

# Mantea Departure Sequencer: Increasing Airport Capacity By Planning Optimal Sequences

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## Abstract

*In this paper, we present a planning decision support tool for airport tower controllers. The tool assists controllers in the establishment of optimal departure sequences and the planning of initial climb phases.*

*Airports are getting more and more congested with their available runway configuration as one of the most constraining factors. One of the possibilities to alleviate this congestion is to assist controllers in the planning process. In this paper, we focus on runway departure planning, but nevertheless show that this should not be a stand-alone process. Departure planning must be seen as part of an integrated and co-operative decision making environment.*

*The runway can be regarded as a resource where departing aircraft need to be scheduled given that numerous technical and operational constraints apply. Constraints determine separation between aircraft, departure timeslots, and aircraft performance limits. A novel way of departure planning is introduced: the planning process starts by sequencing the aircraft at the runway instead of*

*the gate. We use a constraint satisfaction technique to specify the problem and we have designed and implemented a prototype. An optimisation function is used to select the best sequence. Evaluations of the prototype show that sequences can be calculated in real-time.*

## Introduction

With the increase in air traffic in Europe, airports are becoming a major bottleneck in air traffic control (ATC) operations. Expansion of airports is an expensive and time-consuming process and has a strong impact on the environment. Aviation authorities are seeking methods to increase airport capacity, while at least maintaining the current level of safety.

Within the context of A-SMGCS (Advanced Surface Movement Guidance and Control Systems) operations, we have designed and built a prototype for a planning function to support airport tower controllers in the establishment of optimal departure sequences. This planning tool provides a decision support function that has been designed to achieve an optimal throughput at the runway and in addition

reduce the controller's workload and the number of delays while at least maintaining the current safety level, even under bad weather conditions (i.e. low visibility).

Planning of departure sequences comprises sub-problems as runway (entry) allocation, SID (Standard Instrument Departure) allocation, and the application of specific airport procedures (such as the take-off after procedure). The objective of a runway departure sequencing function is to establish an optimal sequence in which aircraft can depart from the available runways and to plan their initial climb phase. Numerous technical and operational constraints and rules restrict the usage of runways, such as separation criteria, departure timeslots, and aircraft performance limits.

The work presented in this paper is based on findings in the Mantea project (MANagement of surface Traffic in European Airports), which was partly funded by the European Commission. The designed and prototyped departure sequencing function is called MADS (MAntea Departure Sequencer).

This paper will firstly address the problem of departure management by describing current practice and identifying the role of departure planning function at airports. Next, the departure planning process is described in detail and it is shown how constraint satisfaction can be used. Some aspects of the implementation of a prototype are described and results are shown.

## **Departure management background**

In Europe, departure planning is part of the departure management function that is defined in EATCHIP (European Air Traffic Control Harmonisation and Integration Programme [EATCHIP95]) phase III, which should be implemented in 2002 at major airports. Several studies involve the departure planning process, such as PHARE (Program for Harmonised ATC Research in Eurocontrol) [Blom93] and TARMAC (Taxi And Ramp Management And Control) project [Dippe94].

The A-SMGCS working group of AWOP (All Weather Operations Panel [AWOP96]) regards planning as part of the routing function. AWOP describes routing as "the planning and assignment of a route to individual aircraft and vehicles to provide safe, expeditious, and efficient movements from its

current position to its intended position". For departure planning, this definition implies that aircraft should take off without conflicts (safe), as early as possible (expeditious), and make optimal use of airport resources (efficient).

Departure planning is a difficult process; even under normal operating conditions at least three different controllers (one for each of the "pre-flight", "taxiways" and "runways" areas) manage the aircraft on the airport. Under stress situations, even more controllers may be assigned to handle all airport traffic. Each controller will try to establish an optimal plan for his/her own area and will try to provide the aircraft to the next controller in an efficient way. Unfortunately, this next controller is not always fully aware of the plans of the previous one. The runway controller is the last planner in line and is dependent on the sequence of aircraft that is handed over by the previous (taxiway) controller. At the runway only minor changes to the provided sequence can be made through the use of runway holdings and intersection take-offs.

The problem in the current way of working is that the actual provided departure sequences cannot be modified sufficiently to optimally use the available runway capacity. Hence the need exists to carry out co-operative planning and decision making by controllers to increase airport capacity.

Departure planning must become an integral part of the overall air traffic management system (see e.g. [Dippe95] and [Böhme94]). An integrated A-SMGCS must be able to support controllers and pilots to optimise the traffic flow of incoming and outgoing traffic. Planning must not be done independently, but in co-ordination and co-operation with other systems. In this integrated environment, a departure planning function co-operates with an arrival planner, a surface movement planner, and a conformance monitoring function, which compares the aircraft observed positions to their planned positions, to detect and solve deviations. Further, a guidance function should be implemented in order to assist controllers and pilots in enabling the possibility to have the aircraft stick to their plans.

## **MADS**

The Mantea Departure Sequencer, MADS [Hesselink97] [Hesselink98], is integrated in a co-operative environment of methods with

accompanying tools, where several controllers act on one plan for each aircraft. MADS starts the planning process at the runway, usually the scarcer resource, and a taxi plan is then generated by the surface movement planner backwards through time. The process ends with the establishment of a start-up time by a push-back or pre-flight planner. The MADS tool is able to handle mixed mode operations in co-ordination with an arrival planning tool.

### **Problem definition in constraints**

External constraints that play a role in the planning process are numerous, ranging from long term runway use strategies through current meteorological conditions to pilot, airport operator, and controller actions and external schedules. The runway departure planning tool that we have designed and prototyped, assures that each aircraft takes off within its allocated time slot, is safely separated with respect to other aircraft (both on the ground and in the air), and guarantees that feeders to the next sectors are not overloaded.

Departure sequencing is based on wake vortex separation (weight and speed categories) and an optimal use of SIDs. At most European airports, the structure of the SIDs is such that several routes can be taken from the runway to one TMA (Terminal Manoeuvring Area) exit point. The planner will normally assign shortest routes, but will consider longer ones to ensure separation at the exit point and to make optimal use of the route structure itself (e.g. separation at waypoints where two SIDs cross).

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. Separation constraints also specify the relation between arrivals and departures when using a runway in mixed mode.
- Runway usage constraints. These determine the runway that will be used, based on runway availability, the necessary runway length, meteorological conditions, runway surface conditions, 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 and en route constraints. Separation in the air must be guaranteed and the feeders to the following control sectors must not be overloaded. SID operations and separations must be followed.
- Sequencing and timing constraints. These specify that each aircraft must take off within its time slot and give specific constraints for sequencing.

### **Constraint satisfaction**

Constraint satisfaction is a well-understood technique for solving planning problems (see e.g. [Beck94], [Stumptner97]). A general model of constraint satisfaction is to describe the problem as a set of variables each with a domain of allowed values. Constraints define the combinations of values for several variables that are not allowed. A solution for a problem defines for each variable in the problem a single value, while making sure that all constraints are satisfied.

All search algorithms for constraint satisfaction start with an initial search space which contains all possible values for all variables in the problem. An algorithm for solving constraint satisfaction problems that uses backtracking is the following:

Restrict the domains of all variables as much as possible, using the constraints and the values of the variables (constraint propagation).

When this has been completed the remaining search space can be in one of three possible states:

1. All variables have only one possible value left:  
A solution is found and returned.
2. One or more variables have no possible values left:  
This state is called a contradiction because the chosen values result in a violation of the constraints. A failure is returned.
3. One or more variables have at least two possible values left:  
The search space may still contain solutions. To actually find a solution to the problem a value for a variable has to be guessed. Now, the algorithm is entered recursively, starting from the constraint propagation again.

This algorithm ultimately finds a solution or a contradiction. If a guessed value leads to a

contradiction, it was apparently not a good guess and the domain of the variable can be reduced by removing the guessed one.

## Heuristics

Heuristics are needed to speed up the search process. Even with the use of constraint satisfaction and thus excluding numerous possibilities, the number of valid sequences can be enormous. It is important therefore, that the guess described in the algorithm is a smart guess so that contradictions are not found (or if they exist, as soon as possible) and the algorithm converges to the best solution as quickly as possible.

The strategy for determining which variable to examine first has been extensively described in literature. Domain independent strategies are general problem solving strategies and will try to find a *feasible solution* as quickly as possible. Domain dependent strategies add a component to this, to relate the heuristic to the runway departure sequencing problem, so that the search converges rapidly to the *best solution*.

## Departure planning with constraint satisfaction

To specify the departure planning problem so that it can be solved with constraint satisfaction, we need to define variables, their associated domains (i.e. allowed values), and constraints. The constraints restrict certain combinations of variables (e.g. no two aircraft can take off at the same time from the same runway). The planner tries to find a single value for each variable in such a way that none of the constraints are violated.

The basic object in this model is the flight object. A flight contains an aircraft, its crew, and a flight plan. The latter is an object that contains general information like departure and destination airport and a detailed 4-dimensional path. The underlying problem concerns the creation of this detailed path.

Let  $F_1, F_2, \dots, F_N$  be the set of flights to be planned. For each flight  $F_j$ , is given:

- The departure point, i.e. the gate or parking position.
- The destination point, which is the TMA exit point in our case.

- The CFMU (Central Flow Management Unit) time interval for departure, or a requested ETD (Estimated Time of Departure). There are two types of flights, scheduled and non-scheduled. Scheduled flights will need take-off within their CFMU time slot; non-scheduled flights do not have a mandatory take-off time interval, but wish to depart as soon as possible.
- A pilot preferred plan (4-dimensional).
- Aircraft performance.

For each flight  $F_j$ , the following will be planned:

- A take-off time, the time at which the aircraft should start the run on the runway.
- A sequence number, the number that indicates for the specified runway the order in which the aircraft must depart.
- A SID route to the TMA exit point, if there are more available. Part of the actual SID structure of Rome Fiumicino is shown in Figure 1.
- The time on the way points between the runway and the TMA exit point.

A number of constraints,  $C_1, C_2, \dots, C_M$ , specifies restrictions for a specific flight or restrictions between two flights. They are now modelled as relations between aspects of a single flight and its 4D position or as relations between two or more flights. Hard constraints must be satisfied for each flight, such as separation criteria and the necessary and available runway length. Soft constraints are preferred to be satisfied, such as a pilot preferred plan and the wish to give priority to aircraft that are late in their time slot.

An example of a constraint is the following. Aircraft in lighter weight categories should be scheduled at least three minutes after their preceding one (separation constraint to avoid wake turbulence effects). This constraint defines the situation where the aircraft of flight  $F_i$  is heavier than that of flight  $F_j$  and then specifies the four conditions,  $C_k$ , that should *not* apply (otherwise it is allowed to schedule flight  $F_i$  before  $F_j$ , e.g. when they are on different runways):

$$C_k = \forall F_i, \forall F_j, \text{ where } F_i \neq F_j$$

$$\mathcal{S}((R(F_i) = R(F_j)))$$

$$\mathcal{WS}(t_{takeoff}(F_i) > t_{takeoff}(F_j))$$

$$\mathcal{WS}(w(F_i) <= w(F_j))$$

$$\mathcal{WS}(t_{takeoff}(F_i) + 3 <= t_{takeoff}(F_j))$$

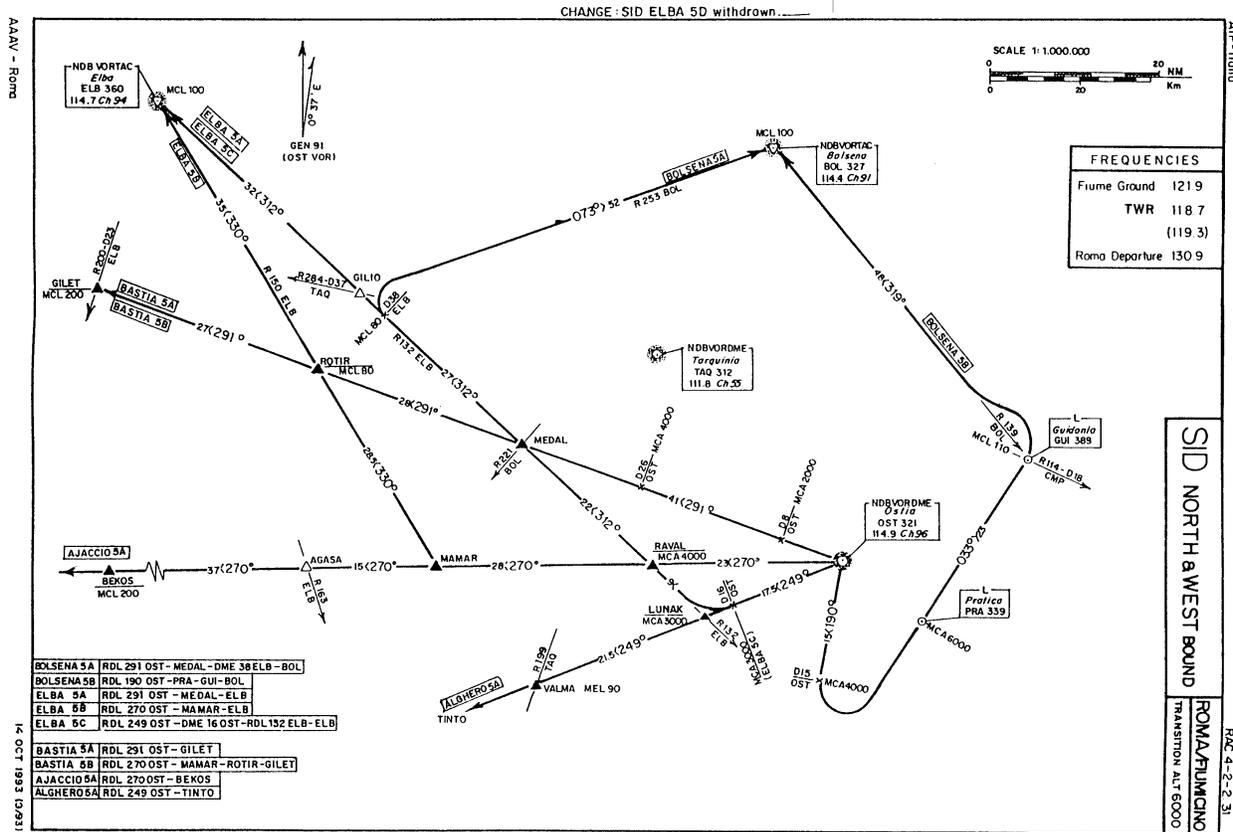


Figure 1 North and West Bound SIDs of Rome Fiumicino (from AIP)

where

- $F_i$  and  $F_j$  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.

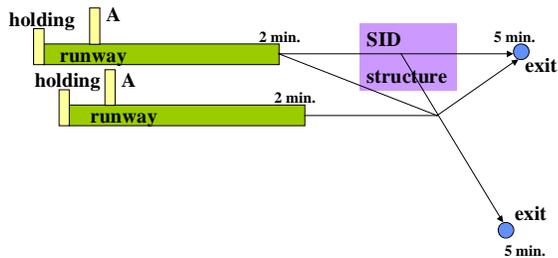


Figure 2 Model of the sequencing problem

Figure 2 shows the model used to represent the sequencing problem. In this figure the 2 min. and 5 min. separation values are intended as examples.

### Prototype

We have developed an object oriented prototype that has been implemented in C++. The prototype is integrated in a tower control simulation environment. Co-ordination between the MADS prototype and the other (planning) tools in MANTEA has been established using the Orbix implementation of the CORBA standard. The planner has been compiled and tested on several UNIX based systems (Solaris and Linux) and on Windows 95/NT.

### Operational aspects and controller interaction

There are usually several possible solutions for planning a number of departing aircraft at an airport. Once a solution is found, it will be evaluated against a predefined 'cost' function that indicates how 'good' this solution is. The MADS planner can be

used in any-time mode so that it will present each new better solution at the moment it is found.

Because there is no guarantee that a departure sequence for all aircraft actually exists, the MADS planner has been designed to always provide a departure sequence for as many aircraft as possible. So even if no complete solution exists (i.e. a sequence that lets all aircraft depart), MADS will generate a safe departure sequence for as many aircraft as possible.

One of the capabilities of MADS is that it allows the controller to manually specify additional requirements to the sequence if these are desired. These requirements are in terms of “this aircraft must depart before that aircraft” and “this aircraft must depart at time t”. MADS will then only suggest sequences that comply with both the safety constraints and the controller imposed requirements.

### Performance results

Results of our planner prototype show that acceptable performance can be achieved to enable practical use of MADS. Table 1 gives an example for planning aircraft with the same performance characteristics, within one time interval (sixteen minutes), on one available SID, and on one runway. In this scenario, the following parameters were used:

- Separation at runway = 2 minutes.
- Separation at way points = 3 minutes.
- Acceptance rate next control sector = 5 minutes.

Two types of heuristics were used for the backtracking algorithm, one for selection of a variable and one for the selection of a value within the domain of that variable. For the variable selection we used the following: take the departure time variable that has at least two possible values left of the aircraft which has the earliest end time in its interval. This flight has the least possibilities left for shifting to a later time and as such is planned as quickly as possible. For the value selection we used:

- In case of a departure time: try the earliest untried time value first.
- In case of a SID: try the shortest untried SID first.

The optimisation function we used minimises the total departure time (i.e. minimum throughput time

at the runway and all aircraft as early as possible) and minimises the total length of the flown SIDs.

In the example of table 1, the aircraft will be sequenced five minutes apart, because the acceptance rate to the next control section is set to five minutes leaving only four aircraft to be scheduled within the available time interval. Increasing the number of aircraft to five implies that one of the aircraft will not be included in the solution. As mentioned, one of the aircraft will now be considered “not plannable”, but the planner still provides a solution for the other aircraft.

#ac	#points in search space	#complete solutions	Best solution (s)	Total search (s)
1	16	16	0.02	0.1
2	256	132	0.04	1.4
3	4096	624	0.06	10.8
4	65536	16	0.11	36.5
5	1048576	0	0.17*	170*

Table 1. Results of scheduling 1.. 5 aircraft.

\* One of the aircraft is considered “not plannable”. There is no complete solution possible where all aircraft are scheduled within the available time interval. The algorithm now will schedule four out of the available five aircraft.

Increasing the number of available SIDs implies an increase of complexity. The aircraft can be sequenced taking into account the distribution of TMA exit points. Table 2 shows the results of scheduling the aircraft over two available SIDs to different TMA exit points. The same separation parameters as in the previous example were used.

#ac	#SIDs	#exit points	Best Solution (s)	Total Search (s)
1	2	2	0.04	0.13
2	2	2	0.03	1.56
3	2	2	0.06	9.42
4	2	2	0.07	60.43
5	2	2	0.07	349.06
6	2	2	0.11	1177.45
7	2	2	0.15	>2000

Table 2. Scheduling multiple SIDs.

We see from both tables that with increasing the size of the problem with more aircraft, the search space increases exponentially, but the search time for finding the best solution and for exploring all solutions does not scale with the same order. In table 1 for exploring the total search space, between test 1, 2, and 3, we find a factor 10 increase in the search time, but between tests 3, 4 and 5, the search time is only increased by about a factor 4. The rationale for this is, that the constraints eliminate more combinations when more aircraft are to be planned resulting in only a limited number of complete solutions. The same effect can be seen in table 2.

Table 2 shows that adding multiple SIDs does not increase the search time for the best solution and only increases the total search by a factor that appears to reduce with each step.

### **Operational evaluation**

MADS has been evaluated by tower controllers at Paris Orly and Rome Fiumicino airports. This evaluation has been an off-line activity, where complex scenarios have been created on forehand and controllers were asked to provide their best solution on paper. Then, the tool was run and the results compared.

During the evaluations, it appeared that the solution presented by MADS sometimes differed from the one that was proposed by the controller. In a number of occasions, controllers indicated that the solution found by MADS was also a good option. In other occasions, the controllers wanted a different optimisation function. Once this function was changed, MADS found similar solutions as controllers did.

As can be seen in tables 1 and 2, if the tool has to examine all possible sequences, the search can last quite long. Two aspects must be mentioned in relation to this.

Firstly, the first solution is always found very quickly. During the evaluations we also found that for complex scenarios the search only took a few seconds. Implementation of a good heuristic function is necessary so that the optimum solution is found within acceptable search time. We implemented an interrupt, which stopped the planner after twenty

seconds. Always, a solution acceptable to the controller was found within this time period.

Secondly, during operational use, the planner will not have to plan 20 aircraft at once, but will be given aircraft one by one so that the problem complexity only increases slowly. We have implemented an incremental planner, which includes new aircraft in already found solutions instead of starting the search all over again.

Both these aspects should prevent the planner from running too long, before an acceptable solution is found. However, one of the items we will be examining in the future is how to increase performance of the algorithm.

### **Conclusions and Further Work**

MADS allows co-operation with other controllers and other tools (like surface movement planning and plan conformance monitoring). As a consequence runway capacity will effectively be enhanced, without any physical changes to the airport infrastructure. The major advantage of using MADS is that all safety regulations are checked automatically, not only after the departure sequence has been created, but also during planning where they are used to optimise runway usage.

In order to improve the performance of the algorithms we can mention several aspects. Firstly, it is important that good heuristics are used. Further, literature already provides several solutions for performance optimisation of constraint satisfaction solvers. Possibilities are the use of branch-and-bound and/or hill-climbing techniques to remove search paths, which on forehand can be estimated as “too expensive”.

A knowledge based approach, like constraint satisfaction, is favourable for solving the departure sequencing problem. Knowledge is separated from the inference algorithm, in such a way that constraints, the optimisation function, and the heuristics are separated from the search algorithm. We found that airports operate under different constraints and controllers at different airports have different optimisation functions. In a co-operative environment with airport operators and airline planners, who have different interests, again we will find other optimisation functions.

Now that we know that controllers agree on the solutions that are proposed by MADS, we have planned validations with controllers in a real-time simulation environment. Controllers will then validate the tool in its environment and will be able to judge its use in terms of workload reduction and airport capacity increase.

We expect that the acceptance of the tool will be high because controllers will remain involved in the planning process. They will be able to make any modification they like to the proposed plan and thus let the planner only find solutions that match their idea of a 'good' solution.

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