englewood Cliffs, N.J., 1975.
6. A. Pritsker and C. Pegden. *Introduction to Simulation and SLAM*. John Wiley-Halstead Press, New York, 1979.
7. E. Russell. *Simulating with Processes and Resources in SIMSCRIPT II.5*. CACI, Inc., Arlington, Va., 1963.
8. F. Cellier and A. Blitz. GASP V: A Universal Simulation Package. *Proc., 8th AICA Conference on Simulation of Systems*, Delft, Netherlands, Aug. 1976, pp. 391-402.
9. A. Clementson. *Extended Control and Simulation Language: User's Manual*. CLE.COM Ltd., Birmingham, England, 1982.
10. P. Bobillier, B. Kahan, and A. Probst. *Simulation With GPSS and GPSS V*. Prentice-Hall, Englewood Cliffs, N.J., 1976.
11. A. Pritsker. *Modeling and Analysis Using Q-GERT Networks*. Halstead Press-Pritsker and Associates, Inc., West Lafayette, Ind., 1977.
12. D. Hu. *Programmer's Reference Guide to Expert Systems*. Howard W. Sams, Ind., Ind., 1987.
13. J. McCredie. The Structure of Discrete Event Simulation Languages. *Proc. of the 1970 Summer Computer Simulation Conference*, Denver, Colo., June 1970, pp. 88-97.
14. L. McCabe and T. Carberry. Simulation Methods for Airport Facilities. In *Special Report 159: Airport Landside Capacity*, TRB, National Research Council, Washington, D.C., 1975, pp. 112-123.
15. L. McCabe and M. Gorstein. *Airport Landside Simulation Model (ALSIM)—Volume II: Description and User's Guide*. Report FAA-EM-80-8-II. Federal Aviation Administration, Transportation Systems Center, Cambridge, Mass., June 1982.
16. D. Low. Use of Simulation in Airport Planning and Design. *Transportation Engineering Journal*, ASCE, Vol. 100, No. 4, Nov. 1974, pp. 985-996.
17. B. Schriver and W. Seifert. *Air Transportation, 1975 and Beyond: A Systems Approach*. MIT Press, Cambridge, Mass., 1968.
18. D. Gentry and K. Doyle. *The FAA's Airport Landside Model: Analytical Approach to Delay Analysis*. Report FAA-AVP-78-2. Federal Aviation Administration, Jan. 1978.
19. J. Pararas. *Analytical Models for the Design of Aircraft Terminal Buildings*. M.S. Thesis. Massachusetts Institute of Technology, Cambridge, Mass., Jan. 1977.
20. D. Fay. *An Evaluation of Alternative Terminal Design for Airports*. M.S. Thesis. Massachusetts Institute of Technology, Cambridge, Mass., 1971.
21. R. Horonjeff. Analysis of Passenger and Baggage Flows in Airport Terminal Buildings. *Aircraft Journal*, Vol. 6, No. 5, 1969, pp. 446-451.
22. R. Belshe. *A Study of Airport Terminal Gate Utilization*. Graduate Report. ITTE, University of California, Berkeley, Aug. 1971.
23. H. Van Wyen. *A Look At Airplane Arrival and Departure*

- Maneuvering Times in the Gate and Apron Areas*, Graduate Report. ITTE, University of California, Berkeley, Aug. 1968.
24. G. Stewart. *Utilization of Gate Positions at Metropolitan Airports*. Graduate Report. ITTE, University of California, Berkeley, Aug. 1969.
 25. J. Edwards. *A Look At the Factors Which Affect Gate Requirements at Airports*. Graduate Report. ITTE, University of California, Berkeley, Aug. 1967.
 26. J. Tanner. *A Queueing Model for Departure Baggage Handling at Airports*. Graduate Report. ITTE, University of California, Berkeley, Aug. 1966.
 27. W. Barbo. *The Use of Queueing Models in the Design of Baggage Claim Areas in Airports*. Graduate Report. ITTE, University of California, Berkeley, Sept. 1967.
 28. E. Smith and J. Murphy. *Pier Finger Simulation Model*. Graduate Report. ITTE, University of California, Berkeley, Aug. 1968.
 29. E. Keely. *A Study of Processing Characteristics for Departing International Airlines Passengers*. Graduate Report. ITTE, University of California, Berkeley, Aug. 1968.
 30. A. Hammond. *A Study of the Departure Process at the San Francisco International Airport*. Graduate Report. ITTE, University of California, Berkeley, Aug. 1972.
 31. P. Castellon. *An Empirical Investigation of the Arrival Process at San Francisco Airport*. Graduate Report. ITTE, University of California, Berkeley, Aug. 1970.
 32. E. Kaneko. *Passenger Enplaning and Deplaning Characteristics*. Graduate Report. ITTE, University of California, Berkeley, Aug. 1967.
 33. J. Widmer. *Effect of Alternative Operation Policies on Check-In Counter Design*. Graduate Report. ITTE, University of California, Berkeley, July 1977.
 34. J. Roman and G. Jackson. *Analysis of Airport Security Processing*. Graduate Report. ITTE, University of California, Berkeley, Aug. 1974.
 35. R. Paullin. *Passenger Flow at Departure Lounges*. Graduate Report. ITTE, University of California, Berkeley, July 1966.
 36. W. Dunlay, F. McCullough, et al. *A System Analysis Procedure for Estimating the Capacity of an Airport: System Definition, Capacity Definitions and Review of Available Models*. Council for Advanced Transportation Studies, University of Texas at Austin, Oct. 1975.
 37. W. Dunlay. *Model of Airport Employee Access Traffic*. *Transportation Engineering Journal*, ASCE, Vol. 104, No. 3, May 1978.
 38. W. Dunlay and C. Park. *Tandem-Queue Algorithm for Airport User Flows*. *Transportation Engineering Journal*, ASCE, Vol. 104, No. 2, March 1978, pp. 131–149.
 39. N. Gualda. *Modeling the Airport Terminal Building for Capacity Evaluation Under Level of Service Criteria*. Ph.D. Thesis. University of Texas at Austin, 1978.
 40. F. McCullough and F. Roberts. *Decision Tool for Analysis of Capacity of Airport Terminal Buildings*. In *Transportation Research Record 732*, TRB, National Research Council, Washington, D.C., 1979, pp. 41–54.
 41. S. Mumayiz. *A Methodology for Planning and Operations Management of Airport Passenger Terminals: A Capacity/Level of Service Approach*. Ph.D. Thesis. University of Technology, Loughborough, England, 1985.
 42. W. Olsen. *The Development and Testing of AIRSIM—A Computer Simulation Model of the International Terminal at Miami International Airport*. Department of Urban and Regional Planning, Florida State University, Tallahassee, Fla., April 1973.
 43. G. Calderbank and A. Kirke. *AIR-Q: A Program Package for the Simulation of An Airport Terminal Complex (ABACUS)*. University of Strathclyde, Glasgow, Scotland, 1972.
 44. L. Laing and J. Gentles. *AIR-Q Mk II: A Comprehensive Simulation Package*. Paper No. 47, (ABACUS), University of Strathclyde, Glasgow, Scotland, Jan. 1976.
 45. D. Bennetts, N. Hawkins, P. McGinity, M. O'Leary, and N. Ashford. *Survey Analysis of Airport Terminal Passenger Processing*. Department of Transport Technology Report TT 7502. University of Technology, Loughborough, England, April 1975.
 46. D. Bennetts, N. Hawkins, P. McGinity, M. O'Leary, and N. Ashford. *Stochastic Modelling of Airport Processing*. Department of Transport Technology Report TT 7509. University of Technology, Loughborough, England, July 1975.
 47. C. Cheng and P. Gilmour. *Computer Simulated Passenger Service Levels for Airport Terminals*. *Airport Forum*, No. 4, 1978, pp. 106–107.
 48. T. Rallis. *Terminal Transportation Engineering—Part I: Airport*. Technical University of Denmark, Copenhagen, Denmark, 1963.
 49. E. Bastiansen, J. Hviid, and P. Matthiesen. *Simulation Defines Alternatives for Copenhagen Terminal Expansion*. *Airport Forum*, No. 1, 1981, pp. 21–24.
 50. P. Baron. *A Simulation Analysis of Airport Terminal Operations*. *Transportation Research*, Vol. 3, No. 4, Dec. 1969, pp. 481–491.
 51. P. Baron and D. Henning. *The Passenger Terminal—A Systems Analysis Approach*. *Airport Forum*, Feb. 1974, pp. 69–82.
 52. E. Hauer. *Runway Simulation—Readings in Airport Planning*. Center for Urban and Community Studies, University of Toronto, 1972.
 53. J. Braaksma and J. Shortreed. *Methods for Designing Airport Terminal Concepts*. *Transportation Engineering Journal*, ASCE, Vol. 101, No. 2, May 1975, pp. 321–335.
 54. S. Yagar. *Analysis of Passenger Delays in Airport Terminals*. *Transportation Engineering Journal*, ASCE, Vol. 99, No. 4, Nov. 1973, pp. 909–921.
 55. J. Braaksma. *Computerized Design Method for Preliminary Airport Terminal Space Planning*. Ph.D. Thesis. University of Waterloo, Ontario, Canada, 1973.
 56. Battelle Memorial Institute. *Computer Program Description: Airport Demand/Capacity Analysis Method*. Battelle-Columbus Laboratories, Columbus, Ohio, Sept. 1974.
 57. R. Nanda, J. Browne, and R. Lui. *Simulating Passenger Arrivals at Airports*. *Industrial Engineering*, Vol. 12, March 1972, pp. 12–19.
 58. S. Hamzawy. *Management and Planning of Airport Gate Capacity: A Microcomputer-Based Gate Assignment Model*, Presented at the 65th Annual Meeting of the Transportation Research Board, Washington, D.C., 1986.
 59. W. Chang, C. Lee, and F. Mangano. *Computer Simulation of Terminal Utilization*. *Airport Forum*, No. 3, 1978, pp. 63–67.
 60. C. Lee et al. *User-Friendly TEXAS Model for Intersection Traffic*. Research Report 361-1F. Center for Transportation Research, University of Texas at Austin, July 1988.
 61. L. McCabe and M. Gorstein. *Airport Landside Simulation Model (ALSIM)—Volume I: Planning Guide*. Report FAA-EM-80-8-I. Transportation Systems Center, Cambridge, Mass., June, 1982.

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