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Title of Paper Simulation Modelling of Airways and Airport Systems

Abstract

The application of simulation modelling to the planning and development of airways and airport systems is discussed. Airport capacities are explained and also the relationship between capacity and aircraft delay. Some examples of current work on Sydney airport are presented. The development of a new airways simulation model is discussed together with an indication of the types of problem it is hoped to investigate with the model.

SIMULATION MODELLING OF AIRWAYS AND AIRPORT SYSTEMS

INTRODUCTION

For several years the Department of Aviation has used simulation techniques to study various aspects of operational systems. Work to date has centred largely around the operation of airports and the assessment of various options for improving aircraft traffic handling and reducing delays. Future work will extend this to studies of air route and airspace design and usage.

WHY USE MODELS?

The use of models to investigate the structure and operation of complex systems is an old-established technique. It is sometimes possible to study a system by experimenting with the system itself, but there is usually the need to assess how systems will perform before they are built and without the trouble and expense of constructing prototypes. Alternatively, we may wish to examine how changes to existing systems would affect their operation without the inconvenience and possible risks involved in actual experimentation.

The more complex the system, the more important modelling becomes, not only in terms of resources but also because intuitive solutions to multi-parameter problems become progressively less reliable as the number of parameters increases. Complex models, of course, bring their own problems. They have to be developed and tested and not the least problem is validation - the process of ensuring that the model does, in fact, represent the real system to some acceptable degree of accuracy in the areas of interest and importance.

TYPES OF MODELS

A model can be considered an assemblage of information which describes all or part of a system. In certain models such information is embodied in the physical properties of the model and in others it is represented by mathematical symbols. There is no unique model of a system since they can be, and usually are, designed to represent only those parts of the system of immediate interest. In many respects models are therefore simplifications of reality and this in turn can lead to predictive inaccuracies if they are used inappropriately.

The major families of models are

- physical models
- mathematical models
- simulation models

sub-families of which are static models, which are used to represent steady-state systems, and dynamic models which follow the changes over time that occur in a system. All models are only approximations of reality and balances must be found between the competing requirements of realism and ease of construction and use.

Physical Models

Physical models are mechanical representations of systems. Some well known examples are

- scale models used to assess the performance of ships' hulls
- aircraft models for use in wind tunnel experiments to study air flow
- hydrological models to study water flow in rivers and estuaries
- industrial pilot plants.

Mathematical Models

Many simple systems can be accurately described by mathematical equations. Some examples are

- queues
- moving bodies
- oscillating systems with or without damping
- electrical circuits

The behaviour of the model is studied by solving the appropriate equations either analytically or, where the equations are not capable of simple solution, by numerical methods.

Simulation Models

Many real systems are not capable of adequate representation either by physical models or by mathematical equations. Such systems are generally characterised by

- large numbers of interacting variables
- boundary conditions and discontinuous functions
- the inclusion of one or more stochastic processes
- incomplete understanding of basic system mechanisms

The modelling of such systems normally involves a process of continued recalculation of system parameters taking into account, as far as is necessary, the interdependent nature of the causes and effects operating on the individual system elements. Such models therefore invariably require the use of computers to process the large numbers of calculations required.

Transport system models are usually in this category and the work described in the remainder of this paper documents the use and development of computer based simulation models of airways and airports.

MODELLING AIRPORTS

The simulation model currently used by the Department of Aviation is an enhanced version of one developed for use in a project on Sydney Airport and which has been described by Atack (1978). The later enhancements incorporated into the model have generally been to enable the study of operational modes not envisaged when the original model was developed. Such modes included the use of less than the full length of runway for aircraft departures or arrivals. At some airports with crossing runways (e.g. Sydney) it is possible to use parts of long runways independently of traffic using the crossing runway. This is accomplished by allowing departures from a point past the runway intersection or instructing landing aircraft to stop before the intersection. (A landing chart showing the physical layout of Sydney airport is shown in Figure 1)

This model is used primarily to estimate

- airport capacities
- delays to aircraft due to congestion
- the cost of these aircraft delays
- the value of airport development projects in reducing delays and costs
- the effect of new air traffic control procedures
- the impact of traffic regulation measures such as peak-hour surcharges, the exclusion of low priority traffic, and slot systems (1)
- the effect of special procedures, such as those required for noise abatement, on traffic flow

Capacity

Because of the randomness of demand on airport facilities over short periods, some delays and some delay costs will accrue to aircraft operations even at comparatively low overall traffic levels. At the other end of the scale, the absolute physical capacity of an airport can be considered as the maximum hourly handling rate (MHHR) multiplied by the number of operational hours

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1. Slot systems involve the allocation of specific movement times, or 'slots' to individual aircraft and are useful in reducing delays. Such systems can be applied over long periods based on airline schedules or over shorter periods depending on weather or air traffic control workload. Some systems in use overseas involve payment by users for peak-time slots.

In a simple Poisson process, where arrivals into the system appear at random intervals and where the service time is constant, the mean queue length, Q, is given by

$$Q = \frac{r(1 - r/2)}{1 - r}$$

where r is the traffic intensity

given by

$$\frac{\text{mean service time}}{\text{mean inter-arrival time}}$$

Mean delays and delay costs are proportional to Q and these quantities therefore increase without limit as r approaches unity.

Clearly a situation of continuous demand implies extremely long queues and unacceptably high levels of delay and delay costs. Thus any statement of practical capacity depends on the pre-determination of a maximum acceptable level of delay or delay cost. This can be expressed in terms of mean delay, delays in peak hours (the U.S.A. Federal Aviation Administration approach), marginal delay increments, the percentage of passengers delayed more than x minutes, total delay costs of more than $y, and so on, normally averaged over a long period, typically a year.

This concept of 'practical capacity' rather than absolute or maximum capacity is normally what is meant by the simple term 'capacity' and this is the sense in which the word is used in this paper. Nevertheless maximum hourly rates are of interest in the planning of facilities such as aprons, gate positions, and terminal sizes which are dependent on peak load requirements.

The following definitions of the above terms are those used by the Department of Aviation:

Maximum Hourly Handling Rate (MHHR)

> the mean maximum number of aircraft movements that can be processed in one hour under specified conditions of runway usage, weather, and aircraft mix and under conditions of continuous demand

Annual Capacity

> the number of aircraft movements per year which results in a mean delay of 4 minutes to arrivals and departures under specified conditions.

It is evident that the term annual capacity does not represent some discontinuity below which operations proceed smoothly with mimimum delay, and above which chaos reigns. Frequently, however, this is just the interpretation assumed by many in the airport planning field. The annual capacity is merely a point on a continuum of increasing delays and delay costs, but which represents a level of traffic at which substantial interference to airline schedules can be expected and obvious dis-satisfaction felt by the travelling public.

At any level of mean delay, the delays themselves have some distribution which generally is assymetric with a significant tail. Even at sub-capacity traffic levels there will be some aircraft suffering quite significant delays at peak times, possibly 30 minutes or more.

Useful Functions

The relationship between delays or costs, and aircraft movement numbers is a rapidly increasing function. In many practical situations the relationship appears approximately exponential, and such an approximation over small intervals is sufficiently accurate for most purposes.

The two most useful relationships which can be derived directly from the model are

- the delay-movement function (DMF) which describes mean delays as a function of aircraft movement numbers

  and

- the cost-movement function (CMF) which describes total direct operating costs to aircraft operators as a function of aircraft movement numbers.

The CMF is an aggregation of direct operating costs to aircraft operators and includes such items as fuel, oil, air navigation charges, crew costs, maintenance, depreciation and insurance. A passenger value-of-time cost can be included if required but this is normally not done, due partly to the lack of a universally accepted method of assessing the value of passengers time and partly to the desire to consider only actual expenditure.

Two additional, and equally useful, functions result from the transformation of aircraft movement numbers to expected dates by the application of appropriate forecasts. They are

- the delay-time function (DTF) which describes expected mean delays as a function of date

  and

- the cost-time function (CTF) which describes expected total direct operating costs to aircraft operators as a function of date.

The use and value of these functions will be considered later in the paper when some specific applications to Sydney Airport are discussed.

In practice, the costs of delays will also include a component due to costs accruing at other locations because of schedule disruption but these are largely unquantifiable and are normally ignored. There can also be other hidden costs to industry where development projects impose changes in operational procedures. In this context, it is interesting to note that Wheatcroft (1982) estimated that any major development of Stansted Airport (near London) would involve British Airways in a requirement for 40 more aircraft at an additional annual cost of £150M to £200M for the same overall level of passenger and freight traffic because of split operations with Heathrow.

Factors Affecting Airport Delays and Delay Costs

The major factors which affect delays and delay costs, and which are all input parameters to the simulation model are

- the number and disposition of runways
- the suitability of the runways for different aircraft types
- taxiway positions and design exit speeds
- the proportion of different aircraft types and their
  - acceleration/deceleration characteristics
  - touchdown speeds
  - crosswind and downwind capabilities
  - ability to fly in poor weather
- meteorological factors
  - frequency of instrument conditions
  - wind direction and speed distributions
  - frequency of wet runway conditions
- distribution of demand throughout the day
- distribution of daily movements throughout the year
- air traffic control procedures
- noise abatement requirements

AIRPORT PLANNING AND DEVELOPMENT

The objective of airport planners should be the provision of a facility which operates at minimum total cost to the aircraft operators, the travelling public and the community at large. In addition, sound planning will allow this situation to continue, as demand levels change, by the timely provision of additional or changed facilities within practical limits imposed by forecasting uncertainties.

There is sometimes a tendency to over-emphasise the importance of the numerical annual capacity of an airport and to use it, in conjuction with activity forecasts, to determine developmental strategies. This approach is too simplistic. Optimum airport developments at appropriate times can only be determined by detailed analysis of all the costs and benefits involved and their expected timings. It should also be appreciated that the problems of long delays and their associated costs can also be ameliorated by methods other than the provision of additional airport facilities. Delays occur basically because of the randomness of the demand for service. Some planning and control of the demand pattern will result in more efficient traffic flow and a reduction in delays for the same throughput. Such control can be imposed by techniques such as slot systems (mentioned earlier) or by wide-area multi-airport flow control. Other traffic regulation measures available include the restriction of certain types of operation, such as private flights, in peak hours.

In addition, if delays can be preferentially absorbed on the ground rather than airborne or if they can be imposed on aircraft with low operating costs, total delay costs will be reduced.

SYDNEY AIRPORT STUDIES

Sydney airport is the busiest major airport in Australia and handled around 180,000 aircraft movements in 1984. There are many busier major airports in the world, some examples are shown in Table 1. Sydney, however, has only two runways and these also intersect which considerably restricts throughput (see Figure 1).

Table 1

Airport Movements at Selected International Airports - 1983

Chicago (O'Hare) Intl	668,000	
Los Angeles Intl	479,200	(1982)
Dallas - Ft Worth	430,100	
Miami Intl	341,600	
Honolulu Intl	333,000	
New York (JFK)	289,600	(1982)
London Heathrow	274,300	
Sydney	174,500	

ICAO Civil Aviation Statistics of the World 1983

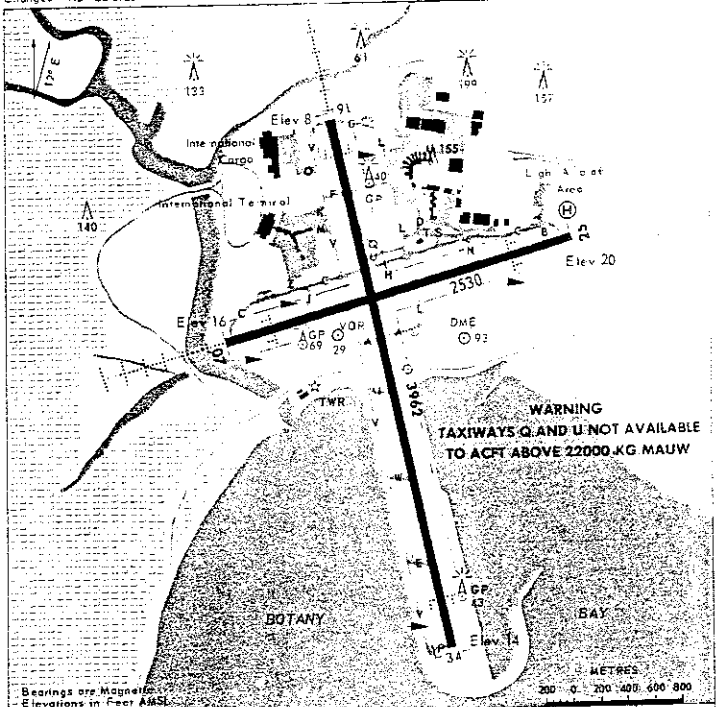
Possible Options for Airport Development and Traffic Regulation

The Department of Aviation's airport simulation model has been used to evaluate many options for the development of Sydney airport and also for the regulation of traffic to minimise delays. The various options examined fall into five categories

- additional runways
- additional taxiways
- changed air traffic control procedures
- slot systems
- exclusion of various types of operation at certain times of day.

LANDING CHART

Changes AD Co-ords SYDNEY (KINGSFORD SMITH) N S W



RWY NR	TAKE-OFF MINIMA CEILING (ft) VIS (km) DAY	NIGHT	LIGHTING APPROACH	RUNWAY	USABLE LENGTHS LANDING	TAKE OFF	WIDTH RWY	RWS
16	300 2	300 2	Precision Approach Category 2	6 STAGE			45	300
34			T-VASIS 6 STAGE	3 STAGE				
07	300 2	300 2	T-VASIS 6 STAGE HIAL 6 STAGE	6 STAGE			45	300
25			T-VASIS 6 STAGE	3 STAGE				

AIRWAY AND AIRPORT LIGHTING
Aerodrome Beacon Alt WG
Hazard Beacons
Obstacle
Wind Direction Indicator
Taxiway: Centreline Green & Sideline Blue

AIP Australia Dept of Aviation — AD Elev 21 — LANDING CHART

29 AUG 1985 — 33° 56 51"S 151°10'33"E — SYDNEY (KINGSFORD SMITH) N S W

Figure 1. Sydney Airport - Landing Chart

The following examples have been chosen to provide an indication of the type of work that has been undertaken

(i) the airport layout and air traffic control procedures in use prior to December 1983
(i) the effect of an additional high-speed taxiway exit for light aircraft landing on runway 16 which was commissioned in December 1983
(iii) changed air traffic control procedures introduced in July 1985 to allow some independent use of the southern end of runway 16

Results

The delay-movement functions (DMF) and the cost-time functions (CTF) were derived from simulation model runs and are shown in Figures 2 and 3. The results are summarised in Table 2

Table 2 Sydney Airport - Summary of Results

	Case (i) Pre Dec 1983	Case(ii) Dec 1983-Jul 1985	Case(iii) Post Jul 1985
Annual Capacity	193,000	202,000	206,000
Maximum hourly handling rate	52	55	56

Comment

The additional taxiway for light aircraft landing on runway 16 provides a significant improvement in airport operations by reducing interference with crossing traffic on runway 07/25. The reduction in delay costs expected from the project were estimated from these and similar simulation model runs before the construction of the taxiway. The results provided substantial prior justification for the necessary capital expenditure.

The changes to air traffic control procedures in case (iii) only apply when runway 34 is in use (i.e. landings and take-offs to the north). Because of noise abatement requirements this is a non-preferred operating mode and is only used about 5 per cent of the time as dictated by wind conditions. Thus, although the improvement in traffic handling is significant when the new procedures are in use, the overall improvement is not great.

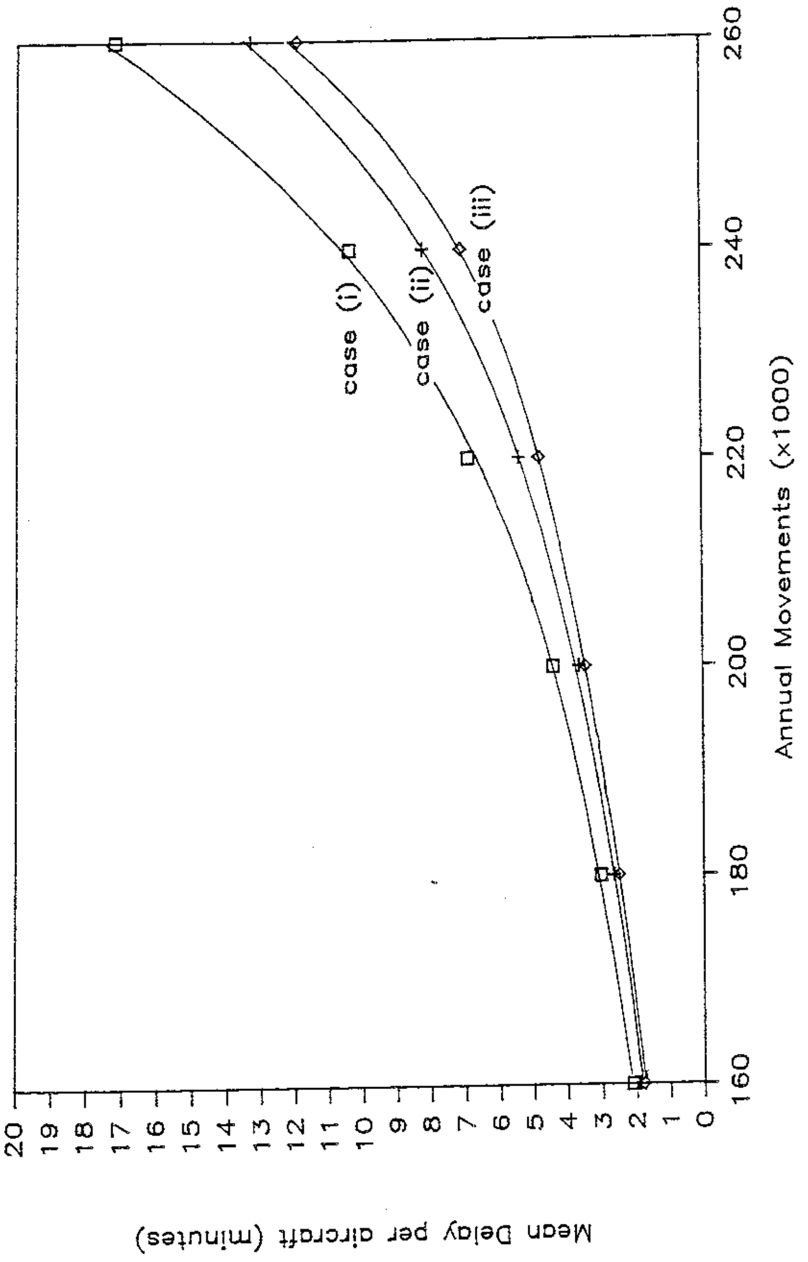


Figure 2. Sydney Airport - Mean Delays v Annual Movements

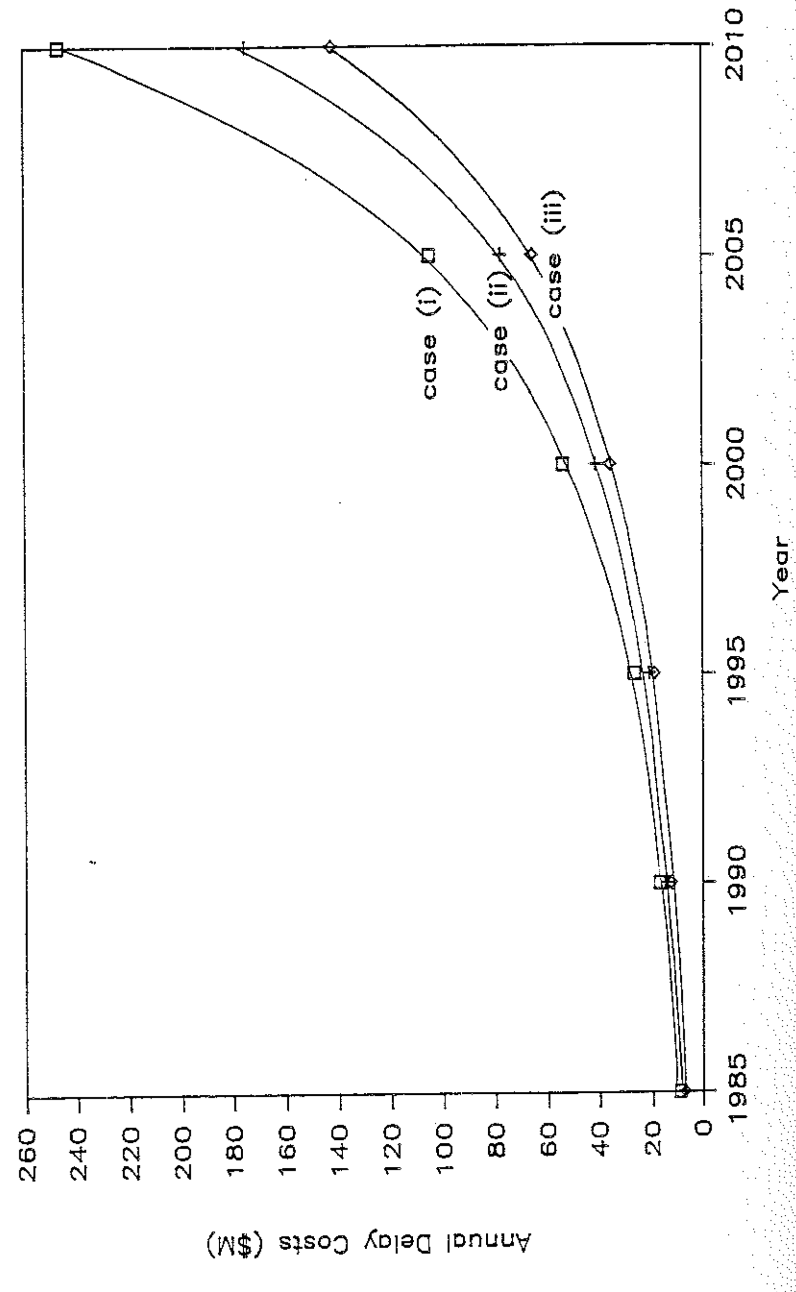


Figure 3. Sydney Airport - Mean Delay Costs v Expected Dates

MODELLING AIRWAYS SYSTEMS

Airport traffic handling represents only part of the Department of Aviation's operational system. The other major element is the rest of the airways system which comprises air routes and airspace, together with the various control and advisory services provided to aircraft. There is considerable complexity in the interactions between taxiways, runways and airspace and the use of simulation models can help improve operational efficiency and contain or lower eventual end costs to the users. The simulation model described earlier is restricted in use to runway systems and to the airspace immediately associated with each runway. To study the wider areas of airspace and air traffic management in general there is a need to develop an extended model to include these elements. Future planning for such a model is now described.

Air Routes and Airspace

Efficient traffic flow requires, as far as possible

- uniform route segment capacity to minimise bottlenecks
- good wide-area flow control to govern peak load levels
- minimum numbers of track crossings and other confliction points.

Good airspace and air route design is also very important in keeping air traffic control and cockpit workloads as low as possible. Not only does this make for efficient use of personnel but the possibility of human error is also minimised

In addition, the need to reduce aircraft operating costs to a minimum means that air routes should be as short as possible and also that aircraft should be allowed to adopt their optimum climb and descent profiles and cruise at their optimum levels. It can be seen that these requirements do not necessarily coincide with those mentioned above, the aim of which is good traffic flow and low workloads. Compromises must often be sought, and modelling techniques can be used to assess and evaluate the compromises.

Control and Advisory Services

Full, positive, control services are provided to aircraft operations at major airports and in the air routes linking these centres. Outside these areas a traffic advisory service is provided to certain types of aircraft operations.

Decisions about the types of service to be provided in any area revolve around such questions as

- where are the higher-cost positive control services justified in terms of reduced collision risk?
- what is the most efficient division of airspace between different control or advisory positions?

- what scale of facilities is required?
- how many staff will be required?

Modelling can provide considerable assistance in answering such questions.

Airways Model Development

The Future Requirements Section of Airways Division in the Department of Aviation is currently engaged in a project to develop an airways simulation model to examine those areas mentioned. In addition it will be able to generate data on collision risk, aircraft separation rules, and air traffic control workload. A block diagram of the model is shown in Figure 4. It embodies several unique design features to enhance realism and to allow the investigation of different types of air traffic control methods.

It is important here to note the differences between simulation modelling and the use of simulators as air traffic control training aids. Simulators for training provide a realistic operational environment in which trainees control aircraft to improve their efficiency, and to learn operational procedures, particularly those governing emergency situations. In contrast, modelling techniques are designed to study how traffic flows and to identify methods of improving traffic flow to reduce costs.

Aircraft navigation

Aircraft are not simply processed in straight lines from one route point to the next. Instead, an initial great-circle track angle is calculated from the last position. Wind data is then consulted and a heading and ground-speed calculated. A perturbation is then imposed on the calculated heading, the magnitude of which is determined by the navigational capabilities of the aircraft. Periodically track errors are calculated and correcting action taken if necessary. Speed and altitude ranges are defined for various aircraft types and there is provision for aircraft to examine changing wind conditions and initiate requests for different altitudes if this would be beneficial.

Realistic navigation is important since it is desired to investigate the adequacy of assumed positional uncertainties in air traffic control procedures.

Air traffic control data

It is considered important that the parts of the model simulating the air traffic control system do not have access to the precise position of each aircraft, but rather to a degraded position, either simulating a radar display, or a procedural flight information board in the case of aircraft outside radar coverage. In this way it is possible to derive information on collision risk in circumstances where air traffic control is unaware of the true proximity of two aircraft.

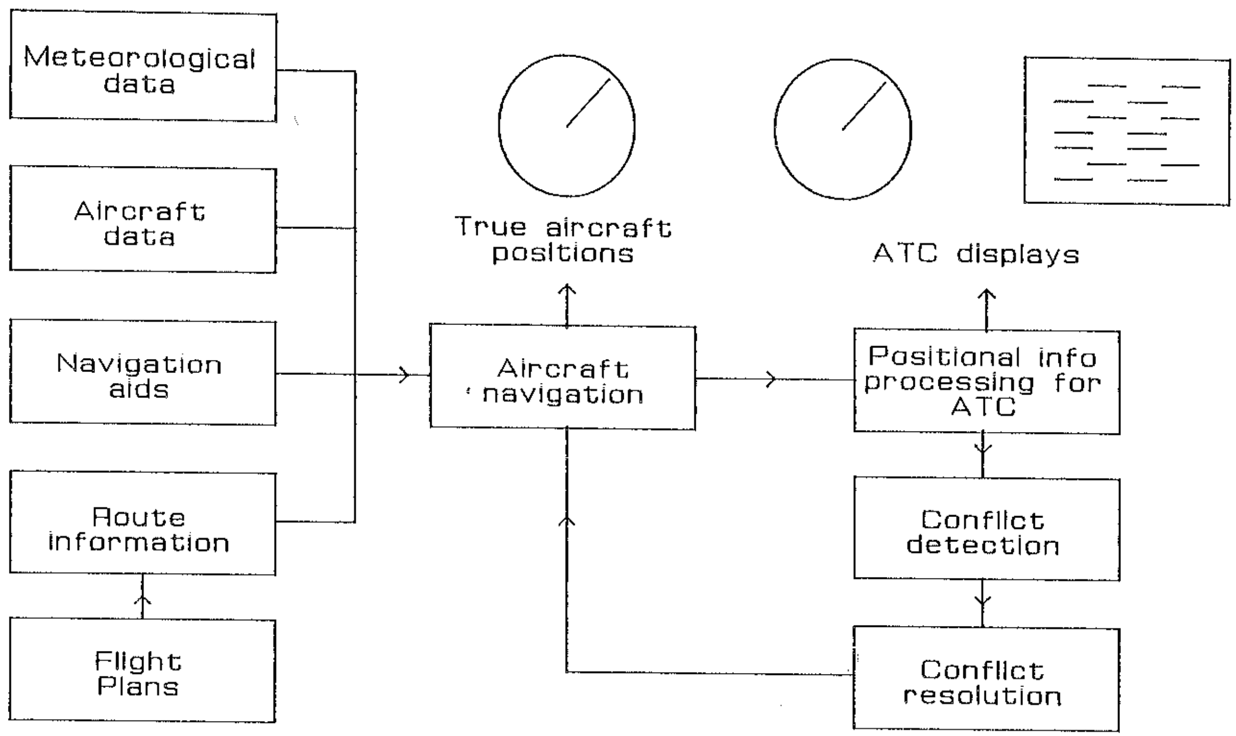


Figure 4. Airways Simulation Model - Block Diagram

This concept of using lower accuracy positional information for simulated control purposes also will allow a study of the information processing system which provides data to air traffic control. The effect of changes in this system, such as upgraded radar displays or computer asistance in the management of procedural type displays can be investigated.

Conflict detection
Models need to apply actual air traffic control procedures in separating aircraft from each other and must therefore include realistic conflict detection and conflict resolution algorithms. As noted in the previous paragraph, the conflict detection module only has access to controller (i.e. degraded) positions and makes judgement on this basis about the need for controller intervention.

The conflict detection module has two other important roles. Firstly, by disabling this function collision probability in uncontrolled airspace can be studied. This, in turn, will provide cost-benefit information on the provision of air traffic control services and allow the derivation of better indicators for the establishment of such services. Secondly, the model can become, in effect, a test facility for the assessment of different conflict detection methods prior to their introduction into actual air traffic control facilities.

Conflict resolution
This is a much more difficult process than conflict detection. Once a possible conflict is identified, resolution action must be commenced.

In practice, a controller can rapidly weigh up a variety of possible courses of action and select the best solution under the circumstances. This could be a solution which minimises his own workload in a busy situation, or perhaps one which minimises additional aircraft operating costs at the expense of added traffic complexity

This part of the model will need to examine each of several posssible solutions to the problem, and then select the 'best' according to some pre-determined set of rules

In a similar sense to that mentioned under conflict detection, the model will eventually provide a valuable test facility for algorithms providing resolution advice.

Aircraft costs
The model will have access to direct operating cost data for various aircraft types Costs will be incremented for each aircraft as its flight proceeds. Corrections will be calculated to allow for climbing and descending flight segments and penalties added where aircraft are required to fly at non-optimum levels.

Graphical displays

Graphics terminals will be able to display aircraft flying in any chosen geographical area. A controller (i.e degraded) display will be available and also a display of the accurate aircraft positions.

Current state of the project

As at January 1986, the high-level systems analysis work has been completed. Considerable work has been done on the navigation, display and costing systems and these parts of the model are expected to be running within three to four months The conflict detection and resolution elements still require further work but basic modules should be designed and operating by the end of 1986

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