Interactive Computing Techniques in Airport Master Planning

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Fully implemented interactive computer techniques were employed at Battelle's Columbus Laboratories during each of 2 site-specific airport case studies for the Federal Aviation Administration: Chicago's Midway (1974) and New York's La Guardia (1975). The runway demand forecasts used during these contract studies varied widely by time of day and by season of the year. These time-varying patterns created a need to estimate corresponding aircraft runway delays and aircraft runway queue lengths. These airport airside level-of-service estimates were computed by using a set of simultaneous differential equations derived from classical nonstationary queuing theory. Many quantitative operating variables have to be accounted for during a computer analysis of this type. Depending on the purpose of the analysis, certain categories of variables may be independent input variables in one situation and dependent output variables in another situation. A high degree of computational and operational computer flexibility is therefore required during such an analysis. This paper highlights the interactive computer techniques developed and used during the 2 airport case studies. A typical application is also presented to illustrate the scope and flexibility of these advanced techniques. The paper concludes with a summary of experience gained with the described computer program and the interactive programming techniques employed to significant advantage.

A common element in airport master planning is the estimation of runway capacity requirements that match future air transportation demand forecasts. The Federal Aviation Administration (FAA) developed a 2-part runway capacity advisory circular in the late 1960s to assist transportation planners in this area of airport master planning (1, 2). Many possible runway configurations are treated in these advisory circulars, including a broad range of runway capacity estimates for aggregate categories of aircraft operating conditions.

Many fixed assumptions were used to compute the quoted capacity values. Outdated air traffic control (ATC) procedures also were strong influences. These characteristics limit the usefulness of the advisory circulars during discriminating analyses of alternative air traffic control conditions that may exist in the future. This is especially true for 20-year airport plans that are common in current airport master planning (3).

The FAA was recently confronted with a situation of this kind in which the existing advisory circular capacity methods did not permit an in-depth analysis of the effects of future operating variables on runway delays and aircraft queue lengths. Battelle's Columbus Laboratories was awarded several FAA contracts in 1973 to conduct 2 site-specific airport case studies (4, 5). These studies were part of a series of FAA case studies concerning the feasibility of using underused secondary airports to increase the air transportation system capacity of major metropolitan cities.

The following discussion highlights the runway delay analysis capabilities that were developed and used during the course of these site-specific airport studies. It will be shown that interactive computing techniques were employed to significant advantage throughout the analysis process.

The methods to be described were not submitted to the FAA as new airport master planning standards. However, this site-specific experience has contributed to the FAA's continuing efforts to improve the state of the art in this field. Other contractor studies are currently under way at the FAA to finalize new runway capacity planning standards (6).

PROBLEM DEFINITION

In classical queuing terminology, a runway is a "server" and the aircraft operating from that runway are the "customers". For safety reasons, a given runway can serve only 1 customer at a time. In actual practice, these customers arrive to be served in a somewhat regimented, time-varying pattern throughout the day. In some cases, a given runway is expected to accommodate both arriving and departing customers. Alternatively, a given runway may be devoted exclusively to either arrivals only or departures only. In either event, there are certain times and conditions when 1 or more customers will queue up and incur delays while waiting to be served by a given runway. It should be noted that this definition of delay is not necessarily the same as the deviation of actual arrival

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time from scheduled arrival time.

The time-varying dynamic characteristics of runway use create the need to estimate aircraft runway delay or queue length of both for different operating conditions. In other words, an airport planner's ability to accurately determine the need for additional runways (more capacity) is greatly improved by the ability to compute the likely impact of growth of aircraft demand on average delay levels. The major analytical problem here is to provide the planner with an efficient computational means for estimating the effects of forecast aircraft demand on runway capacity and runway delay.

EXPANDED RUNWAY CAPACITY DEFINITION

The capacity of an airport runway system can be defined in several different ways. In the absence of a level-of-service criterion (such as average aircraft delay) capacity can be defined rather simply as the maximum number of aircraft that can be processed per unit of time through a given runway system under conditions of continuous aircraft demand. This definition often takes the form of an hourly maximum runway acceptance rate for various operating conditions such as aircraft fleet mix, wind conditions, and weather conditions. The focus of concern is on the physical ability to maintain the maximum possible throughput of aircraft. Delays encountered by aircraft that have to wait to use the available runway capacity are not recognized explicitly under this definition. Alternatively, if concern is expanded to include aircraft that have to wait under continuous demand conditions, an expanded definition of capacity must be used.

The concept of an expanded capacity definition is shown in Figure 1. This characterization can be used to illustrate several important relationships among aircraft demand, capacity, and delay. The first variable of interest is the forecast pattern of daily aircraft demand. This variable must be considered even before the forecast level of daily aircraft operations is treated.

There are several types of demand patterns, and each pattern uniquely defines the relationships shown in Figure 1. The 3 most common patterns encountered at scheduled air carrier airports include

1. Either 1 peak in the morning commuter hours or 1 peak in the late afternoon commuter hours,
2. One peak in the morning commuter hours and 1 peak in the late afternoon commuter hours, and
3. An essentially rectangular pattern between the morning commuter hours and the late afternoon commuter hours.

When the daily aircraft demand pattern is specified for a given airport and time period, the total daily aircraft operations for this condition are required. This is the variable shown as the abscissa in Figure 1.

It is next necessary to estimate the runway system acceptance rate for the previously noted conditions and other variables, such as runway configuration, aircraft fleet mix, weather conditions, and ATC separation standards. A range of possible runway system acceptance rates are illustrated by the family of curves in the upper right-hand portion of Figure 1.

For a given daily aircraft demand pattern, daily aircraft demand level, and runway system acceptance rate, there is but 1 unique value of average daily aircraft delay (that is, ordinate value). For example, given points A and B in Figure 1, a low level of average aircraft delay (point C) can be expected. Alternatively, given points A′ and B′ in Figure 1, a high level of average aircraft delay (point C′) would be expected. It is in this sense that delay can be used to expand the originally stated acceptance rate definition of airport runway system capacity. In actual practice, this requires the deductive selection of an average daily aircraft delay criterion that represents a "satisfactory" level of runway system service. For example, a few minutes of aircraft delay may be considered satisfactory for a given airport (point x in Figure 1). This point then uniquely defines the maximum permissible number of daily aircraft operations (point z in Figure 1) for a given runway system acceptance rate (point y in Figure 1) and a given pattern of daily aircraft operations. Adoption of this expanded runway capacity concept leads to the need for an analysis capability that permits the simultaneous computation of aircraft runway delays and aircraft runway queue lengths for various combinations of future possible operational variables.

REQUIREMENTS FOR ANALYTICAL FLEXIBILITY

Before we proceed with the details of the interactive programming techniques, the reader should recognize that the previously stated concept of runway capacity can be used for analysis purposes in 4 significantly different, optional ways. The major attributes of these 4 analytical options are given in Figure 2.

The basic difference among the options is the category of runway capacity variables treated as dependent, or output, variables as contrasted with the variables that are treated as the independent, or assumed, input variables. A brief definition of each of the 4 categories of variables is necessary for an understanding of the similarities and differences between each analysis option.

The aircraft demand category given in Table 1 is made up of a number of operational attributes that affect the flow of aircraft through the runway system. Quantifiable attributes include such variables as the daily pattern of aircraft arrivals and departures, aircraft approach and takeoff speed, and wake vortex class. The values of these demand variables change slowly with time as airlines modify schedules and acquire new aircraft, and the airport planner must factor these airline trends into his or her demand variable forecasts.

The ATC standards category given in Table 1 consists of various operational variables that air traffic controllers influence through application of FAA-defined flight control procedures. There are 2 basic weather situations in which fundamentally different aircraft separation standards apply. In weather with adverse visibility, instrument flight rules must be employed by the controller to maintain safe aircraft separation distances. In clear weather, visual flight rules may be employed. The FAA continues to improve and automate the electronic aids available to controllers and pilots. These developments periodically permit aircraft separation reductions and thereby increase the maximum throughput rate capability of runways. Airport planners should factor these improvements into their forecasts for future time periods.

The runway configuration category in Table 1 consists of the number and type of runways needed to operate under the various operational conditions described by the previous 2 categories of variables. Runway needs can range from a single runway to a multiple set of dependent or independent parallel or crossing runways depending on the level of airport demand. The airport planner should rely on established FAA standards (advisory circulars) to determine the allowable minimum spacing between multiple runways after their need has been established.

Figure 1. Relation of runway system demand, capacity, and delay.

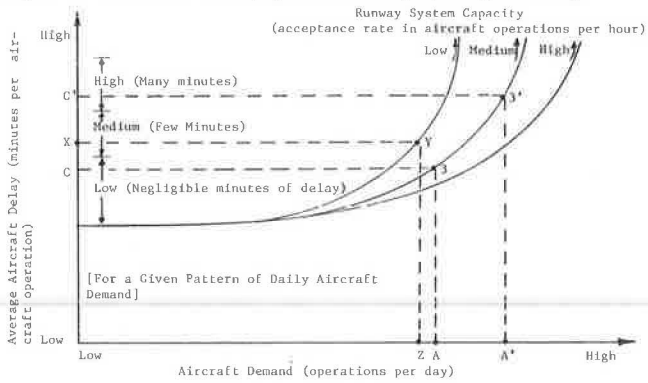

Figure 2. Average delay for current and proposed separation standards.

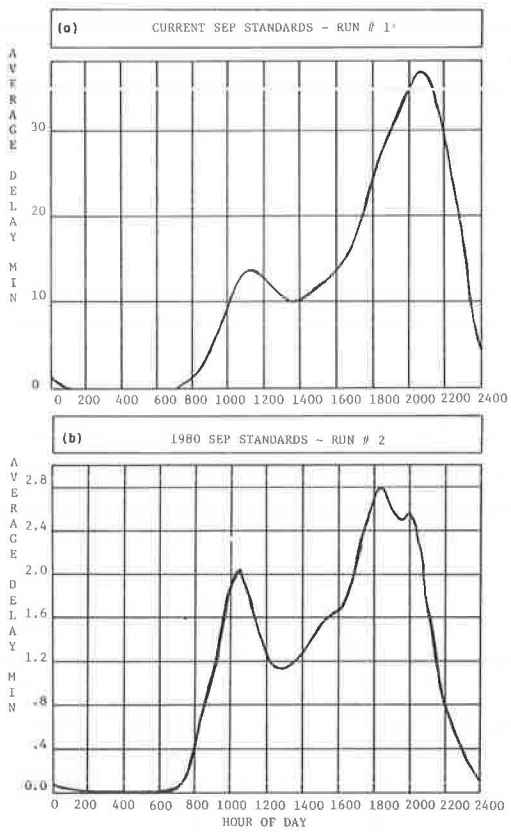

Table 1. Runway capacity analysis options.

Option	Aircraft Demand and Pattern	ATC Standards	Runway Configuration	Average Delay Criterion
1	Independent	Independent	Independent	Dependent
2	Independent	Independent	Dependent	Independent
3	Independent	Dependent	Independent	Independent
4	Dependent	Independent	Independent	Independent

Table 2. Aircraft mix data.

Class	Type	% of Mix	Approach Speed (m/s)	Wake Vortex Class
Jumbo jet	B-747	14	745.9	Heavy
Tri jet	DC10, etc.	29	694.5	Heavy
Long range	B-707-320, etc.	5	694.5	Heavy
Medium range	B-727-200, etc.	12	668.8	Light
Short range	B-737, etc.	40	643.0	Light

Note: 1 m/s = 0.19 knots.

The fourth category of variables given in Table 1 includes 2 interrelated runway performance variables. These variables include aircraft delay and aircraft queue length. These impacts must be computed for any given combination of the preceding variables regardless of the analytical option employed. However, this is a 1-time computation for a given set of assumed independent variables under option 1 whereas a succession of iterative delay and queue length computations may be required to satisfy the analytical requirements of options 2 through 4. For example, under option 2, assume that an average runway delay criterion of 4 min is independently and arbitrarily selected as the maximum average standard for delay. Let it be further assumed that the airport planner is trying to estimate the need for more runways at an existing airport where demand and ATC conditions are specified as independent input variables. A delay computation would first be made to determine whether the existing runways could accommodate the assumed case without exceeding the established 4-min delay standard. One of 3 results could occur. First, analysis might yield a value of, say, 2 min. If this were to happen, the planner would conclude that the forecast case could be accommodated without more runways. Second, the delay result might be very close to 4 min. The planner would again conclude that additional runways would not be needed for the time period of the assumed case. However, the planner would also know that no further aircraft demand growth could be accommodated without exceeding the preestablished 4-min delay standard. Third, the delay computation might yield an answer of 20 min. This outcome clearly leads the planner to conclude that the existing runways cannot simultaneously satisfy the established delay criterion and accommodate the assumed level of demand. It now becomes necessary to iterate the delay computation by successively modifying selected demand variables until a value of 4 min is attained. When this determination has been made, all of the removed demand is then analyzed separately to establish how many additional runways are needed to finally satisfy the 4-min delay standard for all aircraft operations. This phase of the analysis may require a succession of iterations before a combination of variables and runways is found to satisfy the preestablished delay criterion.

This brief discussion highlights the analytical flexibility required during Midway (4) and LaGuardia (5) airports case studies. In essence, the capability was sought to manipulate a large matrix of selectable variables, all of which have a varying degree of effect on aircraft delay or aircraft queue length or both. The manner in which this analytical objective was met through the application of contemporary interactive computing techniques will be described in the remaining sections.

DESIGN OF THE COMPUTER PROGRAM

To be effective, a computer program must satisfy many requirements that may be grouped into 2 general categories called the computational and operational requirements. These 2 sets of requirements, although dependent on each other, are quite different.

The computational requirements for a given problem are usually expressed in the form of a mathematical model that describes the calculations required to determine the solution. Computational requirements are application specific and do not lend themselves to many generalizations.

The operational requirements specify the operating environment within which the computational requirements

must be met. These requirements include

1. Manner in which the program is to be used by the analyst,
2. Degree of flexibility desired,
3. Response time required,
4. Form of the input and output, and
5. Degree of interactive user assistance.

In contrast to the computational requirements, a set of operational requirements usually has wide applicability to other similar problems, and much of the programming effort can be used in other similar applications. Transportability of the program may be another operational requirement although it was not a necessity in this case. The program is currently operational on a Control Data 6400 computer. It can be used with either a Tektronix 4012 graphics terminal or a teleprinter. Ninety-five percent of the program is coded in FORTRAN and 5 percent is coded in COMPASS, a Control Data corporation assembly language.

Computational Requirements

In general, the procedure for computing runway delay is to first compute a runway acceptance or service rate (capacity). Using this derived service rate as input with an aircraft demand rate, a queuing model computes the probability that there are 0, 1, 2, . . . n aircraft in the runway system for each step in time. Given this set of probabilities, the average runway queue length and delay can be computed for each step in time.

The service rate computation is a straightforward operation. The derivation of a deterministic service rate model, however, is based on many variables and can become quite complex (5). Computation of the queuing statistics from the probabilities for a single runway is trivial and for more than 1 runway is only slightly more difficult (6). The most demanding computation is in determining the probability that there are 0, 1, 2, . . ., n aircraft in the system at a given step in time. This calculation involves the numerical integration of a set of simultaneous first-order differential equations (7) with time-varying coefficients. The coefficients represent the service and demand rates for the runway for a specific step in time. The number of simultaneous differential equations is dependent on the maximum number of aircraft permitted in the runway system. For n aircraft, there is a corresponding set of n + 1 differential equations. The demanding aspect of the computer implementation of this type of queuing model is in making it efficient and cost effective.

A significant improvement in computer time for the program was achieved by varying the number of differential equations in the system instead of maintaining a fixed number throughout the day. An algorithm was designed that permits the program to manage the maximum queue length by tracking the probability that there is an aircraft in the queue corresponding to the maximum permitted length. As this probability reaches a significant value (determined experimentally), the maximum queue length is extended an arbitrary amount (also determined experimentally) thus adding a few more differential equations to the set. The maximum permitted queue length was decreased when the probability decreased below a certain value (determined experimentally).

Operational Requirements

The program had to meet many operational requirements. The more significant ones were to

1. Support an active "person-in-the-loop" iterative solution technique,
2. Be usable by airport planners with little or no experience with interactive programs,
3. Afford a good measure of user protection of the investment in the program learning time yet maintain the flexibility to add new capabilities,
4. Require a minimum of effort to maintain a dialogue with the program, and
5. Display the results in a meaningful manner for end users.

Many of these same requirements are present in most scientific applications that are used by several persons.

The question of whether to implement the program in a batch or interactive computing environment was not a difficult one. Only the interactive environment afforded the degree of user control over the analysis process that was deemed necessary for iterative solutions. The interactive environment, however, is much more demanding in the programming effort required to control and maintain an effective dialogue with the user (8).

Several techniques were used to accommodate airport planners unaccustomed to using computers in an interactive environment. These techniques included use of a simple program-control scheme, reduction of the effort required to communicate with the program, and use of extensive diagnostics.

Two different approaches may be used for program control in an interactive environment. The user-driven control is one in which the user selects the next operation to be performed; the procedure-driven control is one in which the program proceeds automatically to the next predetermined operation. The familiar on-line text editor is an example of a user-driven control scheme that relies on the user to specify which type of text editing operation is to be performed next. The procedure-driven approach first prompts the user for the input required at a given step in the procedure and then performs the programmed operation. Although the user-driven approach is much more flexible, it is more difficult to learn than the procedure-driven approach. The procedure-driven approach was well suited to this application because of the nature of the methodology of the solution technique. Sufficient "backtracking" and override capabilities were built into the program at various points to compensate for limited flexibility.

A minimum of effort in program communication is usually achieved by use of a translator that supports a tailored language. Rather than expend the effort required in development of the translator, we used the standard FORTRAN NAMELIST as an input mechanism for most of the data required by the program. With this input mechanism, the user is presented with a list of variables, of which some, all, or none may be changed for a given computation. This type of input is of the general free field form variable = value in which spaces and decimal points are not important within data fields. NAMELIST input also has the advantage of being transportable to other machines.

To reduce errors and protect the user from selecting illogical choices, we used extensive diagnostics to test for inconsistencies of input variables. One such section applies nearly 50 diagnostic tests to the input data before proceeding to the next request for input. User learning time was protected by freezing the basic program operating concepts with the adoption of an add-only policy. This concept required that no programming changes could be made to dialogue meanings or operating procedures after new versions were released.

Thus, after a long time, the original user would find that the program functioned exactly the same as it had previously.

The output of the program is in the form of tables and plots. The tables are used to summarize the input and output, and the plots provide detail for the queuing statistics as a function of the hour of day. The program is operational on either a teleprinter or a direct-view storage tube and presents either printer plots or line plots, depending on the type of terminal being used.

SAMPLE PROBLEM AND RESULT

This typical application will illustrate how the developed program was used to forecast the impact of improved FAA air traffic control procedures on aircraft delays for a large metropolitan airport. FAA analysts were concerned with improvements in technology for the year 1980 that could permit significant reductions in the minimum airspace separation distances between aircraft. The described interactive program was used with data for the existing (1973) situation at the airport from a recently published FAA report (9) and then was exercised to determine maximum aircraft delay and aircraft queue length levels. A second run immediately followed in which only the forecasted improvements in the separations standards were changed.

Runway configuration was as follows:

1. Two parallel and independent runways,
2. Takeoffs and landings interleaved 1:1, and
3. High-speed [23.15 m/s (45 knots)] turnoffs.

Aircraft demand daily pattern was for Friday, May 4, 1973; the peak-hour demand was 142 operations. Instrument flight rules longitudinal separation standards (9, p. A-17) were as follows:

Leading Aircraft Wake Vortex Class	Run 1, 1973 ATC (km/h)	Run 2, 1980 ATC (km/h)
Heavy	9.3	5.5
Light	5.5	3.7

Aircraft mix data are given in Table 2. A complete definition of the input data used is available elsewhere (9). The interactive computer dialogue required to enter the input data is not shown in this paper in the interest of brevity. To indicate the degree of effort required, however, a total of 20 values were entered to obtain the first run and 2 values were changed for the second run. Selected output for the 2 computations is shown in Figure 2 and indicates that, for the same demand rate, the peak aircraft delay can be expected to improve significantly from 37 min to only 2.8 min. The major impact of reducing the assumed aircraft approach separation distances is largely a significant improvement in the maximum runway acceptance rate (aircraft operations per hour). For these 2 cases, the rate improved from 127 to 170 operations/h.

SUMMARY AND CONCLUSIONS

The computer program described in this paper originally took approximately 4 person-months to develop and has been used over a period of 2 years at Battelle's Columbus Laboratories to perform various airport analyses during 4 U.S. Department of Transportation contracts. The program has undergone 9 modifications since initial development, but the result of the add-only policy has been to increase the capabilities of the program such that the first version remains a subset of the current version.

It is difficult to quantify the time savings and efficiency gained by having an on-line computer analysis capability that is always ready for transportation analysts deeply involved in a wide variety of studies. The results have been gratifying. The program has been used by several analysts with no prior interactive computing experience after a minimum of learning time. The ability of these analysts to use the program without having to rely on an experienced programmer speaks well of the operational efficiency designed into the program.

The range of the program has been from studies of small general aviation airports to studies of large metropolitan airports. In some cases, the problem was to estimate future runway capacity requirements for a given forecast of aircraft demand. In another situation, the problem was to estimate the maximum level of demand permitted by a given level of capacity. In each case, a given maximum runway delay criterion was used to define a desirable level of passenger service. The most comprehensive study performed to date involved a determination of the impact of the FAA's upgraded third generation (UG3RD) air traffic control system on future runway delay levels at the 30 largest U.S. domestic hub airports. This study was part of a larger FAA program directed toward the costs and benefits of implementing various UG3RD component systems. The range of these applications illustrates the flexibility that has been designed into the existing program. Modifications and extensions from the original program version can be easily made to suit the priorities of the particular study. This evolutionary growth capability has maximized the original programming investment and has permitted the development of new capabilities to suit the needs of particular sponsors.

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