

ISSUES IN MODELING A NATIONAL NETWORK OF AIRPORTS

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ABSTRACT

The subject of this paper is models of networks consisting of a large number of geographically-dispersed airports. The need for models of this type has become urgently clear recently as a result of growing system-wide congestion of air traffic, the propagation of delays from one airport to others and the desire, at the national policy level, to allocate intelligently scarce federal resources among competing alternatives and local airport projects.

While research and development activities in this area will undoubtedly intensify in coming years, it is important to recognize some fundamental difficulties associated with network models of this type. Important issues include: problem size and data requirements; the probabilistic and dynamic nature of the airport system's demand and capacity; the combinatorially explosive number of possible network states and the resulting need for careful statistical sampling and analysis; the sensitivity of computational performance to the level of detail in the network model; the difficulty of preparing demand scenarios that predict future connections between pairs of airports; and user requirements for model robustness, portability and transparency.

These issues are discussed and illustrated in some detail, including references to specific existing network models of the ATC system.

1 INTRODUCTION

The use of analytic and simulation models has already become standard practice in air transportation. Models are routinely employed to investigate and resolve both superstructure (airline operations) and infrastructure (airports, air traffic control) issues. Demand for such models at the infrastructure level will undoubtedly grow, in response to increased congestion and resource constraints internationally, nationally and locally.

This paper deals with one particular class of airport/air traffic control (ATC) models those concerned with operations on a network of a large-number of

geographically dispersed airports. We shall refer to them simply as "network models."

This is a new class of models. Until very recently, most modeling research in the airport/ATC area has been directed toward developing the fundamental concepts needed to study the operations of individual airports and ATC sectors or of relatively small regional groups of airports and associated airspace. However, in the mid-1980's, the acute need for network models became apparent as a result of system-wide congestion experienced in the United States and in Western Europe. This type of congestion has resulted from the rapid worldwide growth of air traffic during the 1980's which has created many potential ATC system "bottlenecks" in the USA, Western Europe and, increasingly, in the "Pacific Rim," as well – unlike the 1970's, when these bottlenecks were quite few and relatively isolated. At the same time, the "hubbing" practice of the airlines, which emerged after deregulation in the United States and is now spreading internationally, has led to tight "coupling" between flights at geographically dispersed airports, so that delays at one major airport have a rapidly propagating "ripple effect" throughout a system of airports and, especially in Western Europe, many ATC en route sectors, as well.

Demand for network models also derives from the growing need for large investments of capital and resources into the national airport system and the ATC system in the United States. This need, coming at a time of scarcity at the federal level, requires an understanding of the system-wide effects of major "interventions" at the local level (such as the construction of a new runway at a busy airport or the opening of an entirely new airport) or of changes of a national scope (such as changes in terminal area ATC procedures or separations). Such understanding can be gained only through network models. These models would also assist in allocating international-body (ICAO, Eurocontrol) resources in a rational way as well as make possible the continuous monitoring and evaluation, for policy-making purposes, of the efficiency and future directions of ATC operations.

Finally, there is little doubt that, for at least the next 15-20 years, the trend at the operational level will be toward careful management of air traffic flows and toward centralization and coordination of flow control activities. This trend is a natural response to traffic increases and ever-tighter capacity constraints and is illustrated by the growing role of the Central Flow Control Facility in the US ATC system and by the decision of Western European nations to set up a Central Flow Management Unit that, as part of Eurocontrol, will coordinate traffic flow in Europe. In connection with this trend, an extensive array of highly-detailed models at the network level will be needed to help in the planning and design of such flow management units and strategies, as well as to support, in "real-time," the activities and operations of these units.

It is safe then to anticipate that extensive activity in network model development will take place within the next few years. For this reason, it is also important at this point to be aware of some difficult challenges that these models present to designers and developers. These challenges are often particular to the airport/ATC environment or to the specific decision-making context within which these models will be applied. It is the purpose of this paper to identify some of these challenges and discuss briefly the related issues from the model-builder's viewpoint. This discussion will also be illustrated with a brief reference to the only two currently existing airport/ATC network models, AIRNET and NASPAC.

For more details and a discussion of additional related topics the reader is referred to a recent report (Odoni, 1991) on which this paper is largely based.

2 ISSUES

2.1 Probabilistic and Dynamic Components

Network models, in our context, comprise a large number of individual interconnected airports as their constituent components. The first challenge to network model designers arises, then, from two fundamental characteristics of individual airports that have major implications for networks of airports, as well.

The first of these characteristics is that at practically every airport, the airport's capacity varies significantly over time and depends on the runway configuration in use. Configuration selection at each airport at any given time is affected, in turn, by four sets of factors: ceiling/visibility conditions; wind direction and strength; characteristics of the demand, such as the aircraft mix, the operations mix (arrivals vs. departures) and the demand level ("high," "medium," "low"); and possible noise-abatement considerations.

Consider, for example, Logan International Airport in Boston which has a total of five runways. Depending on the four factors just mentioned, Logan may be operating in any one of 39(!) different configurations at any particular time. Each configuration is described by a set of active runways, the prevailing weather category and the assignment of operations to runways. It should be remembered that the weather category – VFR-1, VFR-2, IFR-1, IFR-2, IFR-3 – determines the ATC separation requirements and ATC procedures used for each set of active runways.

As a result, the capacity of Logan Airport varies dramatically depending on which configuration is in use. For instance, under what is known as Configuration 1 (runway 04R used for landings and for takeoffs, runway 04L for landings only and runway 09 for takeoffs only) which is available under VFR-1 weather conditions, the capacity of the airport is about 128 operations per hour when the mix is about 50% arrivals and 50% departures. By contrast, under configuration 5 when only runway 04R is being used for both landings and take-offs under poor (IFR-3) weather conditions, the capacity is about 56 operations per hour for 50% arrivals and 50% departures.

The overall situation for Logan is summarized by the airport's annual "capacity coverage chart" (CCC). The CCC indicates how much capacity is available at Logan for what percentage of time, if ATC were to use at all times the highest capacity configuration under the prevailing weather conditions (Odoni, 1991). Ignoring small differences between the capacities of some configurations, we can summarize the situation at Logan Airport by stating that "for about 77% of the time, corresponding to good (VFR-1) weather, the available capacity is about 130 operations per hour, for about 10% of the time corresponding to marginal (VFR-2 and IFR-1) weather, the capacity is about 90 and for poor weather or 13% of the time (strong winds or IFR-2 or worse conditions) the capacity is about 55". (Note that the poor-weather capacity is equal to only about 42% of the good-weather capacity!) Thus, even after some simplification, at least three distinct levels of capacity must be considered for Logan. The percentages of time during which each capacity level is available indicate the probability that an aircraft wishing to use the airport at some random time will find it operating at that particular capacity level.

The following important conclusion can be inferred from all this: "Airport capacity is a random variable, not a constant. A description of an airport's capacity can be given only in probabilistic terms, by listing all the possible values of the capacity and the probability associated with each value."

The second fundamental characteristic of airport operations is that they are dynamic, in the sense that

both demand and capacity change over time. Traffic conditions (i.e., level of congestion) during any given time-period depend not only on the demand-to-capacity relationship during that particular time-period but also during the preceding time-periods. This has important implications for airport modeling because it eliminates the possibility of using a large class of approaches – most notably models based on classical, steady-state queueing theory – which compute airport delays on the basis of the "average value" of the demand and of the capacity of the airport. Because they disregard the variation over time of demand and of capacity, such models – which have, unfortunately, been proposed often – are likely to produce largely meaningless results. Only methodologies that can account for dynamic behavior are therefore appropriate for the study of airport delays and congestion – especially, when it comes to detailed modeling. Such methodologies include simulation as well as dynamic mathematical models based on queueing theory.

2.2 Combinatorial Set of Network States

As a direct (and complicating) consequence of the fact that the capacity of any given airport is a random variable that takes on a range of distinct values according to a set of associated probabilities, it should be clear that a model of a network of airports has a combinatorially explosive set of states. To see this consider, for instance, a model that includes 20 different major airports and assume that, as in the case of Boston's Logan Airport the capacity of each of these airports can be approximated as taking only three different values (corresponding roughly to "good," "marginal," and "poor" weather conditions). We shall say that "each airport can be in any one of three possible 'states' with respect to its capacity." It then follows that the network of the 20 airports can be in any one of $3^{20} \approx 3.5$ billion possible states! For example, the two most "extreme" states would correspond to "good" and "poor" weather, respectively, at all 20 airports simultaneously.

To draw meaningful conclusions about overall system behavior from a model with as enormous a total number of states as this, it is necessary to study the airport network's performance under a large and statistically representative number of network states. (The analysis must necessarily rely on statistical sampling of the network's states since it is impossible to study all the states.) To be able to do this, the model requires two attributes: it should be very fast and it should have the capability to generate internally the logic for selecting the network states to be studied so that they would provide a fair statistical representation of overall (i.e., for the entire set of network states) performance. These

attributes, in turn, mean that the computer implementation of network models must be highly sophisticated (so that very efficient performance can be achieved) and that these models must also be supported by solid statistical analysis.

2.3 Estimating State Probabilities

There is another point to be made concerning the probabilistic properties of network models: obtaining the probabilities associated with the underlying states of the network is a difficult task in itself, the reason being that the states of different individual airports may not be mutually independent. This is best explained through an example. Consider two relatively proximate major airport sites A and B (e.g., Boston and New York). Assume for simplicity that site A has "good" weather conditions approximately 70% of the time and "poor" weather 30%. The corresponding figures for site B are 80% and 20%. The problem now is that, due to the proximity of the two sites, it is very unlikely that the percentage of time when both airports have good weather is only 56% – as would have been the case if the "states" of the two sites were mutually independent ($(0.7)(0.8) = 0.56$). In fact, it is reasonable to expect that: the event "both A and B have good weather" has probability greater than 0.56; the event "A and B both have poor weather" has probability greater than 0.06 ($=(0.3)(0.2)$); and the events "A good weather, B poor weather" and "A poor weather, B good weather" have probabilities less than 0.14 ($=(0.7)(0.2)$) and 0.24 ($=(0.3)(0.8)$), respectively.

The implication of this observation is that one cannot simply rely on knowledge of the state probabilities of each individual airport (these probabilities are well-known) to obtain the probabilities of the states of a network of airports. To develop a statistically representative set of states for studying the performance of a network of airports, it is unfortunately necessary to examine weather data for all airports together, not for each airport separately. In other words, one must develop a large set of national weather "scenarios" by ascertaining from nation-wide weather data that these scenarios do provide an adequate (statistically) sample for the range of possible network states.

2.4 Preparation of Demand Scenarios

The preparation of demand scenarios poses another formidable problem when it comes to network models. It is again instructive to compare the problem at the network level to that at the single-airport level. For individual airports it is easy to develop alternative demand scenarios for the future given some fundamental specifications. For instance, if one is told that the

number of operations at airport A is expected to be 25% higher ten years from now and the future mix of aircraft is also described, it is then quite simple to prepare a set of daily demand "profiles" for airport A that essentially capture the entire range of possibilities (e.g., one demand profile would maintain the same daily peaking patterns as today but increase overall demand by 25%, a second profile would "smoothen out" today's "peaks and valleys," etc.).

At the network level, however, one must also describe how airports are inter-connected. In terms of our previous example, one cannot simply add, in some fashion, the requisite number of new flights (e.g., 25%) to the existing set of flights but must also specify the origins and destinations of these flights. In fact, for airline flights one must provide a daily itinerary for each aircraft in the fleet!

It follows from the above that network models must be accompanied by "modules" that produce system-wide schedules of flights (such as those given by the *Official Airline Guide*) which satisfy certain forecast specifications. These schedules constitute the "demand scenarios" that are a necessary input to network models. If the database of the network model already includes a complete "baseline" schedule (e.g., the "OAG" for Summer 1990) and if the future conditions of interest represent only a marginal change from the baseline (e.g., a 5% growth in traffic by the summer of 1992 in a stable, highly regulated market environment) then it is not too difficult to develop heuristic algorithms that would generate reasonable variations to the baseline schedule which satisfy the specified changes. However, when potential changes are large (e.g., schedules five or ten years from now in a deregulated, highly-competitive environment), baseline schedules may not provide a good starting point. The schedule generation process for network models becomes a difficult and highly speculative exercise under such circumstances.

2.5 Problem Size and Data Requirements

In addition to the four preceding points, which are specific to the airport/ATC environment, there is the more obvious difficulty of the size of the problem that one must contend with. The amount of data required and the number of events to be depicted in a network model of airports and ATC sectors is very large. As an illustration, the number of daily flights in the continental United States is currently of the order of 100,000 and the number of simultaneously airborne aircraft in the national airspace often exceeds 5,000.

2.6 Level of Detail

All the challenging problems mentioned so far have a major implication for the designer of network models: one must be cognizant at all times of the objectives of the model so that one can select exactly the right level of detail. Including an excessive amount of detail or unnecessary capabilities can mean a dramatic reduction in computational performance and a model of little practical utility. Conversely, oversimplification of reality in the interest of computational efficiency may render the model useless for some types of applications. To put it another way, one can "get away" with some design mistakes in the case of single-airport and, even, regional-airport-system models, but not in the case of network models.

For these reasons, it is probable that successful network models, at least initially, will be "problem-oriented," i.e., will be designed with specific applications in mind. At least three different types of models can be identified, in response to strongly divergent application requirements:

(i) Policy-analysis models which are macroscopic (i.e., omit a great deal of detail) in exchange for the ability to explore quickly a large number of network "states" or "scenarios" for the future or proposed alternatives; such models can be used to investigate, in an approximate manner, issues that arise at high policy-making levels – for instance, evaluating the benefits of alternative ways to allocate federal airport and ATC funds.

(ii) Models for detailed planning and design which employ a high level of detail and would be used, as a rule, in connection with long-term studies that examine a relatively limited number of engineering design (or operating procedure) alternatives – for instance, the design of new Central Flow Control procedures for air traffic.

(iii) Operations-support models, which are also highly detailed but also have a fast-response, "real-time" capability so they can be consulted in the course of daily ATC and airport operations, for instance in providing decision support for traffic flow management for the Central Flow Control Facility in Washington or for Europe's Central Flow Management Unit.

A much longer discussion of these alternative types of models and associated characteristics can be found in Odoni (1991).

3 STATE OF THE ART

To our knowledge, only two models that can be characterized as "network models" currently exist. Both are simulations.

AIRNET is a PC-based macroscopic simulation model

that has been developed very recently by the ATAC Corporation for the Federal Aviation Administration (Abkin et. al (1989), FAA (1990)). It encompasses the entire US airport network and focuses on 63 of these airports. The level of detail in AIRNET is the appropriate one for a policy-analysis model, as described in Section 2.6. For example, the model is not concerned with the en route segment of a flight and uses constant travel times for each type of aircraft on each origin-destination pair. AIRNET has several attractive features – including efficient computational performance – that make it a promising tool for its intended uses.

NASPAC (National Airspace System Performance Analysis Capability) refers primarily to a simulation model prepared by the MITRE Corporation for the FAA's Office of Operations Research beginning in 1987 (Lacher (1989), Frolow and Sinnott (1989)). NASPAC covers a network of 58 major airports in the United States and is the only existing network model that attempts to provide a capability for simulating not only airport operations but some aspects of en route operations as well. Some of NASPAC's features would typically be associated with a macroscopic, policy-analysis model and others with microscopic-level models for detailed planning and design (cf. Section 2.6). In this sense, NASPAC is a less "focussed" model than AIRNET. Partly for this reason NASPAC requires significant user effort and computational resources to set up and run (Odoni (1991)).

The databases assembled for NASPAC and for AIRNET contain impressive amounts of information on flight schedules, airport characteristics and other aspects of the ATC system (cf. Section 2.5). These databases constitute important resources in their own right.

Both models are capable of generating system-wide schedules of flights which satisfy certain forecast specifications (cf. Section 2.4). In both cases, the approach used consists of straightforward heuristics which project future flight schedules by making marginal changes to a current OAG schedule. As noted in Section 2.4, this may work well for small overall traffic changes (of the order of 5% or so) but may not for more significant changes. Thus, the problem of improved capabilities for generating demand scenarios is one that deserves more future research.

Similarly, the issues of dealing effectively with the combinatorially explosive state space of network models (cf. Section 2.2) and of estimating the associated state probabilities (cf. Section 2.3) need to be examined at the basic research level, since they have not yet been discussed explicitly in the existing literature, including that associated with AIRNET and NASPAC.

In conclusion, the development of practical models of airport/ATC networks of national or international scope

represents a major area of need and opportunity. However, several related questions of a fundamental nature are open at this point and need to be addressed.

In terms of methodologies, simulation is certainly a natural approach to pursue in developing network models of all three types (Section 2.6). NASPAC and AIRNET provide good starting points and important "building blocks" for simulations of the policy-analysis type.

At the same time, other methodologies must be pursued, particularly when it comes to policy-analysis models. One is the possibility of developing high-speed network models by taking advantage of existing dynamic queueing models of individual airports which perform very efficiently. A second possibility is the development of statistical/econometric models that provide relationships on a system-wide basis between delay (or other desired "dependent" variables) and demand, capacity, fleet composition or other appropriate independent variables. Both of these possible alternative methodologies (queueing-based models, statistical/econometric models) again require research at the basic level.

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