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AIRPORT IMPROVEMENT TASK FORCE DELAY STUDY: DELAY MODEL VALIDATION PLAN

AUGUST 1977

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16. Abstract

A validation plan is presented for an airside simulation model. The plan stresses basic principles of validation and inherent problems associated with comparing simulation model delay estimates with observable real-world data. A methodology is proposed that consists of three major steps: (1) evaluation of model logic, inputs, and outputs; (2) comparison of model estimates with collected data; and (3) a sensitivity analysis of the delay simulation model. A Model Validation Group, established to oversee the validation process, is described. Suggestions are given on sources of data on airside operations for model inputs and for comparisons with model estimates.

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Model Validation Working Subgroup

Chairman: John R. VanderVeer - Analysis Branch, National Aviation Facilities Experimental Center (NAFEC), FAA

Members: George P. Vittas - Director/Airport Planning, American Airlines

Ronald F. Birk - Manager/Airfield Planning, Eastern Airlines

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Dr. William J. Dunlay, Jr. - Dept. of Civil & Urban Engineering, University of Pennsylvania

The substantial contributions of these individuals to the development of the model validation plan is gratefully acknowledged.

The author is also grateful to Mr. Ray H. Fowler, the Technical Officer of this contract, for his valuable assistance and guidance.

DELAY MODEL VALIDATION PLAN

by

William J. Dunlay, Jr.

I. INTRODUCTION

Purpose

The purpose of this report is to present a validation plan for a fast-time, stochastic, delay simulation computer model. The validation effort is part of Phase I of contract No. DOT-FA77WA-3961 with Peat, Marwick, Mitchell & Co. The objective of the validation is to test whether the model is satisfactory (to the Technical Officer) for its intended application in Phase II of the contract, namely for delay estimation at seven airports in support of six Airport Improvement Task Forces.

Model Validation Group

A Model Validation Group has been appointed by Technical Officer to oversee the validation process. This is a very significant aspect of the validation plan since a variety of expertise is required to evaluate a model of a system as complex as the airport airside system.

There are many precedents to using an overseeing committee in the validation of simulation models. In fact, Van Horn suggests below that it is part of an ideal validation:

> "Ideally a comparison test should handle nonstationarity, compensate for noisy data, simultaneously evaluate a number of output measures and work for small samples. Does such a test exist? The answer is yes if one is willing to define test very broadly. The test is simple. Find people who are directly involved with the actual process. Ask them to compare actual with simulation output."[1]

The Model Validation Group consists of the following individuals:

[1] Van Horn, R. L., "Validation of Simulation Results," Management Science, Vol. 17, No. 5, Jan. 1971, p. 252.

DELAY MODEL VALIDATION GROUP

Philip J. LaRochelle - Chairman
Ray H. Fowler - Vice Chairman

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1. Dr. William J. Dunlay, Jr. - Dept. of Civil and Urban Engineering, University of Pennsylvania
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3. Cecil B. Smith - Airfield Planning Engineer, Delta Airlines
4. Ronald F. Birk - Manager/Airfield Planning, Eastern Airlines
5. James V. McGinn - Vice President, Regional Operations, Air Transport Association of America (ATA)
6. Leo F. Duggan - Vice President, Technical Affairs, Airport Operators Council International (AOCI)

General Considerations

The validation of any computer simulation model of a complex system is a very difficult task. It is a part of a more general problem, namely the validation of any kind of model or hypothesis, about which there is much literature but very little agreement. One textbook on computer simulation states that "...the problem of verifying simulation models remains today perhaps the most elusive of all the unresolved problems associated with computer simulation techniques."[2] Richard L. Van Horn mentions two important characteristics of the validation problem:

> "1. The objective is to validate a specific set of insights not necessarily the mechanism that generated the insights.
>
> 2. There is no such thing as 'the' appropriate validation procedure. Validation is problem dependent."[3]

Van Horn's point is that it is the major attributes of the particular processes to be simulated that must guide the general approach to a validation.

Validation holds a special and important role in computer simulation models. Unlike most analytical models, simulation models tend to conceal their assumptions and internal processes from the casual observer. Furthermore, the nature of simulation models can vary dramatically. For example, as Van Horn points out, "The simple statement that model x is a linear programming model conveys a great deal of information about its structure, assumptions, and limitations. The statement that model y is a simulation conveys virtually no information."[3] Therefore, the validation of a simulation model requires an investigation of the model's internal structure in addition to comparing the input-output transformations generated by the

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[2] Naylor, et al., Computer Simulation Techniques, New York: John Wiley & Sons, Inc., 1966, p. 310.

[3] Van Horn, R. L., p. 248.

model to those generated by the real world.

Any model validation should be carried out in two basic steps:

(1) a check of the validity of the assumptions and logic of the model; and

(2) a comparison of the estimates produced by the model to real world observation.

There is very little disagreement among modelers that both of these steps are required. In his book on systems analysis, de Neufville states that "... statistical analysis cannot be a sufficient test of any model. The validity of a systems model also rests on the plausibility of its a priori theoretical base."[4]

That the two foregoing steps are required follows from the fact that it is the predictive power of the model that is of concern, not the explanatory power. That is to say, it is not sufficient to test just the goodness-of-fit of the model to observed data. Naylor states that "... the ultimate test of a computer simulation model is the degree of accuracy with which the model predicts the behavior of the actual system (which is being simulated) in the future."[5]

Unfortunately, because one cannot observe the future, it is not possible to directly validate the predictive capabilities of a simulation model. Instead, one must rely on the evidence of how well the model fits observable data coupled with the evidence of how well the logic and assumptions of the model seem to make it extrapolatable to other (non-observable) situations.

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[4] deNeufville, R., Systems Analysis for Engineers and Managers, New York: McGraw Hill Book Co., 1971, p. 266.

[5] Naylor, et. al., p. 318.

The foregoing difficulties apply to situations where the real-world situation is easy to observe (measure). "The problem of model validation becomes even more difficult if the available data about the 'actual' behavior of the world is [sic] itself subject to error."[6] This certainly applies to the simulation model being considered. Observed values of delay, travel time, holds, etc., are subject to significant field measurement errors. Even if these quantities could be accurately measured, they are subject to large random fluctuations.

There are a few more complications that apply particularly to when one tries to compare delays suffered by arrivals in the airspace, a very important component of total airside delay, as estimated by the model to corresponding real-world values.

First of all it is difficult to separate airspace delays due to destination-airport congestion from those due to en route congestion or ATC instructions. A second and closely related problem is that those airspace delays that are attributable to the destination airport's capacity constraints are not all incurred at one point. Such delays, for example, may be incurred en route at the advice (say speed control or path stretching) of a controller or dispatcher, i.e., delays can back up to various distances before the aircraft arrives at the terminal airspace.

Overview of Validation Approach

This validation must proceed in spite of, but also cognizant of, the foregoing inherent problems of validation. Towards this purpose, the validation plan incorporates the following two key ideas:

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[6]Naylor, et al., p. 318.

(1) A variety of comparisons should be made between model estimates and real-world measures rather than rely on just a single validation variable. By doing so the Model Validation Group can weigh all the evidence in deciding whether or not the model satisfactorily fits measured data.

(2) It should be recognized that, in the end, the decision as to the model's acceptability for its intended application is a subjective one based on a combination of statistical hypothesis testing and just "eyeballing" certain aspects of the model's outputs, logic, and sensitivities. Hypothesis tests should be conducted in such a way that they don't presume to make the decision as to acceptance or rejection, but instead, simply supply a quantitative measure of goodness-of-fit of the model's estimates.

Listed below are the three major steps to be followed in the validation of the delay simulation model.

(1) Evaluation of the model's detailed logic and assumptions, the scope and kinds of inputs, and scope and kinds of output.

(2) Evaluation of how well model estimates of delays, travel times, and flow rates compare with our best available real-world measurements of these variables.

(3) Evaluation of the sensitivities of the model to changes in certain key inputs and assumptions.

Each of these three stages of the approach is described in detail in the following sections.

II. MODEL LOGIC AND ASSUMPTIONS, INPUTS, AND OUTPUTS

Scope and Kinds of Inputs

One aspect of the contractor's simulation model that should be evaluated is the required inputs for its application. There are about five specific questions about the inputs that should be addressed as listed below:

(1) Are the inputs sufficient to represent the operations at an airport? In answering this question one must consider the list of inputs in the contractor's User's Manual and other inputs provided by the pre-processors.

(2) Are the inputs sufficient to distinguish among the different possible runway-use configurations at a major airport and also the different airspace routings of aircraft to these different use patterns?

(3) Are the inputs sufficiently sensitive to local, i.e., airport-specific, conditions?

(4) How difficult is it to obtain the required inputs? Is this excessive given the expected benefits of applying the model?

(5) How sensitive is the required set of inputs to possible future changes in

   (a) runway-use configurations?

   (b) aircraft mix?

   (c) terminal building size and configuration?

   (d) noise abatement strategies?

   (e) energy and fuel conservation measures in aircraft operation?

   (f) aircraft separations and other ATC rules?

Model Logic and Assumptions

There are two major kinds of assumptions made in any simulation model: (1) simplifying assumptions and (2) statistical assumptions.

As abstracts of the real world, simulation models necessarily involves simplifying assumptions. Examples include constant aircraft speeds on approach, runway exit used independent of airline, and arriving-aircraft taxiing route dependent only on runway exit and destination gate (or hold area). These assumptions should be clearly identified and listed by the contractor to facilitate evaluation by the Model Validation Group.

There are three major types of statistical assumptions. The first is whether a given quantity is assumed a fixed constant or a random variable. The second is a probability distribution for each random variable. The third type of statistical assumption has to do with the statistical dependencies among the various random variables. For example, aircraft approach speeds are assumed a random variable with a normal distribution with parameters dependent upon aircraft class. Furthermore, in assigning approach speeds, successive aircraft speeds are assumed to be statistically independent.

All such assumptions should be clearly specified in the contractor's presentation of the model. In addition, any prior empirical validation of the assumptions should be described. The validation group should decide whether any additional empirical comparisons are desirable.

The model logic consists of the foregoing assumptions and the relationships among the variables of the airside system as implied by the way the model manipulates the variables. These relationships and manipulations should be evaluated by each member of the Model Validation Group against his knowledge and understanding of airfield operations. To facilitate such an evaluation, the contractor should provide macro-logic flow charts that "walk the group through" the simulation showing what happens to a particular aircraft from the time it enters the system on arrival to when it departs the system. The contractor should describe the types of aircraft interactions and other airside situations that the model can handle. The Model Validation Group should judge whether these interactions and situations are representative of conditions actually encountered at large complex airports.

At the meeting where the contractor discloses the model logic to the Model Validation Group, the contractor should also describe the details of prior validations of the model. All prior sensitivity analyses of the model should also be presented by the contractor at that meeting. Furthermore, the contractor should demonstrate that the model is operational on a time sharing computer system at the time of the model disclosure meeting.

The overall behavior of the airside system being simulated is strongly influenced by air traffic controllers and dispatchers acting as decision makers and information processors. The fact that these influences are not explicitly modeled in the contractor's fast-time model complicates the process of validation. There are, however, implicit elements of the model logic designed to reflect certain types of controller and dispatcher actions. These elements will be evaluated as to their realism by the Model Validation Group.

Scope and Kinds of Output

The quality of the outputs can, of course, be no better than that of the inputs and logic. Nevertheless, one evaluation criteria for the model is level of output detail that it presents about the level-of-service experienced on an airfield by a given demand pattern. For example, does the model provide delay information by cause, location, type of aircraft, airline, etc.? Is there sufficient flexibility in cross tabulating and aggregating the outputs for subsequent analysis? To answer these questions the Model Validation Group should evaluate the raw model outputs and the outputs of the post-processors.

Besides outputs related to delays, the validation group should also investigate the options for obtaining output data on level-of-service measures such as queue lengths, travel times, flow rates, and known bottlenecks.

Approach to Validating Inputs, Logic, and Outputs

It is proposed that the validation of the model inputs, logic, and outputs be accomplished by a contractor presentation to a working sub-group of about eight persons.

The contractor should provide macro-logic flow charts of the model to the members of the working sub-group ahead of time so that they can examine the logic of the model in detail. Members should then submit written questions to the contractor at least one week in advance of the presentation so that the contractor can focus and structure his presentation on the issues raised by the questions. In addition, the presentation should include a description of all prior validations of the model logic and assumptions.

The contractual requirement for the model is that it be a fast-time, stochastic simulation which simulates arriving aircraft within terminal airspace, landing and movement through the taxiway system up to and including operations in the gate area and similarly through the departure phases. Operation of the delay model should provide information which includes the magnitude and time distribution of airfield delay.

As part of the full and complete disclosure of the workings and code of the model, the Chicago Model Validation Group will require a description of the airport operation characteristics that are simulated in the model, e.g., runway occupancy, approach aircraft interaction with other aircraft, gate management and operations for different gate configurations, taxiway usage (intersections, aircraft taxi speeds, etc.), departure interaction and interarrival gap spacing based on departure queues. This information will permit comparison with the coded logic to verify that the described operations are simulated by the logic. Secondly, the group would determine during this effort if the simulation can represent real-world operations at Chicago.

It is often desirable to check one of the very basic elements of a simulation model's logic, namely its arithmetic, by relaxing all of the stochastic assumptions of the model and using it to solve a very simple (even trivial), hypothetical example that can be checked by hand or by using simple deterministic models. The contractor should describe in his presentation any such checks of the model that were performed in the prior construction and development of the model. The validation group should then decide whether or not any further checking of this type would be desirable.

III. EMPIRICAL VALIDATION OF MODEL OUTPUTS

As stated earlier, a variety of comparisons will be made between model estimates and actual observed data; in particular, comparisons based on the following variables:

(1) airspace delays to arrivals and departure delays

(2) ground travel times for both arrivals and departures,

(3) aircraft flow rates

(4) departure queues , and

(5) penalty box (holding) and pushback delays.

The first three variables require some additional explanation; this is presented below.

Airspace Delays to Arrivals and Departure Delays

If data on airspace delays are used as a validation variable it is essential to know the specific runway configurations in use when the delays were incurred. This information can be obtained either from tower records or from direct observations made in the tower. The problems associated with obtaining an adequate sample of delay data for particular runway-use configurations will severely limit the number of runway-use configurations that can be validated especially at an airport like O'Hare where conditions are so variable.

The problem of obtaining an adequate sample for a given runway configuration is illustrated in Fig. 1.

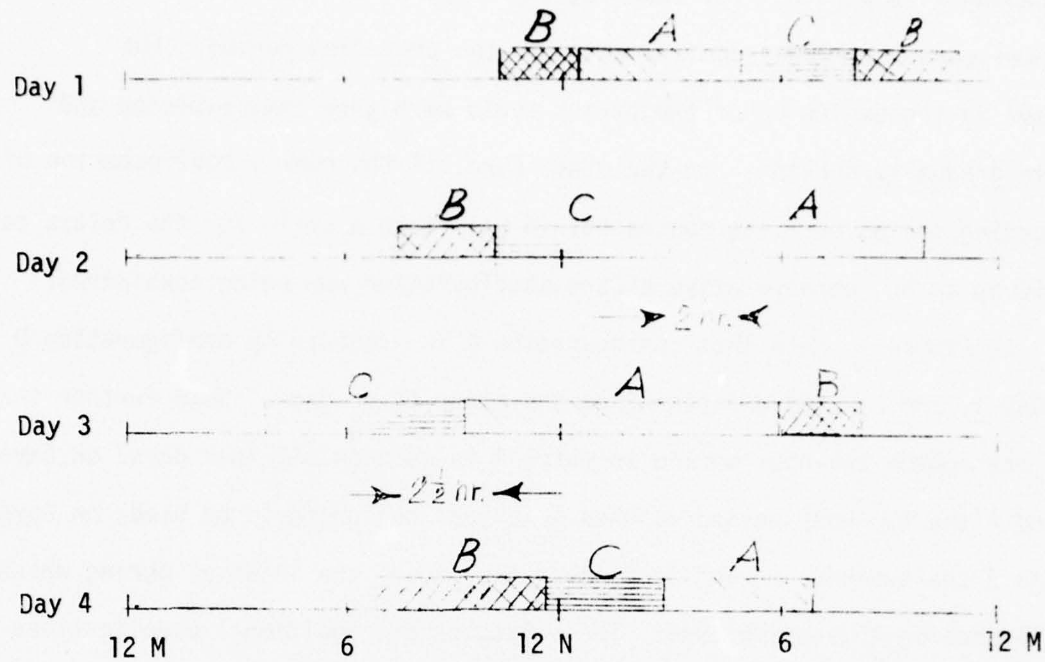

Fig. 1 Occurrence of Particular Runway Use Configurations, A, B and C.

The shaded bars in Fig. 1 represent the time during which three runway configurations (A, B, and C) are in use. Suppose it is desired to observe a given configuration, say A, during approximately the same time period for a sample of n days.

Note that, for all four days of Fig. 1, there is a common 2-hour period (see dashed lines) during which configuration A is used. Configuration B, is not so repetitive; it is, however, used during a common 2-1/2 hour period on Days 2 and 4; similarly for configuration C.

It is important to note that the delays encountered in a given time period (especially at the beginning of the period) with a given runway configuration may depend heavily on the runway configurations used the immediately preceding time period. For example, there may be aircraft left over from a lower-capacity runway configuration in the preceding period; thus delays in the beginning of the period would be higher than expected and would gradually decline. On the other hand, if the runway configuration of the preceding period was less congested, it will take a while for the delays to build up to be representative of the configuration now being considered.

In Figure 1, note that configuration A is preceded by configuration B on Day 1, and by configuration C on the other three days. Note further that, for the common two-hour period in which A is used on all four days; on Days 2 and 4 the two-hour period is when A is just beginning to be used; on Days 1 and 3 the two-hour period falls near the end of the interval during which configuration A is being used. These factors are additional complications to the process of choosing appropriate samples of actual data for comparison with model estimates.

For the reasons cited above, it is probably not feasible to obtain adequate samples of identical time periods on successive (assumed-independent) days. Instead, samples will consist of a number of observations made on individual days, i.e., in successive time intervals on the same day. Thus, different days will represent different samples to be treated separately rather than averaged together.

The foregoing treatment may be characterized as time series analysis. More will be said about the particular time series analysis assumptions and techniques recommended for this validation later in this report.

Ground Travel Times

Travel times accumulated by the model are fixed at a minimum level by the model input for the airfield layout. They will increase depending upon runway occupancy time and delays. Average travel times can be calculated without model operation directly from the model input by summing all paths to the gates from the runways and assigning weights based on the exit taxiway utilization factors. Average travel times are determined by and reflect the conditions of the airport and runway-use configurations. The results of the model output for negligible delays can serve as calibration data. The addition of delays to travel times in the model logic appears to be an evaluation factor for consideration by the Model Validation Group.

Travel times (both in the air and on the ground) are an important output of the simulation model because they may differ for different runway configurations. Thus, travel times are an important level-of-service measure of a particular runway-use configuration that should be considered along with delays when comparing configurations. It is important, therefore, that the model be able to predict differences in the travel times, both in the approach airspace and on the ground, associated with alternative configurations.

Airlines have taxi-in times measured from wheels-on to the gate and taxi-out times from the gate to wheels-off. These differ slightly from the model outputs; the discrepancies, however, are small (say 5-10 seconds) and, because they are relatively constant, could be factored out of airline data.

The travel times produced by the model are random variables. For comparison with the model estimates, a random sample of airline data on ground travel times will have to be obtained. The airline data should be field checked for accuracy and to see if the actual taxiway routings and the model routings are comparable. If it is judged that the airline data are not satisfactory, then field measurements of travel times will have to be used.

Aircraft Flow Rates

Aircraft flow rates are recommended as a third validation variable. Flow rates accumulated by the model are a function of the number and type of aircraft arriving in a given sequence at the runway and the separation standards employed in the input. The flow rates are limited by the capacity of the runway-use configuration.

The number of operations accomplished in various size time intervals (e.g., a particular fifteen-minute or a one-hour period, the morning peak, the whole day) as estimated by the model should be compared to corresponding field measurements of these operation rates. This should be done for both arrivals and departures. The contractor should also present details of prior validations of the model's ability to accurately estimate flow rates.

Statistical Treatments

One of the most difficult and troublesome aspects of validation is the statistical comparison of model estimates with observed, "real-world" data. This can take many forms. According to Van Horn, "Often simple comparisons of means, ranges and variances and graphical comparison of distributions or time behavior will capture most of the available information."[7] Going beyond this and doing statistical hypotheses testing is possible, but great care must be taken in selecting appropriate tests for this purpose.

The literature contains frequent warnings about the statistical nature of the output of simulation models. Hsu and Hunter, for example, warn that,"... data from many simulation models are often not serially independent of time, a fact which seriously affects the validity of the (standard statistical) tests."[8]

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[7] Van Horn, p. 252.

[8] Hsu, D. A. and Hunter, J. S., "Analysis of Simulation-Generated Responses Using Autoregressive Models," paper accepted for Management Science, 1977, p. 2.

Fishman and Kiviat similarly point out that, "As simulation data are generally autocorrelated, an investigator cannot apply the statistical tools commonly used for studying independent observations."[9]

The autocorrelation[10] problem mentioned in the foregoing caveats cannot be ignored. Fishman and Kiviat go on to say that, "Ignoring autocorrelation is clearly unacceptable, since the reliability of the sample means and variances are thereby overestimated."[11] Besides, as Hsu and Hunter point out, "...serial correlation in time is itself an important characteristic of the system being simulated," that can be compared statistically to the corresponding serial correlation structure of the real world data as part of the validation of model outputs.[12]

Based on the above discussions, there are two principal candidate methods for use in a statistical analysis of the output of the contractor's fast-time simulation model vis-a-vis observed data, one proposed by Hsu and Hunter and the other proposed by Fishman and Kiviat. Both of these methods are time-series methods that consider the autocorrelation structure of the simulated data and the observed data.

The method of Hsu and Hunter is an autoregressive time series model that simultaneously compares means, variances, and autocorrelation structures of two time series. More precisely, "...an inferential statistic...is used to compare two time series simultaneously with respect to their estimated autoregressive parameters and variances. A second inferential statistic...is then employed to examine the differences in the means of the two autoregressive time series."[13]

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[9]Fishman, G. S. and Kiviat, P. J., "The Analysis of Simulation-Generated Time Series," Management Science, Vol. 13, No. 7, March, 1967, p. 526.

[10]Autocorrelation is a measure of the linear dependence of a process on its past.

[11]Fishman and Kiviat, p. 526.

[12]Hsu and Hunter, p. 2.

[13]Hsu and Hunter, p. 3.

Appendix D shows an example of applying the Hsu-Hunter method to an air traffic control model.

Fishman and Kiviat suggest applying "spectral analysis" to the study of time series data generated by simulation models. They use an autocorrelation function, a spectral density function, and a statistic called "correlation time" as a statistical description of the two time series being compared. The variance of the sample mean of each time series is shown by Fishman and Kiviat to depend on these statistics and, once obtained, can be used as the basis for hypothesis testing that involves comparing the spectral density functions of the simulated and observed time series.

One of the two foregoing methods will be used to compare the various time series output by the contractor's model, e.g., delays, travel times, queue lengths, flow rates, to the corresponding measured time series for these quantities. Both methods involve the assumption of a covariance-stationary process.[14] Comparisons will be made of single realizations, i.e., the model output for a single random number seed, versus data observed on an individual day, and also of averages over several random number seeds and days. The sum total of these statistical comparisons will enable the Model Validation Group to make a reasonable judgment as to how closely the simulation output approximates the real-world data collected at O'Hare.

It is assumed in the foregoing statistical analysis that the random number streams corresponding to the different "seeds" are not correlated. The contractor should guard against choosing seeds that give streams of random numbers displaced by only a small number of values. In his presentation of the model logic, inputs and outputs to the eight-man working

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[14]A convariance-stationary process is one in which neither the covariance structure nor the expected value of the time series is a function of time.

sub-group, the contractor should describe how the different random number seeds are chosen and whether or not a check has been made that the different streams are uncorrelated.

Concluding Remarks - Empirical Verification

By comparing model estimates of airspace delays, ground travel times, and flow rates with measured data, one can base an evaluation of the goodness-of-fit of the model on a variety of empirical evidence. The decision as to the adequacy of the model for Phase II, however, must also be based on an evaluation of the model's logic and its fine-grained sensitivity as described in the next section.

IV. SENSITIVITY ANALYSIS OF THE MODEL

This third phase of the model validation is aimed at exploring certain properties of the model itself. It will probably not involve any field data collection or statistical hypothesis testing.

A sensitivity analysis usually involves evaluating the change in one or more key outputs (e.g., estimated delay) resulting from systematic changes in one or more input parameters. There are several reasons why one might want to do this. One is that if the model outputs are very sensitive to small changes in one of the input parameters, then that parameter will have to be measured very accurately and assumptions about that parameter closely scrutinized; if not, less measurement accuracy is satisfactory.

A second reason is to evaluate how extrapolatable the model is to new, non-observable situations by systematically varying one or more inputs and then judging the resulting output changes predicted by the model against what we would expect to happen from our knowledge and experience. Thus, the sensitivity of the model is a very important aspect of its logic, For example, one may wish to examine the delay (flow rates, gate congestion, etc.) that result from incrementally adding new aircraft to the existing demand. Or one may want to determine whether the model can reasonably predict the effect of a major perturbation such as a sudden drop in ceiling and visibility that is known, a priori, based on past experience at a particular airport to have a dramatic effect on delays.

A third possible reason for a sensitivity analysis is to evaluate how sensitive the results are to simplifying and statistical assumptions. Suppose an assumption is made that is, for one reason or another, not well documented. If it turns out that the model output is very sensitive to small deviations from our assumption, then an effort should be made to further check (and possibly revise) the assumption. This is another indication that the sensitivity analysis is a very important adjunct to our evaluation of the model logic.

The eight-man working sub-group, described earlier under model logic, should also oversee the fine-grain sensitivity analysis. They should decide which parameters to fix and which to vary for the sensitivity demonstration. Furthermore, the contractor should describe in detail all sensitivity analyses done during prior model development and demonstrations during the disclosure of model inputs, outputs, and logic to the sub-group.

V. DATA COLLECTION

In this validation exercise data will be required for two principal purposes:

(1) to provide the necessary inputs for the model, and

(2) to provide a sample of observed data against which model estimates can be compared.

The model input data can be further subdivided into four categories: (1) model specification data, (2) airside specification data, (3) demand specification data, and (4) airport operation data. Detailed lists of each of these four categories are given in Tables 1 through 4. These tables also suggest, for each data item, primary and secondary data sources and the party responsible for obtaining the data. Table 5 presents a similar description of data required for comparison with model outputs.

A subsequent plan for data collection, reduction, and analysis will present greater detail on the actual methods and equipment to be employed, manpower required, runway configurations to be studied, etc. It is likely that some minor adjustments will be made to the descriptions of Tables 1 through 5 as the data collection progresses.

Following the approximate three week period of data collection, the data reduction can proceed in two phases:

(1) reduction of data for model inputs

(2) reduction of comparison data on model outputs.

This reduction effort will be very time consuming if it is not carefully planned in advance. Existing computer programs for reading and manipulating the data (say from the contractor or other sources) should be used to the fullest extent possible. Detailed data collection procedures should be planned with the subsequent reduction requirements uppermost in mind.

TABLE 1. INPUT DATA - MODEL SPECIFICATION

No.	Data Type	Data Description	Primary Source	Secondary Source	Responsibility
1	Run Title	Name of simulation run	Designated by Model Validation Group (MVG)	Contractor	MVG
2	Random Number Seeds	No. of different random number seeds to be used in run	Specified by MVG	---	MVG
3	Start and Finish Times	Starting and ending times of simulation run	Specified by MVG	---	MVG
4	Print Options	Options for printing output of simulation run, e.g., level of detail, debugging statements, - see User's Manual	Specified by MVG	---	MVG
5	Change of Inputs	Specified time when inputs change	Specified by MVG	---	MVG
6	Truncation Limits	Limits on the range of the normal distribution from which samples are taken in the model	Specified by MVG after examination of data	---	MVG
7	Processing Options	Options to either print input only or to compute a variable number of data sets	Specified by MVG	---	MVG

TABLE 2. INPUT DATA - AIRSIDE SPECIFICATION

No.	Data Type	Data Description	Primary Source	Secondary Source	Responsibility
1	No. of Runways	No. of runways in use during period simulated	Specified by MVG	---	MVG
2	Runway Names	Names or numbers of runways in use during period simulated	Specified by MVG after examination of observed data	---	MVG
3	Departure Runway End Link Numbers	Names of runways used for departures during period simulated (max. of 4)	Specified by MVG after examination of observed data	---	MVG
4	Runway Crossing Links	For each crossing link on each runway being used during period simulated: a. Intersection clearance for arriving and departing aircraft on the runway by aircraft class b. Clearance times for arriving aircraft on final approach to the specified runway by aircraft class	ATC procedures from tower personnel	Field Observations	MVG
5	Lengths of Common Approach PATHS	Length of common approach path to each runway - n.m.	ATC personnel in O'Hare tower	A spot check of ARTS-III Tapes or observation	MVG

Table 2. (continued)

No.	Data Type	Data Description	Primary Source	Secondary Source	Responsibility
6	Runway Exit Distances	Distances in feet from runway threshold to each exit	The contractor's O'Hare data from previous studies	Field observations	Contractor
7	Holding Areas	Locations where aircraft hold waiting for a gate to become available	ATC personnel in O'Hare Tower	ASDE film or field observations	MVG
8	Taxiway Routes	Routes on the airfield between runway exits and departure-end links and gates, basing areas, and holding areas	ATC personnel in O'Hare Tower	Observations or ASDE film	MVG
9	Two-way Paths	Designation of taxiway paths that may handle traffic in both directions	ATC personnel in O'Hare Tower	Contractor's O'Hare data	MVG
10	General Aviation Areas	Locations of general aviation basing or holding areas	ATC personnel in O'Hare Tower	Contractor's O'Hare data	MVG

TABLE 3. INPUT DATA - DEMAND SPECIFICATION

No.	Data Type	Data Description	Primary Source	Secondary Source	Responsibility
1	Airline Code Names	Names of airlines using airport during period simulates	Airlines and ATC personnel	Contractor's O'Hare data	MVG
2	Airline Gate Assignments	Designations of the gates assigned to each airline	Airlines through ATA	Observations and ATC departure strips	MVG
3	Lateness Distributions	Probability distribution of actual operation times with respect to scheduled times	Airlines through ATA	Contractor's O'Hare data or ARTS-III tapes	MVG
4	Aircraft Schedule	The following scheduled or expected data for all aircraft during validation period: Airline Flight number Gate preferred Type of aircraft Arrival time over fix Arrival time at threshold Departure time from gate Departure time at lift-off Departure time over fix Runways utilized Fixes utilized	a. Arrivals - ARTS-III data tapes b. Departures - OAG and flight strips	ADR and flight strips	MVG

TABLE 4. INPUT DATA - AIRPORT OPERATION

No.	Data Type	Data Description	Primary Source	Secondary Source	Reponsibility
1	Interarrival Gap	A specified critical departure queue length and a time increment that is added to the arrival separations when a departure queue reaches that critical length; alternatively, a trigger value at which a third arrival/departure runway switches to departures only	Observations of and discussion with ATC personnel by airline and ATA representatives of MVG	ATC personnel in O'Hare Tower	MVG
2	Runway Occupancy Times for Departures	(self explanatory)	Contractor's O'Hare data	Observations in field	Contractor
3	Cumulative Probability Distribution for Exit Selection	A cumulative probability of exit utilization for each aircraft class and runway	Contractor's O'Hare data	Observations in field	Contractor
4	Arrival Runway Occupancy Times	Distance/time pairs representing the time to exit at a given runway exit distance	Contractor's O'Hare data	Observations on ASDE films	Contractor
5	Standard Taxiway Speeds (up to six)	Off-peak taxiway speeds assigned according to different taxiway location categories	Contractor's O'Hare data	Observations to spot check existing data	Contractor
6	Link Data	Specification of type of link, a length or travel time for non-gate links, and a largest assignable aircraft class for gate links.	Contractor's O'Hare data	Observations	Contractor
7	Gate Service Times	A mean and standard deviation (assumed normally distributed) for the minimum time in gate by aircraft class	Airlines and ATA	Observations	MVG

Table 4 (continued)

No.	Data Type	Data Description	Primary Source	Secondary Source	Responsibility
8	Approach Speeds	A mean and standard deviation for the speed along common approach path by aircraft class	ARTS-III data tapes	Observation of ARTS-III display	MVG
9	Aircraft Separations	Class pair-specific, runway pair-specific aircraft separations (mean and standard deviation) for following operation type pairs: arrival followed by departure arrival followed by arrival departure followed by arrival departure followed by departure	Observations in field	ARTS-III data and ASDE film	MVG
10	Arrival Delay Proportioning Factors	For each fix: Delay level at which holding delays occur Percentage of delays above delay level which are holding delays Maximum vectoring delay Minimum holding delay Aircraft arrival delay is proportioned between holding delays and vectoring delays at conclusion of model run. The aircraft delay must exceed a specified maximum vectoring delay to accumulate a holding delay.	ATC personnel in O'Hare Tower	ARTS-III data tapes	MVG
11	Departure Runway Reassignments	Length of departure queue at which departures will be reassigned to another runway	ATC Tower Log-Book Notations	ASDE film	MVG

Table 4 (continued)

No.	Data Type	Data Description	Primary Source	Secondary Source	Responsibility
12	Gate Hold Limits	Length of departure queues at which departures will be held at gate, and corresponding holding time	ATC Tower Log-Book Notations	ASDE film	MVG
13	Departure Air-Space Delays	For each departure fix: Percent of flights departing over fix that are delayed due to en route airspace congestion Mean and standard deviation of hold time	Not applicable at O'Hare	ATC Tower Log-Book Notations	MVG
14	Fix Travel Times	For each combination of runway, fix, and aircraft class: Distance from fix to threshold or beginning of roll to fix Average speed over above distances (nonpeak period) Fix traveltime is computed by the model using distance from arrival fix to runway and average speed of aircraft for each aircraft class	ARTS-III data tapes during non-peak conditions	DSF (Routing from ATC Tower personnel	MVG

TABLE 5. DATA FOR COMPARISON WITH MODEL ESTIMATES

No.	Data Type	Data Description	Primary Source	Secondary Source	Responsibility
1	Holding Box Delays	Delays accumulated while waiting in holding box for available gate	Observations in field	ASDE film	MVG
2	Runway Crossing Delay	Delays encountered in runway crossing (taxi-in and taxi-out)	Observations in field	ASDE film	MVG
3	Taxi-out Times	Total time it takes an aircraft to taxi-out from gate to departure link or roll point	Airlines and ATA	Observations and data correlations	MVG
4	Aircraft Flow Rates	Number of arriving and departing aircraft every hour	ATC Tower Watch Supervisor's Report	ASDE film	MVG
5	Taxi-In Times	Total time it takes an aircraft to taxi in from exit of runway to gate	Airlines and ATA	Observations and data correlations	MVG
6	Departure Queue Length	Departure queue length for each runway at specified instants in time.	Observations in field	ASDE film	MVG
7	Arrival Airspace Delays	Actual fix-to-threshold time minus nominal or minimum fix-to-threshold time	ARTS-III data tapes	ADR	MVG
8	Gate Pushback Delays	Start taxi time minus pushback time	Observations in field	ASDE and controller voice tapes	MVG

An important aspect to the data collection to consider is the definition of terms of the delay measurements as reflected in the model. The measurements at the facility must comply with the output of the model; event times specified in the model must be recorded at the facility. (For example, time of arrival and departure time from gate must be defined, collected, and reduced before comparison with the model output.)

The form of the data extracted will be dependent upon the definition of the delay factors and parameters expressed in the simulation model. The following table (Table 6) lists a set of event times along with a description of the position of the aircraft, what the aircraft is doing, and what the aircraft is about to do in the simulation. This description of the event times in the simulation permits the measured data to be sectioned into the various categories of delay at the airport. These event times of the actual simulation model must be clearly defined and reconfirmed (after disclosure of code and listings from the contractor) before data reduction to insure that delay accumulations may be compared with the model output at the conclusion of the validation procedure.

The concept of matching field measurements at the airport with the model's definitions of airport operations applies particularly to the travel times. The model simulation calculates travel time by summing the total times an aircraft occupies individual links on the route to the gate, holding area or runway takeoff point. Therefore, aircraft travel times should be measured at the airport as shown in Table 7.

TABLE 6. DESCRIPTION OF SIMULATION MODEL EVENTS

Aircraft State Number	Description	Aircraft Position	Next Event and Operation
0 or 1	Aircraft Attempting to Arrive or in Arrival Queue	Aircraft on final approach path	Next Event: Time of Arrival Operation: Occupy runway
2	Aircraft on way to gate or holding area	Aircraft occupying link on route to gate or holding area	Next Event: Link move Operation: Link by link movement to gate link or holding area
3	Aircraft in Gate	Aircraft in gate link being serviced	Next Event: Permission to push back Operation: Pushback
6	Aircraft in pushback from gate	At first links from gate	Next Event: Taxi Out Operation: Link by link movement to takeoff
4	Aircraft on way to Takeoff	Aircraft occupying link on route to runway	Next Event: Link move Operation: Link by link movement to take off link or departure queue
4	Aircraft in departure queue	Aircraft on link in queue to departure link	Next Event: Takeoff Operaton: Link by link movement to take off link
4	Takeoff	Aircraft in Takeoff	Next Event: Clearance from runway Operation: Out of simulation
7	Aircraft in Holding Area	Aircraft in one of the holding areas not in queue position	Next Event: Pushback from holding area Operation: Link by link movement to gate
0	Aircraft attempting to depart gate after layover from previous day	Aircraft in gate (scheduled or general aviation)	Next Event: Pushback from gate Operation: Link by link movement to takeoff link

TABLE 7. AIRPORT TRAVEL TIME MEASUREMENTS

Measurement	Description of Measurement Points
Travel time from Runway to Gate	Aircraft arrives at runway threshold and stops at gate
Travel time from Runway to Holding Area	Aircraft arrives at runway threshold and stops at holding area
Travel time from Holding Area to Gate	Aircraft starts movement from holding area, and stops at gate
Travel time from Gate to Runway	Aircraft begins pushback (receives controller clearance) and stops just before takeoff roll (not always at same point on airport).

The accumulation of hourly delay totals will involve the extraction and combination of data. Delay measurements will be classified into areas which agree with the model output. There is a need to define the measurement points for each classification of delay used in the model. In addition, certain conditions which occur during simulation (such as queues) determine the classification of the delay. Table 8 lists the model delays and the corresponding events which define them or the conditions which classify them.

TABLE 8. MODEL DELAY CLASSIFICATIONS

Item	Delay	Event or Simulation Condition
a	Arrival Runway Delay	Aircraft attempts to land at scheduled Time of Arrival (event)
b	Arrival Gate Delay (Holding area delay)	Aircraft at exit taxiway (event) is denied a gate and routed to a holding area. Delay is terminated at the time (event) of the next available gate
c	Departure Gate Delay (accumulated under taxi-out delay)	Aircraft attempts pushback but is delayed because of presence in gate area of an in-bound aircraft (attempt is repeated when de-lay value is exceeded in the sequence of events in the simulation)
d	Taxi-in Runway Crossing	Arriving aircraft is in taxiway crossing link awaiting clearance across runway (aircraft in queue behind this link accumulate taxi-in delays)
e	Taxi-Out Runway Crossing	Same as (d) above for departing aircraft
f	Arrival Taxi-In Delay	Aircraft moves from link to link and if delayed accumulates taxi delay
g	Departure Taxi-Out Delay	Aircraft moves from link to link and if delayed acculates taxi-out delay (departure gate delays are also accumulated under taxi-out delays)
g	Departure Runway Delay	Aircraft is in departure link or in departure queue awaiting departure clearance

APPENDIX A

Summary of Steps

I. Plan for Contractor Disclosure and Recommendation*

   A. Model Inputs

   B. Model Outputs

   C. Model Logic

   D. Prior Validation of

      1. Model Logic

      2. Model Sensitivity

      3. Model Outputs

      4. Model Assumptions

II. Selection of Validation Variables

   A. Arrival Airspace Delays

   B. Departure Delays

   C. Ground Travel Times

   D. Aircraft Flow Rates

III. Specification of Sensitivity Analysis*

   A. Variables to be held fixed

   B. Variables to be systematically varied

   C. Response Variables to be investigated

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*To be accomplished during contractor's presentation. Beforehand, the contractor submits macro-logic flow charts and the working Sub-group submits questions on inputs, logic and outputs. Working Group specifies sensitivity parameters at end of presentation.

APPENDIX B

Meeting Agendas

I. Presentation and Adoption of Validation Plan

- A. Date - May 18, 1977
- B. Place - Washington, D. C.
- C. Attendance - Full Validation Group
- D. Agenda
  1. Presentation and Discussion of Strawman Plan - W. J. Dunlay
  2. Comments, Suggestions, Revisions - Validation Group
  3. Adoption of Final Plan - Validation Group
  4. Discussion of Data Collection and Reduction
     - a. collection assignments
     - b. reduction assignments
     - c. coordination
     - d. schedule and detailed plan
  5. Discussion of Next Meetings
     - a. Full Validation Group
     - b. Working Sub-Group

II. Contractor Disclosure and Presentation

- A. Date: within two weeks after adoption of validation plan
- B. Place: San Mateo, Calif.
- C. Attendance: Working Sub-Group of approximately eight people and a contractor representative.
- D. Preparation:
  1. Contractor should provide members of working group with copies of macro-logic flow charts.

Preparation (continued)

2. Members should study the flow charts and submit written questions to the contractor.
3. Contractor should design presentation to be responsive to submitted questions.

E. Agenda:

1. Overview of Details of the Model Logic, Inputs, and Outputs - Contractor
2. Review and Discussion of Submitted Questions - Contractor and Group
3. Further Questions and Answers on Model Logic, Inputs and Outputs - Group and Contractor
4. Review of prior Model Validations (empirical verifications) of
   a. Model Assumptions
   b. Model logic-arithmetic
   c. Model Outputs - Contractor
5. Discussion and Questions on prior verifications - Group and Contractor
6. Review prior sensitivity analyses of model - Contractor
7. Specification and design of Sensitivity Demonstration - Group
   a. Selection of variables to be held fixed
   b. Selection of variables to be systematically varied
   c. Selection of response variables to be evaluated.
   d. Evaluation Procedure

Agenda (continued)

8. Discussion of Data Collection Requirements for
   a. Model Inputs
   b. Model Validation - for comparison with model outputs

III. Detailed Data Collection and Reduction Plan

A. Data: within two weeks after adoption of Model Validation Plan

B. Place: Washington, D.C.

C. Attendance: Sub-Group

D. Preparation: Members should study validation plan as adopted vis-a-vis the resources of the group for data collection and reduction

E. Agenda:

1. Review of data needs as implied by model validation plan
2. Discussion of manpower needs and a schedule of collection and reduction activities
3. Identification of equipment, software, and manpower resources of the Group.
4. Assignment of specific tasks to Group members
5. Discussion of data collection procedures, forms, and sample sizes - Group and Contractor
6. Discussion of data reduction methods and desired format of reduced data - Group and Contractor

Agenda (continued)

7. Specification of coordination procedures to be followed during data collection and reduction
8. Outline of data collection and reduction plan and schedule

APPENDIX C

STEP-BY-STEP SUMMARY

I. Evaluation of Model Logic, Assumptions, Inputs, and Outputs

A. Begins:

As soon as preparations (see below) can be made, but no later than two weeks after adoption of validation plan.

B. Methodology:

The evaluation will be made by a working subgroup of about 8 persons. No formal evaluation criteria will be used. The evaluation will be based on the knowledge and experience of the members of the working subgroup.

C. Preparations:

(1) Contractor should provide members in advance with whatever written documentation of the model is available, including macro-logic flow charts.

(2) Members should familiarize themselves with the written documentation and submit written questions if they have any.

(3) Contractor should present to the working subgroup details of the model logic, assumptions, inputs and outputs and copies of macro-logic flow charts.

D. Simultaneous Activities:

The preparation of the detailed data collection plan can begin immediately after validation plan adoption and may be carried on simultaneously with the evaluation of model logic, assumptions, inputs and outputs.

E. Subsequent Activities:

The specification and evaluation of the sensitivity analysis by the 8-person working subgroup will have to follow this initial step.

II. Evaluation of the goodness-of-fit of model estimation.

A. Begins:

The planning for data collection and reduction, the first step of this task, can begin immediately after adoption of the validation plan by the Model Validation Group.

B. Methodology:

1. Planning and design of data collection and reduction activities as described in final validation plan
   a. Specific work assignments to participants
   b. Schedule of activities
   c. Required equipment and data collection forms
   d. Specification of data format for
      (1) inputs for model execution
      (2) outputs for comparison in the model estimates
   e. Number of days on which to collect data
   f. Sample size on each day
   g. Measurement (observation) techniques to be employed
   h. Procedure for assembling data for reduction

i. Data reduction procedures

j. Procedure for preparing data for comparison with model estimates

2. Execution of data collection and reduction

3. Execution of model runs with input data

4. Comparison of collected and reduced data with estimates produced by the model runs

a. Statistical hypothesis tests

b. Subjective evaluation of tabular and graphic comparisons

5. Decision as to model's acceptability for Phase II

C. Preparations

Final selection of comparison variables, method of comparison and comparison criteria--Final Model Validation Plan.

D. Simultaneous Activities:

The planning of the data collection and reduction can begin simultaneously with the contractor disclosure of model logic, inputs, and outputs. However, parts of the data collection plan, namely the detailed format for the comparison data and the format for model inputs [see items B-1-d-(1) and (2)], will have to be done after the group has been exposed to the details of the model logic, assumptions, inputs and outputs.

It is possible to do the sensitivity analysis evaluation at the same time as the goodness-of-fit evaluation. It may, however, be desirable to do the goodness-of-fit evaluation after this step because it is desirable to be thoroughly familiar with the workings and output of a model before performing a sensitivity analysis of it.

E. Subsequent Activities

Based on the above discussion, it is recommended that we do the sensitivity evaluation after the goodness-of-fit evaluation.

III. Evaluation of Model Fine-Grained Sensitivity

A. Begins:

Sensitivity evaluation should begin after or simultaneously with the evaluation of the goodness-of-fit of the model (preceding step). Both of these steps require input data and model computer runs.

B. Methodology

The working subgroup of 8 persons should specify the experiments to be performed by the contractor. Each experiment must specify which parameters to be held fixed, which to vary systematically, and which to view as response variables. The contractor should then execute the experiments by making the necessary runs of the computer model. Some additional runs may be made by the Model Validation Group using the NAFEC computer. The subgroup then evaluates the results of the experiments.

C. Preparations:

The working subgroup should be familiar with the model logic, inputs and outputs.

D. Simultaneous Activities:

The final goodness-of-fit comparisons and evaluations can be done at the same time as this step.

E. Subsequent Activities:

Final evaluation of model sensitivity

APPENDIX D*

A SIMULATION MODEL FOR AIR TRAFFIC CONTROL COMMUNICATIONS

In an FAA sponsored study of Air Traffic Control communications, a purely analytical model of the ATC system appeared unattainable. As a consequence, to represent the actual system a simulation model was developed employing GPSS V simulation language with an IBM 360/91 computer facility. The research results are relevant to the (i) evaluation of the efficiency of the present communications performance; (ii) measurement of the capacity of the present communications channels; and (iii) experimentation with various proposed changes in the control structure.

Structure of the Simulation Model

ATC communications associated with 101 control sectors in the New York metroplex, which comprised 12 different control functions, were originally recorded on voice tapes for a busy afternoon period on April 30, 1969, and were subsequently sorted and digitalized for computer analysis. (Each control sector was assigned a radio channel of a specified frequency, and the conversations between the controller and aircraft pilots were open to all who tuned to the frequency.) This large data bank was analyzed to provide a statistical basis for analysis of the complex communications system. The available data were digested in many ways, and whereever possible mathematical models postulated and fitted to historical events that served as components to the larger system. The models were, of course, abstractions of various elements in the historical data, and as each was derived it was tested to determine its adequacy as a replacement for the data.

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*SOURCE; Hsu, D. A. and Hunter, J. S., "Analysis of Simulation-Generated Responses Using Autoregressive Models," paper accepted for Management Science, 1977, pp. 16-20.

In this study the major responses to be simulated are:

(i) aircraft loading, n_t, number of aircraft present in sector at time t;

(ii) channel utilization, C_t, proportion channel time employed at time t;

(iii) number of aircraft in queue waiting to communicate, Q_t.

Each of these responses is a time series reflecting the ebb and flow of air traffic through a sector and the resulting burden of communications.

Validation of the Simulator

The validation of the simulation model depends upon the two responses, aircraft loading, n_t, and channel utilization, C_t. Both these responses are available historically and both are generated by the simulation model as time series. (The Q_t series cannot be obtained from a real system, and was one of the reasons for the computer simulations.)

The essential validation step consists of the inference that the structure of the observed time series, and the structure of the simulated time series, for both responses, are identical.

To supply an example, the observed and simulated time series plots (both recorded for a two-hour period and averaged over each nonoverlapping 60-second interval) of aircraft loadings, n_t, for one of the busiest Low Altitude Transitional (LT) sectors in the N. Y. area, Sector 453, were compared (see Figs. D-1 and D-2). As the first step in characterizing these two series, the sample autocorrelation functions of both were obtained (see Figs. D-3 and D-4). An inspection of the two estimated autocorrelation functions suggested that they were very much alike and both exhibited a damped sinusoid pattern peculiar to the AR(2) model. The AR(2) model was thus fitted and the two autoregressive parameters estimated for both series using the ordinary least-squares method. Various diagnostic tests, following the procedure outlined in Box and Jenkins [2], indicated that the AR(2) model fitted both sets of data satisfactorily. In addition, the residual distributions were checked and found to be consistent with the normality assumption.

As a consequence of repeated applications of these inferential procedures, considerable confidence has been generated in the simulation model. There are occasional individual sectors for which validation has proved impossible, a failure generally attributable to the paucity of data for these sectors, to an unusually large number of maverick observations which make the distribution assumptions untenable, or, to the pronounced lack of independence of the arrivals of incoming aircraft. However, the vast majority of the individual sectors (comprising the enroute, the local control the local and ground control, the radar departure, the radar arrival, and the radar arrival-departure control functions) have been successfully simulated and validated.

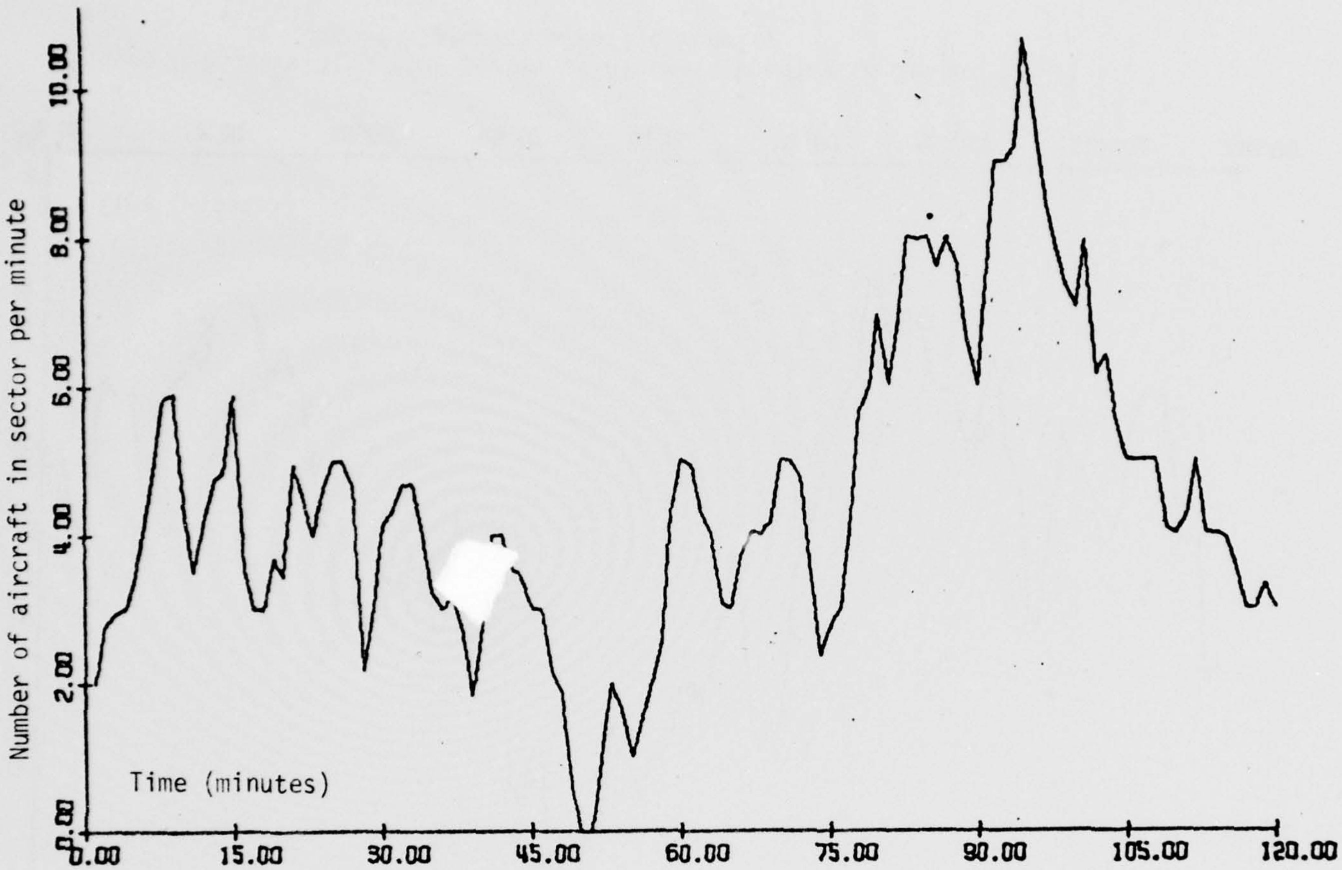

Fig. D-1 Historical Time Series of Aircraft Loading in Sector 453 LT

(Source: Report No. FAA-RD-74-203)

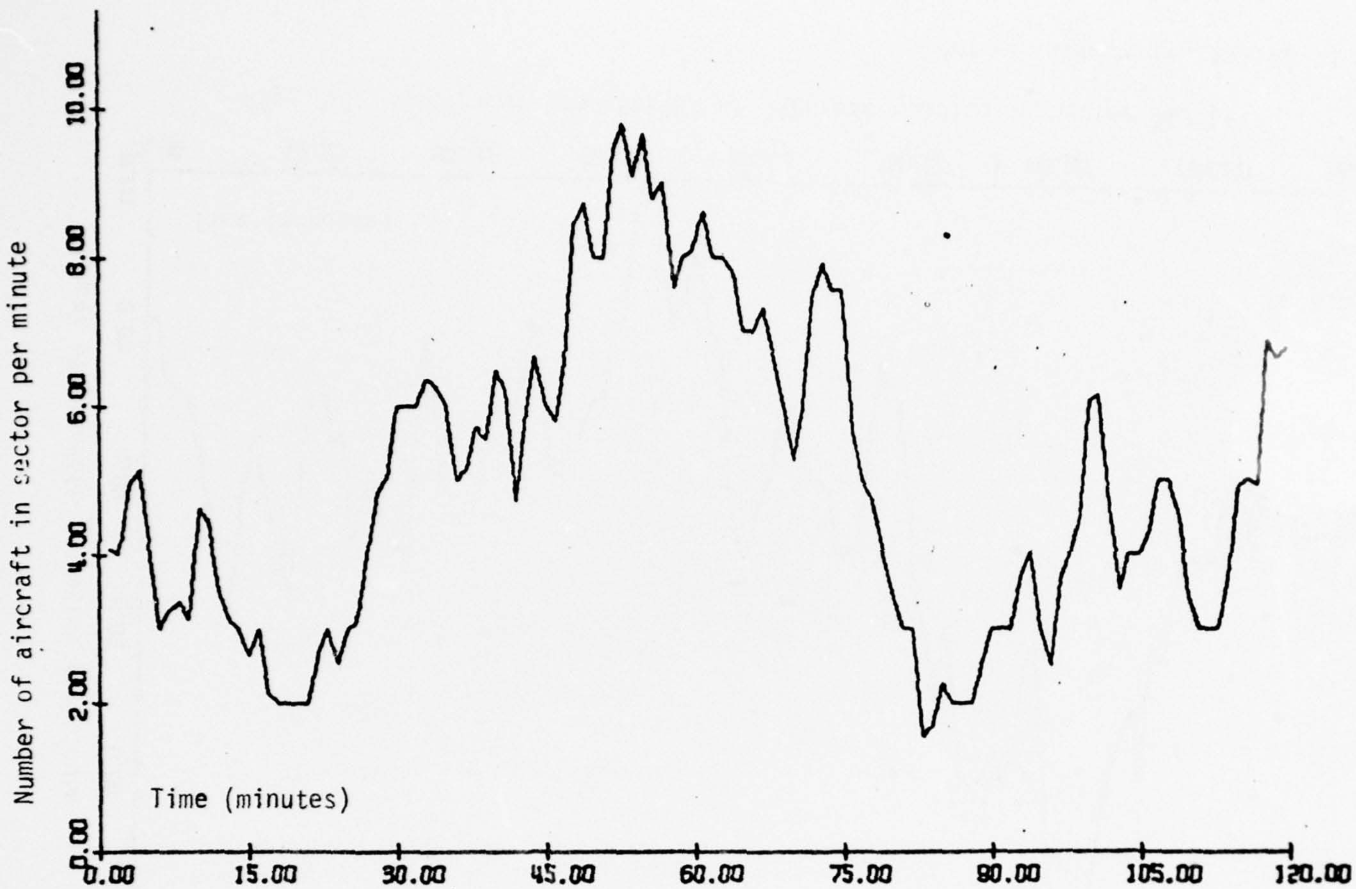

Figure D-2 Simulated Time Series of Aircraft Loading in Sector 453 LT at 100% of Historical Traffic Penalty

(Source: Report No. FAA-RD-74-203)

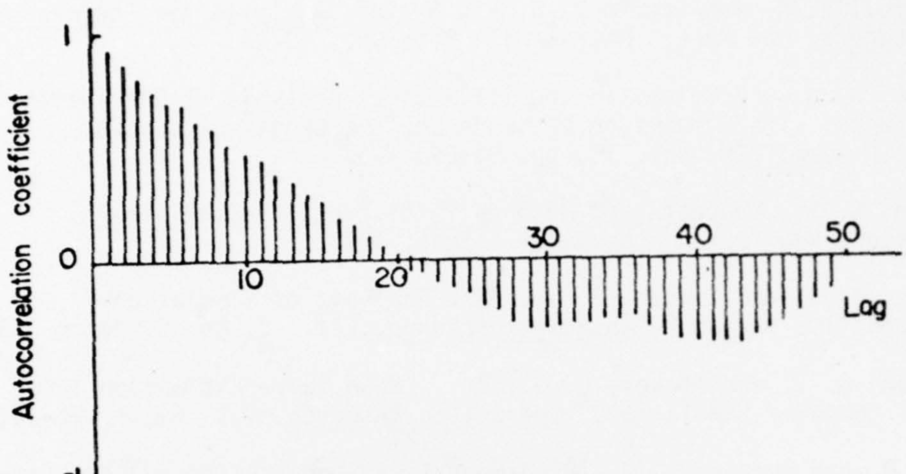

Figure D-3 Autocorrelation Function of Historical Aircraft Loading Series (Sector 453)

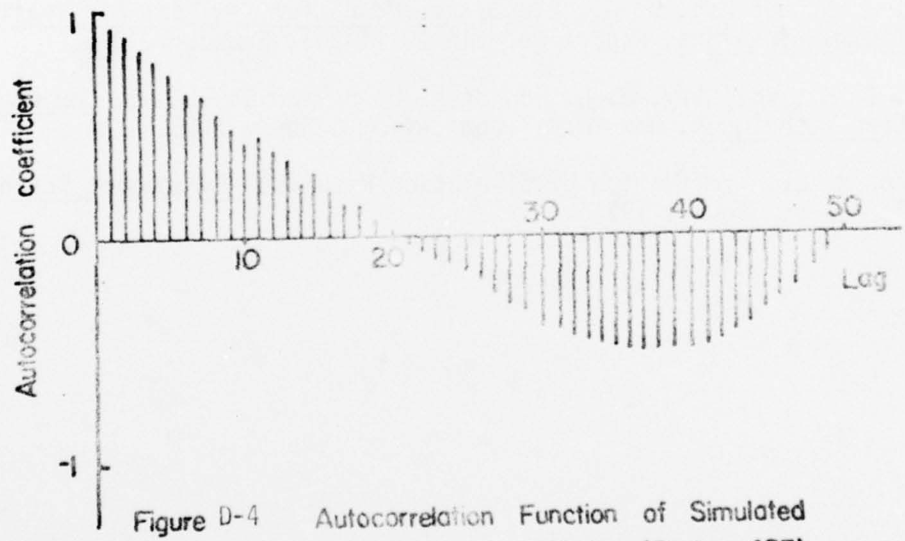

Figure D-4 Autocorrelation Function of Simulated Aircraft Loading Series (Sector 453)

(Source: FAA-RD-74-203)

VI BIBLIOGRAPHY

1. de Neufville, R. and Stafford, J. H., Systems Analysis for Engineers and Managers, New York: McGraw-Hill Book Co., 1971.

2. Fishman, G. S., "Problems in the Statistical Analysis of Simulation Experiments: The Comparison of Means and the Length of Sample Records," Comm. ACM, Vol. 10, pp. 94-99, 1967.

3. Fishman, G. S., Concepts and Methods in Discrete Event Digital Simulation, New York: John Wiley & Sons, 1973.

4. Fishman, G. S. and Kiviat, P. J., "The Analysis of Simulation-Generated Time Series," Management Science, Vol. 13, No. 7, March 1967.

5. Gafarian, A. V. and Ancker, C. J., Jr., "Mean Value Estimation from Digital Computer Simulation," Operations Research, Vol. 6, pp. 25-44, 1966.

6. Gross, D. and Harris, C. M., Fundamentals of Queuing Theory, New York: John Wiley & Sons, 1974.

7. Hsu, D. A. and Hunter, J. S., "Analysis of Simulation-Generated Responses Using Autoregressive Models," paper accepted for Management Science, 1977.

8. Hunter, J. S. and Hsu, D. A., Simulation Model for New York Air Traffic Control Communications, Report No. FAA-RD-74-203, February 1975.

9. Naylor, T. H., Balintfy, J. L., Burdick, D. S. and Chu, Kong, Computer Simulation Techniques, New York: John Wiley & Sons, 1966.

10. Van Horn, R. L., "Validation of Simulation Results," Management Science, Vol. 17, No. 5, January 1971.