Nationaal Lucht- en Ruimtevaartlaboratorium

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Summary

Currently, the European air transport system is experiencing an annual growth of 7%. With an increasing number of flights, airports are reaching their capacity limits and are becoming a bottleneck in the system. Mantea is a European Commission funded project dealing with this issue. This paper focuses on planning decision support tools for airport traffic controllers.

The objective of our planning tools is to achieve a better use of the available airport infrastructure (taxiways and runways). To generate a *safe* plan, many rules must be taken into account that restrict the usage of airport tarmac: international regulations, airport operational procedures, aircraft performance, weather conditions and sometimes even controller "usual practices". To generate a *realistic* plan, extensive monitoring of the traffic situation as well as suitable timing must be achieved. In the life cycle of a flight, 11 out of 15 possible causes of delay occur in an interval of 10-20 minutes, between aircraft start-up request and push-back. This means that precise planning before the end of this period is highly improbable. On the other hand, planning after this period implies the need for fast responses from the system.

In the Mantea project, an architecture is proposed in which a co-operative approach is taken towards planning aircraft movements at the airport. Controllers will be supported by planning tools that help assigning routes and departure times to controlled vehicles, in planning runway allocation (departure sequence) and occupancies, and in monitoring plan progress during flight phases. The planning horizon relates to medium term operations, i.e. 2-20 minutes ahead. The Mantea planning tools implement the following functions: *runway departure planning, routing,* and *plan conformance monitoring.* The tools will reduce the controller's workload, increase the level of safety for airport surface movements, and reduce the number of delays and operating costs for the airliners.

In this paper, we will focus on the constraint satisfaction programming techniques used in Mantea for (1) runway departure planning, (2) itinerary search and taxi planning functions. The airport tarmac and runway vicinity air routes have been modelled as a graph. Real time constraints have brought us to develop fast search strategies through the use of heuristics and hill climbing. For the itinerary search problem, an algorithm linear in complexity has been developed.

Contents

(14 pages in total)

1 Introduction

With an increasing number of flights, the European air transport system is currently experiencing an annual growth of 7%, the airspace and airports are becoming more and more congested. Figures show that in June 1997 (the busiest month of the year), on average 4,500 flights per day experienced delays, compared with under 3,750 in the same month in 1996 (Ref. 1).

In this paper, we focus on the planning of taxi routes and on departure runway sequencing. The latter includes the allocation of air routes to departing aircraft: SIDs (Standard Instrument Departures). Constraint satisfaction programming techniques are used for:

- the runway departure sequencing and SID allocation function,
- the itinerary search problem,
- the taxi route planning function.

The current chapter shows an architecture for airport surface movement functions in which a co-operative approach is taken towards planning aircraft movements. Chapter 2 describes the runway planning and the taxi route planning problems.

1.1 Congestion at airports

The airport infrastructure has been identified as becoming a major bottleneck in the Air Traffic Control (ATC) system. The construction of new airports or the expansion of existing ones, however, is extremely expensive and has a strong impact on the European environment. Aviation authorities are seeking methods to increase the airport capacity with the existing infrastructure (in all weather conditions), while at least maintaining the current level of safety. This paper is based on work that was carried out in the Mantea (MANagement of surface Traffic in European Airports) project, which was partly funded by the European Commission.

In this paper, we propose a planning function to support traffic controllers at airports. The planning function provides a decision support tool to reduce the controller’s workload, make better use of the available airport infrastructure, reduce the number of delays, and achieve an optimal throughput even under bad weather conditions (viz. low visibility).

1.2 Aircraft planning

Controllers in airport control towers are responsible for the management of surface traffic. Inbound aircraft are handed over from the arrival controller (often on another location); the sequence and arrival times of inbound aircraft cannot as such be planned in the tower. The tower receives the arrival information a few minutes before the aircraft lands, so that a taxi plan can be made from the arrival runway exit point to the terminal gate.

Departure plans are made in the control tower. Start-up times, taxi plans, and runway plans can be made in advance. Each departing aircraft is assigned a time slot, which is a co-ordinated time interval of about 15 minutes in which the aircraft has to take off. This co-ordination is done with the CFMU (Central Flow Management Unit) in Brussels before the flight starts; the CFMU planning aims at obtaining a constant traffic flow through all sectors in Europe. For the airport controllers, this CFMU restriction ensures that the feeders (i.e. the points where controllers hand over the flight to the next one) are not overloaded.

The planning process is complicated by the fact that even under normal operating conditions, at least three different controllers handle the aircraft over the airfield. Under stress situations, more controllers may be assigned to handle airport traffic. Several controllers act consecutively on each plan. The plans must be established some 2-20 minutes before a flight comes under executive control.

The decision support tool that we propose overcomes most of the problems listed above. We propose a co-operative approach where the planning process is initiated by the runway sequencer, because the runway is usually the scarcer resource. Arrival plans are generated forwards in time towards the assigned gates; departure plans are generated backwards through time, ending with the establishment of a start-up time. To ensure plan achievement during the execution phase, monitoring and re-planning functions need to be part of the proposed architecture.

1.3 Airport functional architecture

An airport, or A-SMGCS (Advanced Surface Movement Guidance and Control System), is a complex system involving surveillance, monitoring, planning/routing, and guidance functions (see figure 1 and Ref. 2).

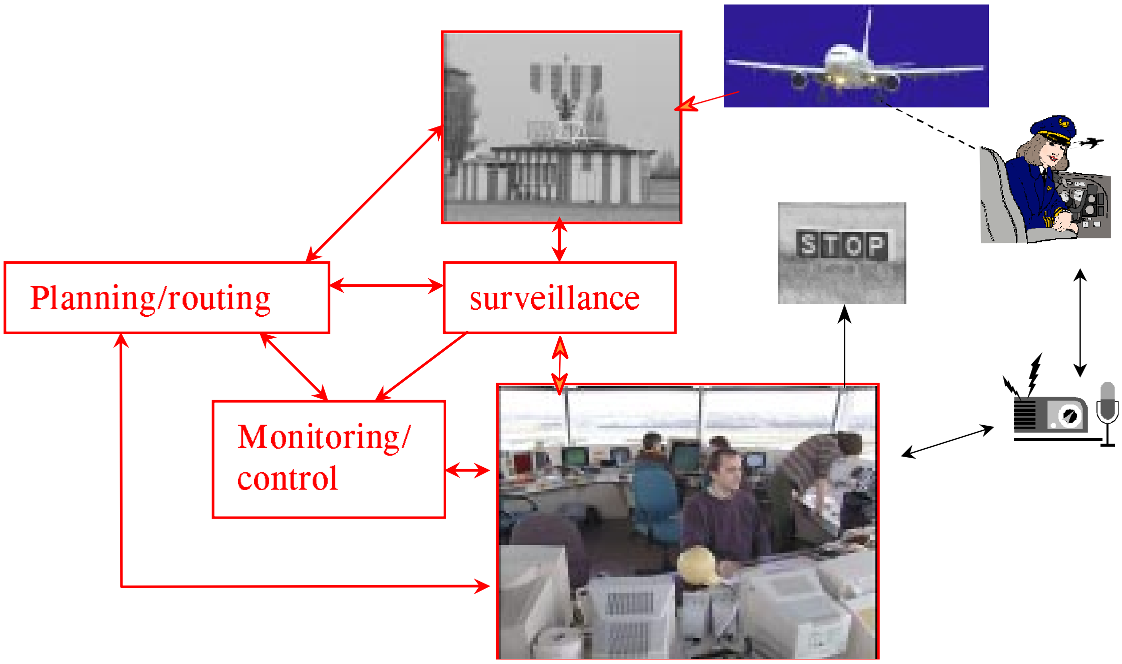

Figure 1: Typical airport functional architecture

On an airport tarmac, aircraft and other vehicles are moving independently. These mobiles are sensed by a Surface Movement Radar (SMR) or some other type of sensor. A picture of the traffic situation is built and shown to the airport controller. To support controllers in their job, they are also provided with monitoring tools, which warn them about potential accidents. The controller uses a radio or more sophisticated means (such as the lighting system) to communicate with pilots and guide the aircraft to their destination point on the airport. Coherent guidance instruction is made possible through the use of planning tools, ranging from paper flight plan strips to computer scheduled ground routes and departure sequences.

1.4 Constraint satisfaction for airport planning

Planning and scheduling have had a long relationship with constraint representation and constraint-based reasoning (Ref. 3, Ref. 4). A constraint is a formalisation of a restriction to the planning process. Constraints usually specify relationships between different plans and specify how scarce resources can be used. The separation rules that are applicable in air traffic control can best be regarded as restrictions or constraints. Therefore, constraint satisfaction seems an appropriate technique for solving the runway and taxiway planning problems.

The airport tarmac and runway vicinity air routes have been modelled as a graph. On the ground, the links are bi-directional, although preferred routes can be modelled. In the air, the graph is a directed graph.

2 Planning

Two planning functions are defined in the architecture: the runway departure planner and taxiway routing management.

2.1 Runway departure planning

The objective of the runway planning function is to establish an optimal sequence in which aircraft can depart from the available runways and to plan their initial (climb) flight phase: the SID (Standard Instrument Departure route). Constraints specify that each aircraft takes off within its allocated time slot, that separation criteria between aircraft (both on the ground and in the air) are observed, and that the feeders towards adjacent control sectors are not overloaded (Ref. 5).

Standard rules for separation of consecutive aircraft prescribe a two minutes interval. Specific rules exist for consecutive aircraft in different categories. Furthermore for planning SIDs, aircraft on the same air route need to comply with air separation criteria, which are usually larger than on the ground.

In this paper, a decision support function for the runway controller is proposed that may be divided into three sub-functions:

1. Runway allocation. Determine which runway is best to use in the given circumstances (e.g. wind direction and force, aircraft type, distance from gate to runway, etc.).
2. Sequencing. Determine an optimal sequence for departing aircraft, obeying all constraints that apply for one specific airport.
3. Multiple line-up position allocation. Determine which line up position is most suitable for a given aircraft in the given circumstances. For efficiency, aircraft may use an intersection to enter the runway, so that not the whole runway has to be used for the takeoff run.

2.1.1 Constraints

To specify the runway sequencing problem in constraint satisfaction, we need to define variables $V = \{v_1, \ldots, v_n\}$, their associated domains $D = \{D_1, \ldots, D_m\}$, and a number of constraints $C = \{C_1, \ldots, C_k\}$ that restrict certain combinations of values for the variables. The underlying problem translates into the following variables and domains[1]:

$$V = \{R, R_{entry}, t_{takeoff}, SID, F\}$$
$$R \in \{25, 16R, 34L, 16L, 34R, 07)$$
$$R_{entry} \in \{Holding\ point, A, B\}$$

[1] The example is from Rome Fiumicino airport, one of the validation sites of Mantea.

$t_{takeoff} \in \{00.00h .. 23.59h\}$
$SID \in \{ELBA\ 5A, ELBA\ 5B, ELBA\ 5C, BASTIA\ 5A\ ...\}$
$F \in \{AZ123, KLM456, BA789, \ldots\}$

where

R is the runway, typically a number and an optional ‘L’ or ‘R’,
R_{entry} is the entry position to a runway, each runway has at least a holding point (the very beginning of the runway) and possibly one or two additional entry points,
$t_{takeoff}$ is the assigned time of takeoff, a one minute interval has been chosen,
SID is the assigned departure route (Standard Instrument Departure),
F are all flights that need to be scheduled during a given period.

We have defined five categories of constraints:

- Separation constraints. These concern restrictions on the departure of aircraft at the same runway because of preceding aircraft that may be too close.
- Runway usage constraints. These determine the runway number that will be used, based on the necessary runway length, meteorological conditions, runway surface condition, and runway equipment.
- Line-up constraints. These concern the possibility of lining up other than at the runway holding point and special operations that may be used under good visibility conditions.
- TMA exit point and SID constraints. Separation in the air must be guaranteed and the feeders to the following control sectors must not be overloaded.
- Sequencing and timing constraints. These specify that each aircraft must take off within its time slot and give specific constraints for ordering.

One constraint defines that aircraft in lighter weight categories should be scheduled at least three minutes after a preceding one (separation constraint to avoid wake turbulence effects):

$$\forall F1,\ \forall F2,\ \text{where } F1 \neq F2$$
$$\neg\,(R(F1) = R(F2))$$
$$\vee\,(t_{takeoff}(F1) > t_{takeoff}(F2))$$
$$\vee\,(w(F1) <= w(F2))$$
$$\vee\,(t_{takeoff}(F1) + 3 <= t_{takeoff}(F2))$$

where

F1 and *F2* are flights to be scheduled,
R is a function that provides the allocated runway,
w is a function that provides the aircraft weight category,
$t_{takeoff}$ is a function that provides the takeoff time.

This constraint defines the situation where the aircraft of flight one is heavier than that of flight two and then specifies the four conditions that should not apply (otherwise it *is* allowed to schedule flight one before number two, e.g. when they are on different runways).

SIDs are defined as of a number of waypoints, leading to the feeder to the next sector. SIDs may overlap or cross. For the scheduling of aircraft at waypoints, similar constraints apply as for runway separation, just like for prevention of overloading the feeders to the next sectors. These constraints can be regarded as separation constraints between two following aircraft. Then, we need to specify the relation between the waypoints in the SIDs:

$$\forall P1,\ \forall P2, \text{ where } P1 \neq P2$$
$$\neg\, (sameSID(P1, P2))$$
$$\vee \neg\, (follows(P2, P1))$$
$$\vee\, (t_{over}(P1) + flying\ time(P1, P2) = t_{over}(P2))$$

where

P1 and *P2* are points to be overflown,
sameSID is a function that checks if two points belong to one SID,
follows is a function that checks if two points follow each other,
t_{over} is a function that provides the time the flight passes a waypoint.

2.1.2 Algorithm

There are several possible solutions for scheduling a number of departing aircraft at an airport. Constraint satisfaction normally finds just *one* solution to a specified problem. For the runway sequencing function we want to find the optimal sequence out of all possible solutions. In our algorithm, once a complete schedule is found, it will be evaluated against some predefined cost function, after which hill climbing and branch and bound techniques ensure an efficient search process.

2.2 Taxiway plan management

Once a runway sequence is proposed, the taxiway planning function needs to get the aircraft from the gate to the runway in time. The main functions of the taxiway plan management function are (Ref. 6):

- routing (i.e. the search and choice of a taxi route),
- computation of the approximate time required by an aircraft to go from one point to another point on the airport tarmac,
- scheduling of aircraft taxi movements resulting in taxi plans.

For all of the above functions, an airport tarmac model is required so that routing can be established.

2.2.1 Airport tarmac model

Basically, the tarmac is represented as a graph with nodes and edges. However, to model the topology, the edges are grouped in logical areas corresponding to a segmentation dependent on the airfield lighting system. Each geographical way (i.e. taxiway, runway) is cut up in logical segments (called logical areas), see figure 2.

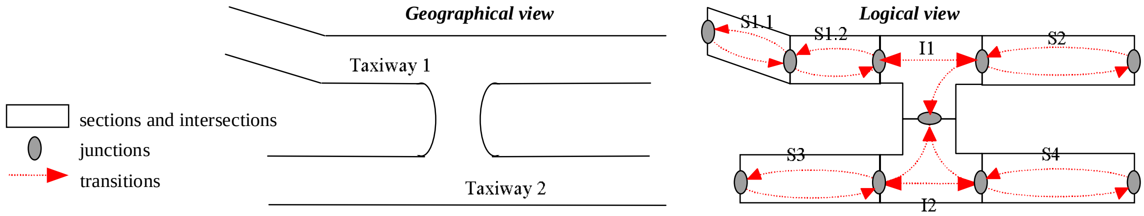

Figure 2: Airport models

The logical areas are terminated by nodes. Each node refers to two logical areas and makes the link between them. Edges are used to go from a node to another one on the same logical area. One edge per direction of traffic is built with operational properties, e.g. a transition is allowed when the traffic regulation authorises to go in this direction; all transitions are maintained since regulations may change dynamically during operation.

2.2.2 Routing

Building a taxi route is basically finding a path between two points of the tarmac (i.e. between two nodes in the graph). The search algorithm we have developed makes intensive use of constraint propagation without needing any generation. Therefore, there will be no backtracking and a search process linear in time can be guaranteed.

A constrained variable called D is associated to each node. D, constrained to be a positive integer, is used to carry the distance of the current node to the route start point. The word “distance” does not necessarily corresponds to the Euclidean distance between intersections but to some cost function that depends on aircraft characteristics and configuration of the taxiways (angles, maximum speed on taxiway…). In figure 3, the constrained variables definition domains are given between square brackets.

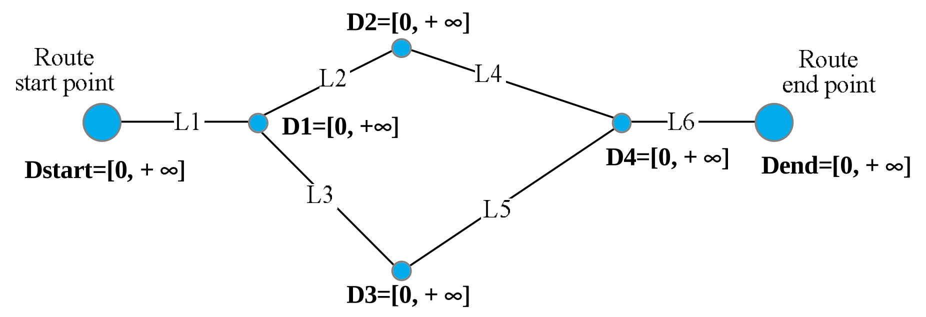

Figure 3: Constrained variables defined for route search

The constrained variable D is set to 0 at the route start point. The following constraints are posted on all other variables: for all adjacent nodes, the constrained variable D on the current node is lower or equal to the sum of the constrained variable D of the adjacent node and the edge length (see figure 4).

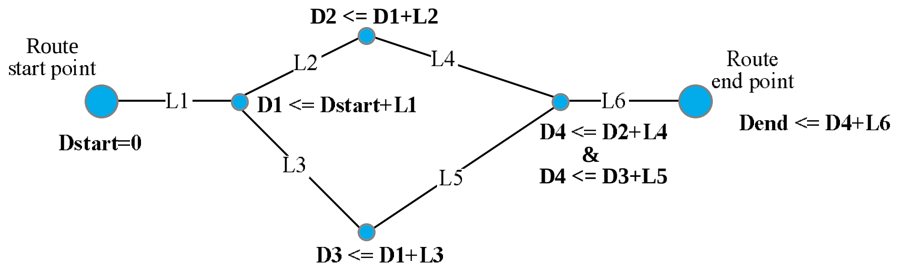

Figure 4: Constraints posted for route search

The above constraints mean that all constrained variables D are lower or equal to the shortest distance to the route start point (see figure 5).

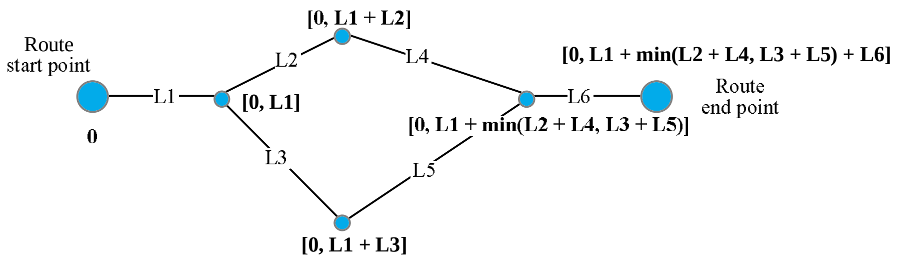

Figure 5: Constrained variables domain definition after constraint posting

When the constrained variable of the route end point is set to its maximum value, constraint propagation will bind all variables on the shortest route. The shortest route will therefore be defined by the set of nodes whose constrained variables are bound (see figure 6).

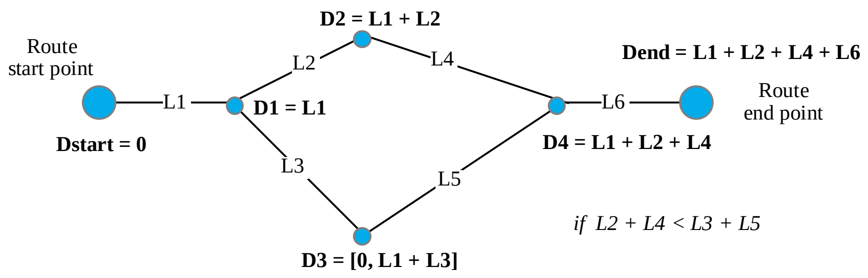

Figure 6: Constrained variables after instantiation of Dend

2.2.3 Scheduling of aircraft taxi movements

After a route assignment for each aircraft, the different aircraft need to be scheduled in time. This scheduling of aircraft taxi movements on the airport tarmac is basically a resource allocation problem. Each edge of the graph is considered as a resource whose capacity is equal to its length. Each aircraft movement on a logical area is considered as a set of two activities: the taxi activity and the reserve activity.

The taxi activity uses the resource corresponding to the edge it is travelling on during the total travel duration. The required capacity is equal to the aircraft length plus some safety margin. The reserve activity uses all the other resources of the logical area covered, at full capacity, during a time sufficient to guaranty the following aircraft from jet blast effects. One side effect of the reserve activity is to prohibit another aircraft entering the logical area in the opposite direction.

To ensure a smooth aircraft movement, all taxi activities on the same route are linked together by time constraints, i.e. taxiActivity($Edge_{i+1}$) StartsAtEnd taxiActivity($Edge_i$).

Aircraft cannot overtake each other on a taxiway. This is ensured by a logical operator between constraints specifying that if a taxi activity on an edge starts before another, then it must also end before.

The goal which is set, is made up of two parts: the inbound aircraft travel activities are required to start as soon as possible (because a landing aircraft cannot stop and wait to taxi) and the outbound aircraft travel activities are required to start as late as possible (because we want to bring the aircraft at the runway, just in time for takeoff).

The cost function associated with the scheduling is currently to limit the global taxi duration. It can be easily changed to favour inbound or outbound aircraft depending on the airport regulations and practices.

3 Conclusion

In this paper, constraint satisfaction has been applied to a route search and scheduling problem. It is shown that the technique can well be applied to establishing optimal taxi routes and runway sequences for airport planning.

The functions we propose are designed as decision aids to traffic controllers in the control tower. We show an A-SMGCS airport architecture in which a co-operative approach is taken towards the planning of aircraft movements at the airport, and where several controllers act on the same plan. Plans are established 2-20 minutes before an aircraft comes under control. The main components of the planner are a runway sequencing function and a taxiway plan management function.

The objective of the runway departure planning function is to establish an optimal sequence in which aircraft can depart from the available runways and to plan their initial climb flight phase. Constraints are formalised to specify standard separation and additional separation rules, i.e. relations between attributes of the flights. A constraint satisfaction algorithm is extended with hill climbing and branch and bound techniques in order to find the optimal solution efficiently.
Taxi plan management comprises the route search for shortest routes and the assignment of aircraft movements to taxi lanes (resources), which are modelled in a graph. Constraints specify the aircraft's position at the resource and the ordering of aircraft through time.

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