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Decision Support for Flight Rerouting in Europe

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ABSTRACT
Congestion has plagued air traffic in the US and in Europe for nearly 20 years. To protect air traffic control from overloads, air traffic flow management tries to anticipate and prevent overloads and limit resulting delays. This paper focuses on understanding the requirements for developing re-routing decision support systems (DSS). It identifies participants in re-routing decisions and investigates the concept and need for a re-routing decision support system. A re-routing demonstrator is discussed as a first step in the development of a DSS and a demonstrator for pre-tactical and tactical re-routings is described. User feedback is described and issues of automation and complexity of re-routing DSS discussed. Finally, the integration of re-routing DSS in future air traffic management systems is addressed.

I. INTRODUCTION

Air Traffic Control (ATC) has existed almost from the start of aviation. Its role is to ensure the safe and expeditious passage of all aircraft in controlled airspace, usually, airspace above 5000 to 7000 ft or around main airports. In Europe, airspace has been mostly divided according to national borders. Within these borders controlled airspace is further divided into 3 dimensional regions, called sectors. A team of air traffic controllers supervises each sector. In Europe, there are around 8 million controlled flights in a typical year.

The capacity of an ATC sector is the number of flights that the relevant air traffic control team is able to supervise per time period. When the traffic expected to cross a sector exceeds capacity, delays occur. For example, over 20% of flights were delayed in European airspace in September 1998 due to ATC capacity constraints. 24% of all intra-European departures in June 1997 were delayed by over 15 minutes and from January to August 1997 18.8% of flights were similarly delayed. Two thirds of these delays were due to ATC capacity constraints. It is claimed that delays caused by a lack of capacity cost European carriers around $5.4 billion in 1998. This estimate does not take into account the cost of delays to passengers, or of the heavier burden on controllers and other elements of the air transport system.

Congestion has been plaguing Europe for more than twenty years and it will get worse as air traffic is projected to grow at a rate of 5% a year. The solution is more investment to increase capacity. However, capacity increases can be only achieved in the long term. On a short-term basis, the best that the ATC system can achieve is to control the flow of air traffic to best match the demand with the available capacity. This activity is called air traffic flow management (ATFM). ATFM is a planning activity that protects air traffic control from overloads and limits resulting delays.

This paper focuses on understanding the requirements for developing re-routing decision support systems (DSS) for ATFM. It identifies participants in re-routing and investigates the concept and need for a re-routing decision support system. A re-routing demonstrator is discussed as a first step in the development of a DSS and a demonstrator for pre-tactical and tactical re-routings is described. User feedback is reported and issues of automation and complexity of re-routing DSS discussed. Finally, the integration of re-routing DSS in future air traffic management systems is addressed.

II. BACKGROUND

ATFM control actions range from departure delays to re-routing flights. Departure delay, or ground-delay, delays departures heading to congested areas. If delays are unavoidable, it is safer and cheaper to delay flights on the ground than in the air. Flights can be re-routed to by-pass already over-loaded airspace or to prevent overloads occurring.

In the US, congestion is experienced mostly at airports. In Europe, with many countries each with their own airspace, co-ordinated air traffic control and flow management is more difficult. Many flights in Europe are short but have to cross several airspaces and so congestion results also in the airspace especially at the junction points of air routes. Thus, the thrust of air traffic management and control efforts in Europe has been to integrate and centralise control activities. The Central Flow Management Unit (CFMU) provides air traffic flow management for the 36 countries of the European Civil Aviation Conference (ECAC).

In the US, most planning is done in the hours before a flight departs, whereas in Europe planning starts six months before departure and involves flow managers, national administrations, area control centres and aircraft operators' representatives. US researchers tend to term planning before take-off 'strategic' and after the flight takes-off 'tactical'. In Europe, strategic planning covers the period from six months to a few days before departure, pre-tactical planning occurs on the two days before departure, and tactical planning takes place on the day of departure until take-off. Measures affecting airborne flights are strictly in the realm of ATC rather than ATFM.

At pre-tactical and tactical levels, flow managers in Europe handle congestion by negotiating increases in capacity with ATC, allocating slots, and vertical or horizontal re-routings. Slot allocation is, in practice, the same as ground-delay. A departure slot, usually at a later time than initially scheduled, is issued to flights heading for congested locations. Slots can be at airports, air traffic control sectors or just airspace junction points.

The CFMU uses TACT, a computer-assisted system for traffic monitoring and ground-delay allocation in the tactical phase. TACT is linked to an automatic system for flight plan processing which provides detailed, updated information on predicted demand. However, Europe lacks accurate traffic data to support planning, especially at strategic and pre-tactical levels.

CFMU is supported by simulation studies at an experimental centre. These range from evaluation of new flow control procedures to testing of contingency routing schemes. For the other flow management measures, there are no support tools available. Most decisions are taken by consulting maps, building charts and tables by hand, or combining figures that flow managers obtain from different sources. The problem is currently acute because many flow managers lack experience due to a rapid growth in their numbers.

Research on decision support for ATFM is about a decade old. Odoni [1, 2] defines the ATFM problem domain, identifies some of the major issues, and suggests decision support needs, mostly based on the US situation. Leal de Matos and Ormerod [3] provide similar European mapping work. Research has concentrated on tactical optimisation models for allocating ground-delays for the US case, with congestion limited to airports. There is research on optimisation models where congestion also affects en-route sectors.

Andreatta, Brunetta and Guastalla [4] and Odoni [1, 2] identify two reasons why optimisation models are seldom used in practice; first, the difficulty in defining an aggregate optimisation function that will satisfy all the stakeholders; and second, the long execution time of the optimisation models. Most of the models are integer and are very time-consuming to solve. However, Odoni [2] supports the use of optimisation approaches as they provide 'benchmarks' and can lead to the identification of generic strategies and more user-friendly heuristics.

The application of AI to ATFM has been explored, but is not used in practice. Kornecki [5] and Winer [6] describe the development of a knowledge-based system prototype for traffic flow management. Weigang, Pinto Alves and Omar [7] describe expert system prototypes for rescheduling timetables to smooth traffic peaks, and for proposing mitigating actions. Bayles and Das [8] describe a prototype employing case-based reasoning.

Research on decision support models and systems for re-routing flights at the strategic, pre-tactical and tactical levels of ATFM is in its infancy. Some airlines already have sophisticated flight-planning systems that provide alternative routes for flights, but they do not meet the needs of ATFM. This paper focuses on the design of re-routing DSS for ATFM, carried out as action research with the problem owners. The first stage in understanding the problem involves identifying the participants in the re-routing domain.

III. Participants in Re-routing DSS

Bidgoli [9] stresses the overlaps of participants' roles and their dependency on the problem scope. He considers three roles: user, designer - managerial and technical, and intermediary - liaising between the user and the DSS. This typology is useful here. Participants in the development of Re-routing DSS are:

1. Users - flow managers based at the CFMU; flow managers' experience varies.
2. Decision-makers in re-routing control measures: flow managers and airlines. There are others who influence re-routing decision-making: air traffic controllers and national administrations.
3. Designer.
4. Intermediary is the CFMU User Requirements Section.

Taking into account these roles, the functions of a re-routing DSS can be articulated.

IV. Need for a Re-routing Demonstrator

In this section, the need for a re-routing demonstrator is expanded. The demonstrator is a learning tool to explore different functions and levels of aid with the flow managers. Its need stems from: 1) the users having differing levels of experience and different decision support needs; 2) a new system of centralised flow management being launched and the knowledge-base for re-routing control measures still under construction; and 3) the different views on the degree of automation and functions appropriate to a re-routing tool.

The demonstrator provides a visual image of different re-routing decision support possibilities. It follows a script, based on a real traffic situation in Europe. It differs from a prototype in that it offers different decision support possibilities rather than a 'version 0' of a re-routing DSS. The demonstrator functions may result in separate re-routing DSS (for instance, a pre-tactical re-routings DSS and a tactical re-routings DSS). Only some of the algorithms behind the functions are embedded in the demonstrator. However, the demonstrator has many features in common with a prototype: 1) it is a step forward in the development of DSS, and a first cut at the logic and algorithms of the system; 2) it represents the system in a tangible way; 3) it constitutes a pre-feasibility study into the development of DSS; 4) it is a learning tool; and 5) it is cheap to develop.

V. DEMONSTRATOR - USER FUNCTIONS

The demonstrator is for pre-tactical and tactical re-routing. The user functions range from simple queries to complex automated ones. There are seven functions: two provide information on routes, two are aimed at tactical re-routings and three at pre-tactical re-routings.

A. Routes

1. Route Congestion. This allows flow managers, already knowing the route, to obtain updated information on the nature of delays, at a given time, on a given route. For any route, departure time and reference speed, the function provides an estimate of ground-delay. The function provides the capacity still available.
2. Alternative Routes. This enables flow managers to know alternative routes avoiding (congested) airspace. The maximum number of alternative routes is four. Routes are selected according to flying time and the user can specify maximum flying times.

Re-routing Flights - Tactical ATFM

3. Routes for Flights. This assists flow managers reduce ground-delay and provides alternative routes for flights.
4. Flights to Re-route. Given a seriously congested traffic volume, flow managers need to identify quickly which flights can be re-routed.

Re-routing Flows - Pre-tactical ATFM

5. Routes for Flows. Flow managers have already defined which flows to re-route and need to know to which routes to allocate these to minimise overall delays. The function assigns a route to each flow.
6. Flows to Re-route. Flow managers need to know both which flows to re-route and onto which routes. This function generates flows to re-route and routes.
7. Contingency Re-routings. Identical to 6) but prompted by a contingency situation, where the capacity of an airspace element is substantially reduced.

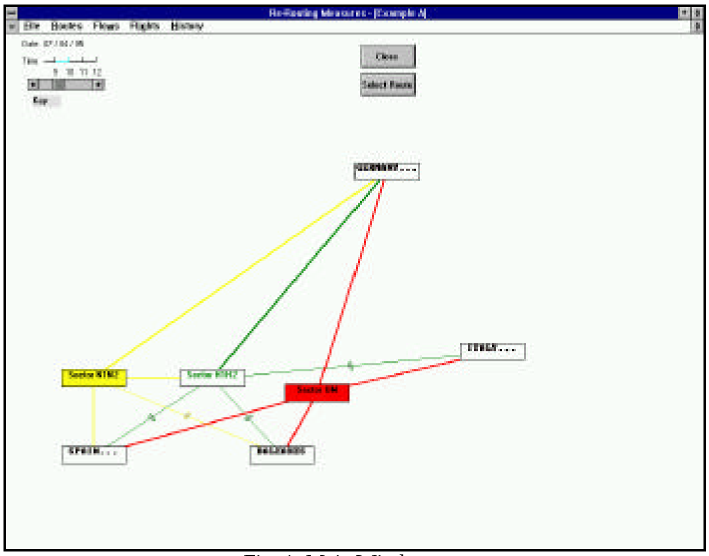

Fig. 1: Main Window

The demonstrator was developed in Visual Basic (see figure 1) and uses features including a network to represent origin/destination areas, ATC sectors and routes, and colours to represent levels of delay. The demonstrator is based on three contiguous ATC sectors of Southern France, using traffic entering these sectors on 7/04/95 between 08.00 and 12.00h. These are busy sectors, routes and times.

VI. MODELS

Fig. 2 shows the links between the different demonstrator functions. The functions to re-route flight and flows make use of the functions providing information on routes. The models for the functions range from information sorting and heuristics to optimisation. They are divided into: 1) Routes and Re-routing of Flights; 2) Re-routing of Flows.

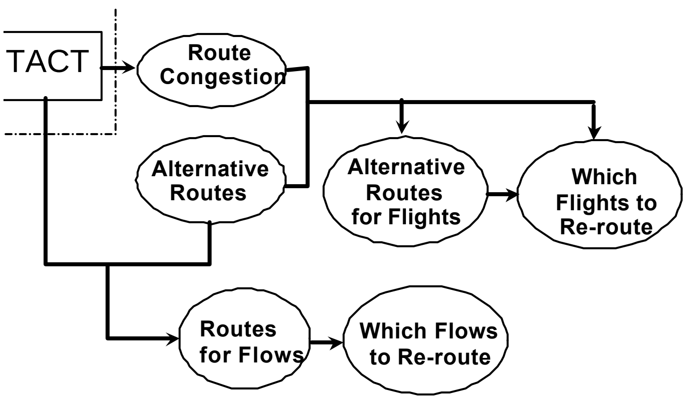

Fig. 2: Structure of the Demonstrator

Routes and Re-routing Flights

1. Route Congestion: a sorting function which utilises data available in TACT:

It takes the minimum available capacity of all capacitated airspace elements crossed by the route.

If any of the airspace elements are regulated, it takes the delay of the most penalising regulation. This could be a 'what if' slot allocation or the most recent estimate of average/maximum delay of the most penalising regulation can be used.

2. Alternative Routes: This uses standard 'shortest route' algorithms (Leal de Matos, 1998). Two criteria are used to select the routes: one based on flying time, the other on the cost of re-routing.

3. Routes for Flights: The routes are chosen using a weighted time criterion:

$$z_{ij} = (d_{i0} \quad d_{ij})w1 \quad (f_{ij} \quad f_{i0})w2 \quad (1)$$

where d_{i0} is the ground-delay of flight i on the initial route, d_{ij} is the ground-delay of flight i on alternative route j, f_{ij} is the flying time of flight i on alternative route j and f_{i0} the flying time on the initial route. $w1$ and $w2$ are the weights given to ground-delay and flying time. The demonstrator uses $w1 =$ 0.5 and $w2$ = 1. This function makes combined use of the functions <Route Congestion> and <Alternative Routes>.

4. Flights to Re-route: Flights are selected applying the following filters, in turn:

Flights whose ground-delay is longer than 45 minutes.

Flights with alternative routes and flying time less than the maximum specified.

Flights whose alternative routes have capacity on a first-come first-served basis.

For each flight filtered the best route is selected and then sorted using function (1).

A. Re-routing Flows

Flow re-routing is more complex to model. The approach is based on current ATFM practice, it assumes that flow managers have authority to issue re-routing measures applying to whole flows during a well-defined period. Routes cannot be changed frequently nor allocated on an individual flight basis.

Flights are grouped into flows according to their origin-destination, and the problem of re-routing solved in two stages: 1) Routes Problem: identify acceptable and alternative routes for each flow; 2) Assignment Problem: given a set of flows, a set of acceptable routes and a set of capacity constrained sectors, assign a route to each flow so that the total cost of re-routings and congestion is minimised.

The Routes Problem is solved using the function <Alternative Routes>. Three integer programming models result from different ways of measuring congestion [10]:

Model 1 BALDIST - Congestion is measured by penalty variables activated whenever traffic demand is above sector capacity. The model minimises the sum of the estimated cost of congestion and the cost of re-routing subject to capacity constraints and constraints on the assignment of routes to flows.

Model 2 DELINT1 - Congestion is measured by the number of ground-delayed flights. Ground-delay variables support decisions on re-routing not to allocate ground-delays to individual flights. Unlike BALDIST, flights ground-delayed can build up over time. The model minimises the sum of estimated cost of ground-delay and the cost of re-routing subject to capacity and assignment constraints plus constraints defining and relating the two types of variables - assignment and ground-delay.

Model 3 DELINT2 - Congestion is measured by more detailed ground-delay variables than in DELINT1. This model takes into account the number and the length of flights ground-delayed.

The three models were tested using real traffic data crossing the whole French upper airspace on 25/04/96, from 03:00h to 22:00h, totalling 3582 flights. French airspace was chosen because it is the crossroads of European airspace, with 25% of all ECAC's traffic resulting in many sectors being congested. The models were solved using off-the-shelf optimisation software: GAMS modelling system coupled with a standard integer programming package LAMPS. Execution time is not as critical at pre-tactical ATFM as at tactical. However, the models have to provide relatively quick solutions. Both BALDIST and DELINT2 provide optimum solutions in fewer than 10 minutes. BALDIST is most efficient in execution time and size, and provides solutions whose value and resulting delays are almost as good as DELINT2's. DELINT1 provides solutions not more than 0.8% from the optimum in fewer than 10 minutes, but is harder to solve, and is significantly larger than BALDIST.

B. Data Requirements

Evaluation of the feasibility of using BALDIST or DELINT2 in a re-routing DSS needs to take into account the size of the data component and the time require to prepare the data to run the optimisation models. The systems at EUROCONTROL provide updated traffic and airspace data. The data is sufficient to run the routes and re-routing flight functions. However, the airspace database is incomplete. The functions to re-route flows require several data processing operations prior to optimisation: flows have to be defined, alternative routes for each determined, and the traffic data grouped into flows and departure time intervals. These require either an experienced user or a partly 'intelligent' system.

VII. Feedback

The demonstrator was made available to flow managers and staff at the CFMU. Flow managers found all the functions useful. Two decision criteria are used in the demonstrator: time and cost. In practice, flow managers use only time as a decision criterion. Most interest was shown in the pre-tactical functions. The demonstrator was used as a basis for developing a re-routing DSS. The CFMU is now introducing a function that provides alternative routes that uses a 'shortest route' algorithm similar to the one proposed. The demonstrator functions have different levels of complexity and represent different levels of aid to the flow manager. The next section uses these to discuss the level of automation and complexity required of a re-routing DSS.

VIII. Automation and Complexity of Re-routing DSS

The re-routing demonstrator functions can be mapped against a referential model of automation and complexity (Fig. 3).

The function <Flights to Re-route> is fairly structured in algorithmic terms, but is substantial in terms of automation, whereas <Routes for Flows> is more complex but requires more intervention from the flow manager. Automation in air transport is a long-sought goal to achieve greater performance and reliability. However, due to the non-repetitive and uncertain nature of many of the tasks, people still predominate. Even in highly automated environments such as piloting an aircraft, people are considered necessary for monitoring, detecting problems and intervening.

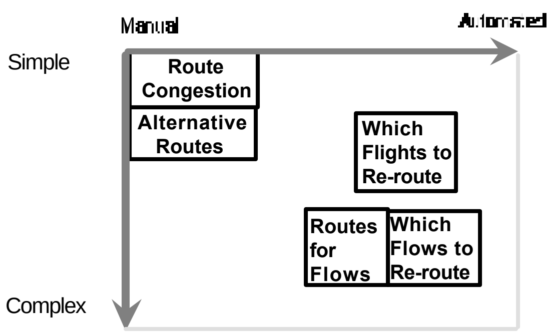

Fig. 3: Complexity and Automation

Supervisory control describes a situation where there is a co-operative relationship between human and machine. The machine has some decision or control capability, but the human supervises it. According to Sheridan [11], supervisory control means that the computer is an autonomous controller for some variables at least some of the time. More loosely, the computer transforms data from human to controlled process and from controlled process to human, but the computer never closes a control loop that excludes the human. Supervisory control is associated with human-centred automation, where the human is the main element of the system [12, 13].

Factors that affect system performance in air traffic management (ATM) [12] include: *situation awareness and attention limitation:* the ability to keep an adequate situation understanding. This is problematic in a highly automated, complex and unstructured environment. *Information overload:* to prevent loss of situation awareness and multi-tasking capability due to excessive information, the quantity, format and pre-processing of information provided to flow managers has to be carefully assessed. *Human acceptance and understanding of automation:* flow managers have to be actively involved in the development of DSS and accept the decision criteria used.

In European ATFM, at tactical level, the environment is volatile, and decisions have to be made continually and quickly, 24 hours a day. At pre-tactical level, 1-2 days before flights, there is time to rethink and review decisions and automation is not used to control traffic situations. The demonstrator functions to support the re-routing of flights are reasonably simple or standard to implement. The functions to support the flow re-routing require more complex algorithms and more expertise in defining the re-routing scope. Thus, a more automated DSS is more useful and feasible for re-routing flights than re-routing flows. In European ATFM, there is some supervisory control at the tactical level. TACT monitors the traffic situation and summarises it to the flow managers. When flow managers issue a slot allocation regulation, TACT allocates ground-delays automatically to flights. The airlines receive slot allocation messages directly from TACT, without human intervention. Flow managers can only intervene in the slot allocation by changing the parameters of the slot allocation regulation. That is, they can only have an indirect influence on computer-determined plans. This mode of supervisory control could also be adapted to re-routing individual flights at tactical level by:

1. flow managers deciding to activate the function <Flights to Re-route>
2. the re-routing system identifying flights and sending a re-routing proposal to the airlines, without human intervention.
3. flow managers changing the parameters used in the re-routing function.

Thus, for re-routing flows, a DSS suggesting routing schemes that flow managers can check, amend and replace, as required, is more useful and feasible. The next aspect is fitting the tools into the environment.

IX. Integration Re-routing DSS in Future European ATM Environment

Future developments in ATM need to be taken into account. These concern the nature of the ATM environment when the re-routing tools become available. Re-routing tools cannot be developed on the basis of present needs. Re-routing tools might become outdated before becoming available as:

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there is a programme that aims to increase ATC capacity through restructuring the air route network and associated airspace sectorisation. This will be more flow-oriented and have far fewer junction points.

direct routings in upper airspace implies more planning of sectors than routes

progress in airlines' standard flight planning systems means it is possible airlines will be able to work out alternative routes without assistance from ATFM. The only information they will need from ATFM is the likely ground-delay on certain routes.

A key issue is how these re-routing tools integrate with existing systems. The demonstrator functions can be divided in two groups: those for re-routing individual flights at tactical level, and functions for re-routing flows. The detail and integration with TACT varies significantly between these. Re-routing flows addresses the distribution of traffic in a more aggregate way. The problem consists of routing sets of flights so that the total delay or cost is minimised and serious overloads are avoided; it is a master scheduling problem. At tactical level, for individual flights, re-routing functions need more detailed information in terms of flight profiles and specific slot allocation delays, and thus interact often with TACT.

X. Conclusions

This paper has investigated the development of re-routing DSS. A re-routing demonstrator is discussed and described. The level of automation and complexity of re-routing DSS are analysed. This reveals there is scope for DSS to assist re-routing flights in Europe because of their potential to respond quickly and consistently to complex problems. A DSS for re-routing flights has to take into account that the users of the tool, flow managers, have differing levels of experience and, consequently, different decision support needs and that different views on the degree of automation of a re-routing tool prevail. Also, given the novelty of centralised ATFM, the knowledge-base for re-routing control measures is still under construction.

The re-routing demonstrator is a tangible representation of different decision support possibilities and an assessment of their pre-feasibility. The demonstrator user functions can be broken down into two groups: functions to re-routing flights at tactical level, and functions for re-routing flows at pre-tactical level. The demonstrator functions represent different levels of automation and complexity ranging from those that sort data on routes to more complex ones suggesting flights to re-route.

A higher level of automation of DSS for tactical re-routings is more useful and feasible than for pre-tactical. For tactical re-routings a form of supervisory control is suggested. For pre-tactical re-routings manual control with the DSS providing advice is proposed.

Given the infancy of centralised European ATFM, the most appropriate approach to the development of a re-routing DSS is a staged one, starting with the simpler functions and incrementally developing the more complicated ones. Finally, the development of a re-routing DSS has to be seen in the context of future developments in the European air traffic management environment such as changes to the air route network and associated airspace structure and progress in the airlines' standard flight planning systems.

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