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The Development of Decision Support Models for European Air Traffic Flow Management

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Summary

Congestion severely affects air traffic in the US and Europe. To protect air traffic controllers from overloads a planning activity, Air Traffic Flow Management (ATFM), emerged during the 1970s. ATFM control actions range from departure delays to the re-routing of flights.

This research explores how models can be used to support decision-making in European ATFM. To date, most research into this subject has been directed at ATFM in the US, which differs from European ATFM both in terms of decision-making and time scales. Fieldwork was carried out at the EUROCONTROL Central Flow Management Unit, the organisation that manages traffic flows in most of the European airspace. The fieldwork was an OR intervention aimed at identifying suitable decision support models for re-routing flights.

The research described here contributes by: 1) describing the European ATFM field and identifying decision support needs; 2) structuring the problems involved in re-routing flights in Europe; 3) providing a framework for the development of re-routing decision support systems (DSS) and 4) assessing the usefulness of optimisation approaches to re-routing flights.

A demonstrator is developed to illustrate different re-routing decision support possibilities to the users. This leads to conclusions on the feasibility of various decision support functions including an identification of models and algorithms which can be used for each of the functions. Conclusions on levels of automation and complexity for re-routing DSS are also taken.

Three integer models for re-routing flows are presented. They differ in the way congestion is represented. The models are tested on data of traffic crossing the whole French upper airspace. The test reveals that the models can be of use in re-routing flows and can provide significant savings in delays. It also shows that an 'intelligent' component to define the scope of the optimisation problem and a component to process all the data for the models, are needed in a re-routing DSS. The models are compared in terms of impact on congestion, size and execution time and conclusions on their feasibility taken. Extensions to the models are suggested.

Abbreviations

AMOC	ATFM Modelling Capability
ANM	ATFM notification message
ARC	CFMU archives system
ATC	air traffic control
ATCSCC	US Air Traffic Control System Command Center
ATFM	air traffic flow management
ATM	air traffic management
CARAT	Computer Aided Route Allocation Tools
CASA	Computer Assisted Slot Allocation
CFMU	EUROCONTROL Central Flow Management Unit
DSS	decision support system(s)
EATCHIP	European ATC Harmonisation and Integration Programme
ECAC	European Civil Aviation Conference
ECDT	US Estimated Departure Clearance Time Programme
ENV	CFMU environment database
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	US Federal Aviation Administration
FMP	flow management positions
ICAO	International Civil Aviation Organisation
IFPS	CFMU Initial Flight Plan Processing System
MFUR	most frequently used route
NASPAC	National Airspace System Performance Analysis Capability
OPTIFLOW	decision support tool research project for ATFM in the US
SMARTFLO	expert system research project for ATFM in the US
SRC	European Standard Routing Scheme
STRAT	CFMU strategic database
TACOT	TACT Automated Command Tool
TACT	CFMU tactical computer system
TOS	European Traffic Orientation Scheme
URS	CFMU User Requirements Section

Chapter 1

Introduction

The steady growth in air traffic over the years, has not been matched by a similar growth in the capacity of the air traffic control (ATC) system. This has started to strain the air transportation system. Congestion is severely affecting air traffic both in the US and in Europe. The number of congested airports in Europe increased from 11 in 1996 to 18 in 1997 (EUROCONTROL, 1998). At some key airports in Europe, for instance London-Heathrow, the saturation point, in terms of capacity, is reached during almost the whole period of operation. In European airspace, many junction points (points where air routes intersect, also called fixes) are congested at peak times. Further, congestion is bound to get worse in the future: In 1993, the International Air Transport Association foresaw that by the year 2000, the number of congested fixes, at that time numbering 100, might quadruple.

The capacity of an ATC sector is defined as the number of flights that the control team of that sector is able to supervise per period of time, usually one hour. When the traffic expected to cross the sector exceeds the capacity, traffic delays occur. The average number of flights delayed in the European airspace in June 1997 (one of the busiest months of the year) due to ATC capacity constraints exceeded 20% of total flights (Jane's Airport Review, 1997). Figures released by the Association of European Airlines (Jeziorski, 1997), show that 24% of all intra-European departures in June 1997 were delayed by over 15 minutes and that from January to August 1997, 18.8% of intra-European flights were delayed by more than 15 minutes. According to the Association of European Airlines two thirds of these delays were due to ATC capacity constraints. These delays mean increased operating costs: it is claimed that delays caused by lack of capacity cost European carriers around $3 billion annually (Flight International, 1996).

On a short term basis, the best that the ATC system can achieve is to limit the extent and impact of delays due to congestion, or in other words, try to control the flow of air traffic in order to best match the demand with the available capacity. This activity is called air traffic flow management (ATFM).

Measures taken to regulate traffic demand range from departure delays to re-routing of flights. The departure delay, or ground-delay, consists of delaying departures of flights heading to congested areas. The idea is that, if delays are unavoidable, it is safer and cheaper to delay the flights on the ground than when they are airborne. Flights can be re-routed to by-pass overloaded elements of the airspace or to prevent overloads.

In continental US there is a single body in Washington DC which co-ordinates flow management: the Air Traffic Control System Command Center (ATCSCC). Congestion problems in the US are experienced mostly at airports. In Europe, a continent with many countries each with a separate airspace, co-ordinated air traffic control and flow management is more difficult to implement than in the US. Many flights in Europe take one hour or less but have to cross airspace controlled by various countries. Congestion is felt not only at airports, but also in the airspace at many of the fixes. Therefore, the thrust of air traffic management (ATM) and control efforts in Europe has been in integration and centralisation of activities. To this end, the Central Flow Management Unit (CFMU), located in Brussels, was created in 1989 to be the sole provider of air traffic flow management in the 36 countries of the European Civil Aviation Conference (ECAC).

The timescale and organisation of ATFM activities are different in the US and Europe: in the US most planning is done a few hours before the flights by the ATCSCC whereas in Europe planning starts six months before the flights and involves not only flow managers but also different national administrations, area control centres and aircraft operators' representatives. Accordingly, concepts differ: US researchers tend to call all the planning done before the flights take-off *Strategic* and after the flights take-off *Tactical*. In Europe, there is *Strategic* planning which goes from 6 months ahead to a few days before the flights, *Pre-*

tactical planning which occurs on the two days before the flights and *Tactical* planning which takes place on the day of the flights until take-off. Measures affecting airborne flights are considered strictly in the realm of ATC rather than ATFM.

Research on ATFM problems started in the late eighties and has concentrated on the use of computer simulation to evaluate ATFM strategies and optimisation models for the allocation of ground-delays. Most models are intended for the US case, with congestion limited to airports. Work has also been published exploring the application of artificial intelligence techniques to ATFM. Odoni (1987, 1994) defines the air traffic flow management problem area, identified some of the major issues in the field and the decision support needs, mostly based on the US situation. No similar ground-clearing work has been done for European ATFM.

The opening of the CFMU equipped with a computer system which allocates ground-delays on a first-planned-first-served basis appears to have contributed to shorter average delays per flight. Figures released by the CFMU (Jane's Airport review, 1997), show that more flights were ground-delayed in 1997 than in 1996 but the average delay per flight (considering all flights, delayed and non-delayed) decreased by about 0.5 minutes. With an expected annual rate of growth of approximately 6% in European air traffic there is more scope for reducing delays, and computer systems providing fast and consistent decision support are urgently needed.

This research explores how models can be used to support decision-making in European ATFM. Its contribution is as follows:

1. it provides a description of the European ATFM field and identifies decision support needs.
2. it structures the problems involved in the re-routing of flights in Europe.

3. it provides a framework for the development of Re-routing Decision Support Systems (DSS). This includes the development of a re-routing demonstrator where different user functions are illustrated.
4. it assesses the usefulness of optimisation approaches to the re-routing of flights in Europe. This includes the development and test of optimisation models.

Chapter 2 discusses the nature of OR and DSS and identifies research gaps in the application of OR\DSS to European ATFM. The discussion of the nature of OR\DSS in general and applied to a particular field leads to a definition of the field of this research and puts the review of the OR\DSS literature on ATFM into context. The identification of research gaps in the application of OR\DSS to European ATFM is made at two interrelated levels: 1) ATFM practice; and 2) the literature on applications of OR\DSS to ATFM. The survey of ATFM practice explains the basics of ATFM and leads to the identification of decision support needs. It is a high level survey which outlines features and decision support needs which are further detailed in Chapter 5. The survey of the literature on the application of OR\DSS to ATFM describes the main modelling approaches to ATFM and highlights gaps in the literature. Both surveys lead to conclusions on the focus of this research.

Chapter 3 defines the research contribution based on the research gaps identified in Chapter 2 and identifies an approach to achieve that contribution. The identification of a research approach is based (i) on the discussion of the nature of OR in Chapter 2; (ii) the approaches used in the social sciences; together with (iii) literature on model-building approaches. The research approach is defined at two interrelated levels: the degree of involvement with the CFMU and the approach taken to build the decision support models. The chapter also describes the fieldwork process and how it led to a change in the paradigm used in the research from an 'OR as scientific techniques' view to an 'OR as socio-technical discipline' view. This change of paradigm resulted in the need to use a different OR method which acknowledged the importance of understanding the context before structuring decision problems and developing decision support models.

Chapter 4 results from the need (identified in Chapter 3) to develop an understanding of the context of European ATFM and lays the groundwork for identifying the issues faced in European re-routing control measures. The chapter describes the development of the CFMU, its organisation and systems, the different control measures, and levels of planning together with how flow managers carry out their work. It also identifies the main stakeholders in European ATFM. In addition, the chapter points out some potential applications of OR to European ATFM.

Chapter 5, building upon the description of the context provided in Chapter 4, sets the main re-routing problems faced in European ATFM with a view to the potential development of re-routing DSS. It describes the different types of re-routing control measures, and examines who has the authority to implement them. Following this, the viewpoints of the main stakeholders in a re-routing decision, aircraft operators and flow managers, are presented covering the usage of re-routing control measures, the decision criteria used, and the tools available and needed to support re-routing decisions. These viewpoints are complemented by a review of the decision criteria contained in the literature on optimisation models for the allocation of ground-delays. This review is aimed at identifying decision criteria which can be transferred to re-routing decision support models.

Chapter 6, drawing on the problem setting provided in Chapter 5, focuses on the initial steps in the design of re-routing DSS. The chapter provides a framework for the development of re-routing DSS and a basis for the optimisation models presented in Chapter 7. The participants in re-routing DSS are identified. The reasoning and user functions of a re-routing demonstrator are presented. Algorithms and heuristics for the demonstrator functions are identified and their feasibility discussed. The feedback from users (flow managers) and other DSS participants is described. The levels of automation and complexity of DSS for the different re-routing control measures are discussed, based on the demonstrator functions. The framework also includes an overview of future developments in the European air traffic management environment which are likely to affect the development of re-routing DSS.

Chapter 7 concentrates on the development of optimisation models for the more complex functions highlighted in Chapter 6, functions to support re-routing of air traffic flows. The chapter provides an account of the modelling process covering the identification of relevant models and the choices and trade-offs made. In addition, it describes the three models which resulted from the modelling process and were selected for further testing. Chapter 8 describes the testing of the three models selected in Chapter 7 using traffic data provided by the CFMU and analyses the results. It describes the input and output of the models, and the stages of definition and sorting of flight plans into formatted input for the optimisation models. Following this, the results provided by the models are analysed and compared and conclusions on their feasibility are made. Chapter 9 proposes extensions to the optimisation models described in Chapter 7 to deal with some of the limitations of the models highlighted in Chapter 8 and addresses different traffic situations. Finally, Chapter 10 reviews the conclusions of the research, its limitations and proposes directions for future research.

Chapter 2

Literature Review and State-of-the-art

2.1 Introduction

This chapter characterises the field of the research and reviews the literature and state-of-the-art in air traffic flow management. The field of this research is applied OR at its interface with DSS. The main drive of this research is to contribute to this field by developing decision support models for European ATFM. To define the field of the research, the chapter surveys the literature on OR, decision support systems and the relation between them. Following this, potential research problems at two interrelated levels are identified: 1) ATFM practice; and 2) the literature on the application of OR/DSS to ATFM.

The section on the nature of OR discusses different views of OR, both in research and in practice, leading to conclusions on what research in applied OR is. The following section defines DSS and discusses their relation with OR putting the review of the OR/DSS literature on ATFM into context. The section on ATFM in practice explains the basics of ATFM and leads to the identification of decision support needs. The section reviewing the literature on applications of OR/DSS to ATFM describes the main modelling approaches to ATFM. and highlights gaps in the literature. Finally, a conclusion on the focus of the research is achieved based on the findings of both the OR/DSS literature survey and the survey of ATFM in practice.

2.2 The nature of OR

The nature of OR has long been debated: whether OR is applied mathematics or a broader management discipline, whether it is a science, a collection of techniques or a technology. At its beginning, OR was seen as an applied science. using the method of natural science to address operational problems. Ackoff (1956) in a paper entitled 'The Development of Operations Research as a Science' stated:

'Operations research is neither a method nor a technique; it is or is becoming a science and as such is defined by a combination of the phenomena it studies, its methods, and its techniques' (p.265). Later, in 1962, in a book entitled 'Scientific Method-Optimising Applied Research Decisions' (Ackoff, 1962), he breaks sciences into two types, pure and applied, the main difference between them being the objectives of the research. Thus, research in pure science is usually for science's sake whereas research in applied science is aimed at more practical problems of the type 'How to do it', in a role 'adjunct to technology'. Ackoff saw OR as an applied science.

This initial view of OR as a science appears to rely on the inductive research method used by the early OR scientists, who had natural science backgrounds. Ackoff and Sasieni (1968) describe the OR (scientific) method in 5 steps:

1. formulating the problem;
2. constructing a mathematical model to represent the system under study;
3. deriving a solution from the model;
4. testing the model and evaluating the solution;
5. implementing and maintaining the solution;

This scientific view of OR is still popular and can be found in many OR textbooks (Taha, 1992; Winston, 1991). However, as explained by Ormerod (1996a), the above concepts of science and scientific method have been contested and changed over time. Scientists and philosophers of science question whether scientists, even in the natural sciences, follow this method and challenge its objectivity and generalisability. Some argue that the scientific method should be seen more as a social and historical rather than a purely logical process. Also, the limitations of the natural science method in addressing human-centred organisational problems have prompted the use of other methods, closer to the social sciences, in OR.

Recent arguments supporting the scientific nature of OR draw on a definition of science by Ravetz (1971). Miser (1988), based on Ravetz' definition, distinguishes three types of problems within science according to their goals:

1. scientific problems whose goal is to solve a problem and the function of its solution is to provide new results in the field;
2. technical problems whose goal is to perform a function;
3. practical problems whose goal is to serve some human purpose.

In a more recent paper (Miser, 1991) he adds that OR/Systems analysis is a science which includes the following scientific activities:

- scientific inquiry as a craft;
- objects of scientific work;
- methods of investigation;
- worth of theories;
- achieving knowledge;
- different classes of problems as described above.

This view of OR is contested by Keys (1989 and 1991) who refutes the definition of science used saying instead that science focuses on 'scientific' problems whereas OR gives primacy to 'technical' and 'practical' problems. Keys (1989) argues that OR as a technology has more to offer in understanding its nature. While acknowledging that 'OR uses scientific methods within its investigations as far as is possible' (p.753) Keys maintains that OR is more akin to technology, that is 'the conscious design process which results in the creation of designed physical and abstract systems' (p.757). Drawing on this, he defines OR as 'a technology which produces designed abstract systems, and as a result may also produce designed physical systems, by scientific means for use in organisations. The designed abstract systems take the form of information about different ways of improving organisational effectiveness, and the associated designed physical systems will be methods of achieving these ends.' (p.757).

Other authors also recognise the technological nature of OR. Boothroyd (1976) states that 'An adequate theory of OR will therefore not simply be a theory of science, it will be a theory of technology' (p.101). Ormerod (1996a) highlights the practical advantages of considering OR as a technology: 'it will accord better with the practitioners' views of their aims and activities in organisational contexts; and by focusing attention on other technologies or professional practices rather than other sciences, I believe that exploration of, as yet untapped, sources of advice on matters of practice will provide fruitful for the practice of OR' (p.9).

The way OR is classified appears also to be interrelated with the prestige and images of OR. Ormerod (1996a) suggests that the attraction of the OR as a science view is partly due to reasons of prestige. Mitchell (1980) distinguishes between the private image of OR, among practitioners, and the public image among the clients. Ormerod favours a private image of OR as a technology and a public image as consultancy.

In summary, the classification of OR as a science, technology, techniques or something else depends to a large extent on the meaning given to these words. If Ravetz's definition of science as described by Miser is accepted (Miser, 1988), then OR can be seen as a science addressing primarily technical and practical problems faced by organisations. If Keys' view on technology-science is adopted then OR can be regarded as a technology focusing on different ways of improving organisations effectiveness.

OR can be seen at two levels: OR practice and research in OR. Both levels are important to this research for two reasons: 1) the development of decision support models for ATFM, being an applied topic requires some knowledge of OR practice; and 2) the survey of research in OR is needed to define this research's contribution and method. Therefore, a literature review of the most pertinent issues about OR in practice is provided in the next section, followed by a literature review of research in OR.

2.2.1 OR in Practice

While there is some debate on how to classify OR, most mainstream authors appear to agree on the way they describe OR in practice. Practically, all authors agree that OR is more than a collection of mathematical techniques. This theme has been debated almost since the beginning of OR. In 1943, Blackett stated that OR should develop its own techniques suited to its own problems. These techniques should not be rigid but should change with the nature of the problems. In the 1970s the debate came to the fore prompted by worries in the OR community that OR was being regarded and taught increasingly as a mere collection of mathematical techniques. Ackoff (1979) in a paper entitled 'The Future of OR is Past', attributes what he calls the death of OR to the obsession of OR with techniques. He states that 'OR came to be identified with the use of mathematical models and algorithms' (p.94). This domination of techniques resulted in a more limited role of OR analysts in organisations. Eilon (1980) complains that OR analysts in most organisations are seen not as advisers but as technicians addressing tactical problems. He argues that 'OR/MS must be problem orientated and not technique orientated: techniques are only convenient means by which generalisations can be sought, not ends in themselves' (p.17). Haley (1984) in a paper called 'Techniques Maketh OR' also objects to 'the commonly held view that OR is a collection of techniques'.

Ormerod (1996a) recognises the importance of techniques in defining a discipline but links it to the meaning of the word 'technique'. He agrees with the previous authors when he says that the perspective of OR as 'analytical routines that are applied to defined problems' is limited and flawed, since many of the mathematical techniques are borrowed or shared with other disciplines. However, he offers an alternative broader definition of 'technique' to include 'the methods and methodologies of intervention' or 'the knowledge base that a practitioner brings to the project' and concludes that in this sense 'OR as techniques is an acceptable perspective'.

One of the major earlier objections to the OR technique orientation was that it was useless in 'messy' and 'wicked' situations frequently encountered in organisations. In the OR as (mathematical) techniques view, it is assumed the problem is already defined and the only task left to OR is to formulate and solve it using predominantly mathematical techniques. Chapman (1992) discusses criticisms of this view and the traditional OR method behind it, namely that it is 'not relevant to messes', it is 'conservatively biased' and concentrates on the analysis phase of an intervention offering little to 'path breaking' and to the implementation phases.

The importance of problem setting or problem structuring in OR interventions has been stressed by many authors (Checkland, 1981; Miser, 1988; Ormerod, 1996a; Pidd, 1988; Rosenhead, 1989; Schön, 1983). In 1980, Pidd and Wooley provided an account of a pilot study of the practice of problem structuring in a number of UK OR groups. The authors concluded that problem-structuring can be seen as a process of exploration as the OR analyst tries to comprehend and manage the complexity of the issues. Schön (1983) argues that problem setting is a recognised professional activity as much as problem solving adding that 'Some engineers, policy analysts and operational researchers have become skilled at reducing 'messes ' to manageable plans' (p.18). Pidd (1988) defines problem structuring as 'the process, whether formal or informal, by which some initially presented conditions and requests become a set of issues for detailed research.' and adds that 'problem-structuring is in some senses a preliminary to detailed data collection, interviews, modelling, computer programming, optimisation, experimentation ... etc.'. In 1989, Rosenhead edited a text titled 'Rational Analysis for a Problematic World - Problem Structuring Methods for Complexity, Uncertainty and Conflict' which constitutes a benchmark in recognising the importance of problem setting in OR. The purpose of the book is 'to provide an introduction to a range of methods for structuring decisions and problems, rather than "solving" them.' (p.xi)

Recognising the importance of problem setting brought about changed models of the OR method and new techniques: Chapman (1992) and Ormerod (1996a) develop updated models of the OR method that acknowledge the importance of the issue-structuring or problem setting phase. Several techniques (e.g. soft systems, cognitive mapping, strategic choice.) aimed at defining problems in complex and 'messy' situations have become available (Rosenhead, 1989). These techniques borrow elements from social sciences, such as organisational behaviour and psychology, highlighting the social content of OR and its context.

Systems approaches have contributed to the development of techniques for problem structuring and more broadly to the practice of OR. The view of organisations as open systems (see Pidd (1979) for an explanation of the nature of systems approaches) has proved to be useful to OR practice. Checkland (1981) developed a problem structuring methodology called 'Soft Systems Methodology' which is based on the idea that most organisations can be usefully regarded as 'soft' systems. Soft because there are different, subjective views of the issues being considered. The methodology involves the conceptualisation of possible system definitions, comparison with what currently exists or is being proposed as a way of debating what changes might be desirable and feasible. The author does not argue that the 'real-world' is systemic, but rather finds that systems ideas are useful to organisations (Checkland, 1989; Pidd, 1985).

The relevance of social factors in OR has long been acknowledged especially among OR practitioners. In 1964, the subject for the first international conference of the UK OR Society was 'Operational Research and the Social Sciences' (Lawrence, 1966). Pidd (1985) argues that the political dimension (as well as the technical and systemic dimensions) should be present in any theory of OR practice. Eden (1989) asserts that best OR practice should combine the 'dispassionate' and 'objective' activities of science with those of social science 'which reflect the passion of interaction in organisation'. In the specific field of project management, Breure and Hickling (1990) argue that a project is a social system and propose a 'socio-technical approach' to project management where technical and socio-political cycles are in a 'symbiotic relationship'.

The importance of language and human interaction in OR interventions has been recognised in the literature. Boothroyd (1978) presents a 'language about action' for interventions which includes key terms such as 'articulate intervention' and 'action programme'. He places the practice of language at the centre of his view on interventions, since the interaction and contribution of both the client and the analyst is made by means of language. Tomlinson (1984) highlights the importance of human interaction in OR: the interaction between the OR practitioner, who is intervening in the system and thus becoming an element within it, and the other 'human actors' in this system.

The social nature of OR interventions means that they cannot be seen as static. Tomlinson (1984) emphasises the importance of 'process' in OR: 'Instead of visualising the problem situation as static and unchanging, we must understand it as dynamic. If the work is related to organisational decision-making, it is necessary to understand that in any living organisation there are frequent changes in the personnel, developments of opinion, changes in the environment, changes in policy.' (p.207). Pidd (1995) discusses the importance of the image of OR as primarily concerned with intervention and change in OR practice. This image of OR is linked to the view that 'organisational life is dominated by flux and transformation'. Checkland (1984) suggests that anyone using systems or management science techniques is attempting to secure change in a social system, and should therefore be aware of this.

More recently, Ormerod (1996a) links some of the developments in social sciences method to the reappraisal of OR: the development of the 'interpretative' or 'humanistic' approach to social sciences as an alternative to the positivistic methods of natural science resulted in more importance being given to subjectivity, language and context. Ormerod talks of 'a recognition both that OR is a social process with a culture and programmes and that the target of the intervention is itself an organisation with its own social culture and programmes' (p.4). In a later paper (1996b), he adds 'To recognise that one is intervening in a social situation is to recognise that there will be a number of actors engaged in different activities, working to their own agendas (which may or may not be aligned with the organisation's agenda), and with their own particular interests.' (p.9). Ormerod's model of the OR method (Ormerod, 1996a), recognises the importance of context and socio-political factors in OR interventions.

The view of OR as a social process in social settings leads to the idea that situations faced in organisations are unique. Several authors stress the specificity of situations faced by OR analysts in organisations (Chapman, 1992; Miser, 1988; Ormerod, 1996a). Many situations have identical facets, recognisable symptoms, that allow for transfer of methods (Chapman, 1992), but the different social contexts and human interaction result in each situation having unique features demanding at least some adjustment of methods.

The OR analyst at the outset of an intervention has often identified a broad class of models or techniques which can be applied, but these tools will have to be adapted or redeveloped for each situation. In order to design situation specific approaches the OR analyst has to get to know the context. Ormerod (1996a) maintains that OR interventions have to be 'thoroughly grounded in the reality (actual or perceived) of the situation'. Chapman (1992) counts 'a sound understanding of practical issues obtained by on-the-job observation ' as one of the key reasons for the success of OR in its pioneering days.

The knowledge of context is fundamental to reduce as much as possible the model-reality gap and prevent the trap of addressing the wrong problem. Chapman (1992) mentions the well-known dangers of *a priori* choice of familiar models and the moulding of the problem in order to apply them. In fact, as pointed out by Boothroyd (1984) and Checkland (1981), reality is too complex to be expressed in any possible model, therefore the OR analyst builds models that are inherently simpler than reality but may be checked against it. Boothroyd (1978) says 'In principle, the claim that precise problem conclusions translate precisely into correct real-problems conclusions is wrong. The mapping of real problems on to precise problems is always accompanied by a considerable simplification in choosing what to map: the properties of any real system are indefinitely many' (p.119)

The OR analyst has to be open-minded about a situation and identify as extensively as possible hidden assumptions. Tomlinson (1984) talks of 'The need to explore the *hidden assumptions* which underlie both the analyst's approach and the systems response' (p.206). Miser (1988) adds 'It appears then, that the prudent analyst should identify as many of the implicit factors as he can, so that he can make considered judgements about whether or not they should be given explicit consideration' (p.502).

2.2.2 Research in OR

Research in OR can be viewed in the light of the three classes of scientific problems suggested by Ravetz: scientific, technical and practical problems. Within this framework, if the travelling salesman problem is seen as an OR scientific problem, research on more efficient algorithms to solve the travelling salesman problem could be considered research on a scientific problem. Research on more efficient algorithms to address production planning problems could be seen as research on a technical problem, and research aimed at the development of a decision support system for a particular company could be seen as research on a practical problem.

Reisman and Kirschnick (1994) suggested another classification of OR research. To shed light on the process variously called 'devolution' (Ackoff, 1987), 'natural drift' (Corbett and Van Wassenhove, 1993) and 'regression' (Abbott, 1988) they analysed the statistical content of papers in US flagship journals. They focused on the theory versus application classification and used a scale to encompass the different meanings given to the words application and data. The paper suggests a classification scheme for the OR/Management Science literature. The papers surveyed are classified as either part of the applications or theory literature. The applications literature is further divided into research on applications (meta-research), philosophy or history of applications, and applications. The theory literature is broken down into literature on methods, with pure or with synthetic data, research on research (meta-research) and philosophy or history.

A five point scale is used to classify papers which claim to be an application:

1. a figment of the modeller's imagination, a result of logico-deductive reasoning;
2. a figment of the modeller's imagination that uses synthetic data;
3. a grounding in the real world, with real-world data;
4. a grounding in the real world with real-world data and a demonstrated application that made a difference;
5. either category 3 or 4 with the additional use of synthetic data to test sensitivity, conduct an error analysis, and/or explore behaviour at the boundaries.

An additional criterion is used for categories 3 to 5: the articles have to include research on the field of application itself. According to the authors, this research comprises 'a discussion of the nature and the relevance of the field of application, assumptions made for any abstractions and a discussion of the source and the accuracy of the data used'. The authors consider that only the papers in categories 3 to 5 can be qualified as true applications. A 0 level is assigned to papers which make no application claims. Ormerod and Kiossis (1997) extend this analysis to UK journals. A second paper by Reisman and Kirschnick (1995) provides a taxonomy of OR research strategies and an analysis of how often they are used in theoretical and in applied OR (Chapter 3 provides an explanation of the taxonomy).

2.2.3 The Nature of OR - Summary

For the purposes of this research OR is seen as a socio-technical discipline with its own methods of research that tries to improve problematic situations faced by organisations. OR has assembled and developed a body of techniques since its start. Some of these techniques borrow elements from other disciplines and range from problem structuring techniques and visual models to more quantitative techniques such as optimisation or simulation. However, in many OR interventions, techniques other than the standard ones are called for: situation specific techniques or techniques imported from other disciplines (e.g. artificial intelligence).

OR interventions have to be grounded in reality and may require (or consist only of) a problem setting phase. Consequently, research on an application of OR to a certain area also has to be grounded in reality and use real data. It also has to take into account the social context, has to structure the problem(s), and has to show to what extent that application of OR can improve effectiveness in that area.

2.3 Decision Support Systems

This section starts describing decision-making processes leading to a definition of DSS and its components. Most texts on DSS (for example, Bidgoli, 1989; Turban, 1990) rely on Simon's (1960) classification of decision-making processes. Simon maintains that decision-making processes range from highly structured to highly unstructured. Structured processes are repetitive and routine problems for which standard solutions can be derived. Unstructured processes are 'messy' and complex problems for which there are no clear-cut solutions.

Simon categorises human decision-making process into three phases:

1. intelligence - searching for conditions that call for decisions;
2. design - inventing, developing and analysing possible courses of action;
3. choice - selecting a course of action from those available.

Turban (1990) and Bidgoli (1989) add a fourth phase to the process: implementation. A fully-structured process is one in which all phases are structured. A phase is considered structured if all procedures are standardised, the objectives can be clearly defined and the inputs and outputs can be clearly specified. An unstructured process is one in which none of the three phases is structured. Gorry and Scott Morton (1971) define a third, intermediate type of decision process - semi-structured. A semi-structured process is one in which some, but not all, of the phases are structured.

Examples of each type of process are:

- structured processes - plant location or vehicle routing problems;
- semi-structured processes - production scheduling or inventory control problems;
- unstructured processes - negotiation and lobbying processes or R&D planning.

As pointed out by Moore and Chang (1980), the distinction between types of processes is not always clear, a process can be described as structured or unstructured, depending on the decision environment. Turban (1990), basing his work on Gorry and Scott Morton (1971), suggests that conventional management information systems and management science approaches are insufficient to address semi-structured and unstructured problems. DSS are deemed to be more suitable to address these (Bidgoli, 1989; Turban, 1990).

The concept of DSS was first articulated in the early seventies by Scott Morton (1971) who defines what he called management decision systems as 'interactive computer-based systems, which help decision-makers utilise data and models to solve unstructured problems'. Keen and Scott Morton (1978) define DSS as 'a coherent system of computer-based technology (hardware, software and supporting documentation) used by managers as an aid to their decision-making in semi-structured decisions' (cited in Turban, 1990, p.9). Turban considers the major features of DSS as:

- they incorporate both data and models;
- they are designed to assist managers in their decision processes in semi-structured or unstructured tasks;
- they support, rather than replace, the decision-maker's judgement;
- they are aimed at improving the effectiveness of decision-making rather than its efficiency.

The early definitions of DSS have been extended over time. Moore and Chang (1980) argue that the concept of structured and unstructured problems is not meaningful in general. In fact, DSS have been used to address all types of problems irrespective of their degree of structure (Bidgoli, 1989; Turban, 1990). In addition, there is evidence showing that improvement in the efficiency of decision-making is rated as important as effectiveness in the approval of DSS projects and in perceived DSS success (Meador and Keen, 1984). Thus, the above set of DSS features identified by Turban can be amended as follows:

- DSS incorporate both data and models;
- DSS are designed to assist managers in their decision processes in semi-structured or unstructured tasks but may also be designed to support structured tasks;
- they support, rather than replace, the decision-maker's judgement;
- they are aimed at improving the effectiveness and the efficiency of decision-making.

Comparing DSS with other types of information systems Young (1989) claims, 'The mode of DSS differs from other management information systems applications in that DSS seek to establish a symbiosis of human mind and computer by allowing for a high degree of human-computer interaction and by enabling the manager-user to maintain direct control over the computer's tasks and their outcome.' (p.185)

Turban views DSS (and expert systems) as being directed more often at top executives and professionals addressing specialised or complex problems. The following advantages of DSS (Bidgoli, 1989; Turban, 1990) can be mapped onto features of problems frequently encountered by professionals in fields such as ATFM:

- ability to support the solution of complex problems;
- fast response to unexpected situations that result in changed conditions;

- ability to try various strategies under different configurations quickly and objectively;
- new insights and learning of the decision process. This includes the training of less experienced staff;
- cost savings;
- objective decisions. The decisions derived from DSS are more consistent and objective than decisions made intuitively.

Turban (1990) presents examples of benefits from the use of DSS such as: a portfolio management system for Great Eastern Bank which has the benefits of better information and communications, better formats, less clerical work and an improved image of the bank; a student financial aid DSS for Wesleyan University which is particularly useful in computing 'what if' questions (for example, what is the budgetary impact of admitting more students?) and in monitoring the financial aid situation of the university. Vazsonyi (1996) gives an example of a DSS for a food company. The DSS was developed to provide information to establish and monitor levels of advertising efforts such as advertising, pricing and promotion. Managers stated that the main benefits of the DSS were the new insights and approaches it provided for corporate decision-making.

DSS have been used in areas such as manufacturing, health care management, finance and investment, human resource management, sales, transportation, or telecommunications to support decisions as varied as pricing of products, airline route selection, network design or facility location. Bidgoli (1989) and Turban (1990) provide numerous examples of DSS applications. Other examples can be found in Garnto and Watson (1989) and Powell *et al.* (1992).

Classically, DSS are considered to have three components, user interface, data and models each with a respective management component to guide use: dialogue management, data management, and model management (Bidgoli, 1989; Watson and Sprague, 1989). From the user's perspective, the dialogue component is the system, as the data and model are, by and large, transparent.

Important aspects to consider in designing a dialogue are: 1) what the user has to know in order to use the system; 2) the options to direct the system's actions; and 3) the alternative presentations of the system's responses.

The data management component supplies the data necessary to take the decisions. Data can be accessed directly by the user, be an input to the models or an output of the models. According to their source, data can be internal or external. Internal data are generated or collected by other systems in the organisation such as marketing, personnel or production or are provided by staff in the organisation (e.g. subjective estimates from managers). External data is generated by sources external to the organisation as for example customers, competitors, government agencies etc. An important factor in the development and success of a DSS is the availability of data (Watson and Sprague, 1989).

The model management component provides the analysis capabilities for a DSS. It often includes mathematical models and algorithms to generate information to support decision-making. It may comprise from few to several hundred models of different types such as simulation, optimisation or regression models. A crucial issue here is that of complementary intelligence. Both the system and the user have skills. The system in data storage and manipulation, the user in insight and experience. It is important that the process of decision making with the DSS makes best use of both elements.

DSS were developed from a background of information systems and OR. On a parallel path from that of DSS, research in artificial intelligence has led to the development of various tools and systems which can also contribute to decision-making. Of these tools, knowledge-based or expert systems are possibly the most well-known and widespread. Turban (1990) defines expert system as 'a computer system that applies reasoning methodologies on knowledge in a specific domain in order to render advice or recommendations, much like a human expert' (p.834). Typically, an expert system has three components: 1) the user interface; 2) a knowledge base of facts and rules related to the domain of application; and 3) an inference engine which interacts with the information in the knowledge base to solve the problem. Expert systems also include a language processor for friendly communication between the user and the computer, and the ability to explain the reasoning and conclusions achieved.

Expert systems are better suited to narrow and very well-defined application domains where interaction between people in decision-making is less important. Some of the best known examples of such systems are in medical diagnosis and mineral exploration. Early applications of expert systems led to the development of general-purpose tools for building expert systems. The differences between expert systems and DSS are amply discussed in the literature (Connell and Powell, 1992; Doukidis and Paul, 1992a; Edwards, 1992; Turban, 1990). The definition of expert system implies that they differ from the DSS because they mimic human experts and thus replace the human decision-maker, whereas the DSS assists the human decision-maker. However, in practice, expert systems have been sometimes used in a role similar to that of 'an assistant' or 'a second opinion' (Edwards, 1992; Doukidis and Paul, 1992a). Edwards (1992) contends that the main distinguishable features between expert systems and DSS are the tools used to build them (e.g. artificial intelligence languages) and the source of the system's models. However, as shown in Edwards (1992), this distinction is not always easy to make, specially for systems which combine DSS and expert systems technology.

Attempts have been made to combine DSS with expert system technology driven by the idea that they can complement each other creating a more powerful decision support tool. Turban (1990) suggests different ways of integrating DSS and expert systems ranging from expert systems being attached to DSS components to expert systems being separate DSS components. Doukidis and Paul (1992a) mention attempts to introduce expert systems concepts into the DSS design framework: natural language processors to improve the user interface, inference engine mechanisms to improve the model base and knowledge representation techniques to improve the data component. Systems in management and administration which combine expert system with DSS technology are also described by Edwards (1992). For the purposes of this research a broad definition of DSS is used, one which encompasses expert systems and all other artificial intelligence tools which can be used to support decision-making.

In summary, DSS are defined as computer-based systems which are designed to support, rather than replace, the decision maker's judgement and are aimed at improving the effectiveness and the efficiency of decision-making. DSS have three main components: user interface, models and data. The user interface is the system, from the user's viewpoint and may include graphical and explanatory capabilities. The models provide the analytical capability to the system and can include models which range from mathematical models to rule-based models. The data component provides the data necessary to support the decisions and may in its more sophisticated versions include a knowledge-base.

2.4 The Relationship Between OR and DSS

This section discusses the interface between OR and DSS with a view to further define the field and potential contribution of this research. OR and DSS can be seen as closely related fields since both are aimed at improving decision-making in organisations. As noted, DSS come from a background of information systems and OR. The link between both is so evident that in the literature discussing the relationship of OR with other fields, DSS are often presented as part of OR (Doukidis and Paul, 1992a; O'Keefe, 1985). Many OR interventions involve the development or use of a DSS. In turn, many DSS are developed using OR expertise in the structuring and modelling of the decision problems. O'Keefe (1985) emphasises the mutual benefits of liaison between OR and expert systems: OR can bring the experience in model-building and OR techniques and expert systems are another tool in the OR toolkit.

The DSS approach can bring some benefits to traditional OR. Watson and Sprague (1989) argue that the DSS approach to modelling attenuates the following traditional problems associated with the use of models in organisations:

- difficulties in obtaining input data for the models;
- difficulties in understanding how to apply the output from the models;

- difficulties in keeping the models up to date;
- lack of confidence in the models by the users;
- little integration among models;
- poor interaction between the models and users;
- difficult for users to create their own models;
- the models' little explanation for their output.

The DSS approach emphasises that a system formed by user interface, data and model components working together is needed. Users are more likely to operate a system successfully, keep it up to date and use it (and consequently use its models) if the user interface has been adequately designed and if they were involved in its development. The DSS database provides the data necessary to build, use and maintain the models. The output from the models is placed in the database accessible to other models. Some DSS also include artificial intelligence capabilities through which the models explain the factors that led to the output.

The interface between OR and DSS is highlighted by O'Keefe (1995) when he stresses the importance of OR focusing on system design rather than on analysis aimed at supporting improvements in existing systems. While recognising that many OR interventions already involve the successful design of systems, the author contrasts two views of OR: a more traditional view which considers that OR should concentrate on the analysis and solution of problems and a 'design-oriented' view which considers that OR should concentrate on designing and implementing new systems. The author then discusses the differences between the two views under the different phases of a project. Whereas OR portrayed in textbooks assumes that any data requirements can be met, 'design-oriented' OR places emphasis on the availability and management of data. An 'OR designer' will also consider how the model integrates with the rest of the system early in the project, the development of the model and how the model is to be used are approached as a combined design problem.

While the development of a ready-to-use DSS is outside its scope, this research contributes to applied OR at its interface with DSS by structuring the problems and producing models with a view to the development of decision support systems for ATFM. In the light of the above 'design-oriented'/DSS view of OR, issues such as user needs, user interface, and data requirements are addressed together with the development of models to support ATFM decisions.

2.5 Air Traffic Flow Management in Practice

Given the focus of this research on the ATFM domain and the understanding of applied OR reached above, this section describes ATFM in practice in the US and in Europe. The description of ATFM in the US is based on the literature whereas the description of European ATFM results from fieldwork which took place between October 1994 and April 1995 and in May 1996 (see Chapter 4).

2.5.1 Air Traffic Flow Management in the US

US authors (Odoni, 1987; Pozesky and Mann, 1989) break down flow management actions into two classes: strategic and tactical. Strategic actions are those taken before the actual take-off of aircraft, such as delays of departure times (ground-holds) for aircraft flying to congested areas. Tactical actions are taken when aircraft are already airborne and include speed control measures, en-route re-routing, etc. According to these definitions, this research focuses on strategic actions, i.e. flow management before aircraft are airborne.

The body co-ordinating flow management in continental US is called Air Traffic Control System Command Center. To assist the ATCSCC and take actions at the local level, traffic management units operate at regional Air Route Traffic Control Centers and at the major terminal radar control facilities. Booth (1994) describes the four strategies ATCSCC can use to tackle flow management problems: 1) ground-delay or estimated departure clearance time programme (EDCT), which consists of issuing departure delays for flights heading to airports whose capacity is expected to be below demand; 2) miles-in-trail restrictions which are aimed at controlling the rate of traffic flow in en-route sectors; 3) severe weather avoidance programme which involves re-routing flights to by-pass bad weather; and 4) ground-stop which is a last minute ground-hold measure used in contingency situations, like extremely bad weather. The EDCT is the most widely-used strategy.

The event which contributed most to the widespread use of air traffic flow management in the US was the air traffic controllers' strike in 1981. To alleviate congestion and avoid airborne delays, the Federal Aviation Administration (FAA, the body in charge of the US air traffic system) had to resort to extensive ground-delays. The potential of this measure was then recognised and ground-holds rapidly became the most important measure to deal with congestion. According to Odoni (1994), the systems since implemented to support flow management, 'have evolved in an essentially *ad-hoc* way' under the pressure of growing traffic.

One of the system development areas, where progress has been substantial, is in automated information gathering, processing and display (Odoni, 1994). During the late 1980s a system called Enhanced Traffic Management System and Aircraft Situation Display was developed in the US. This system aims to 1) provide accurate and up-to-the-minute information for monitoring airborne traffic flows; and 2) stepwise development of more sophisticated decision-support tools for ATFM. This system is able to assemble data from varied sources in real time and the information can be easily displayed.

Despite these impressive data gathering facilities, there are still important gaps in the area of data provision: Booth (1994) explains that 'ATCSCC is plagued with inadequate data' particularly traffic demand data. This can be attributed to last minute changes in airlines schedules and also to unscheduled flights (Frolow and Sinnott, 1989). There is also a need for improved representation of aircraft trajectories, including arrival and departure procedures, and user and ATC preferences (Frolow and Sinnott, 1989; Odoni, 1994).

As to the development of decision support systems which go beyond the information processing and displaying stages, this is still in infancy. At present, an EDCT is prepared for each affected airport, using a simulation approach to allocate ground-delays, independently of similar programmes affecting other airports. The interdependency of airport operations is ignored (Booth, 1994). The allocation of delays is reportedly done on a first-scheduled-first-served basis (Vranas, 1992). The FAA started developing a decision support tool, called OPTIFLOW (Odoni, 1994) for preparing daily traffic flow plans, which in the allocation of ground-delays takes into account the propagation of delays in the airport network. Its development has reportedly been halted.

2.5.2 Air Traffic Flow Management in Europe

The European airspace is controlled by many different national administrations, making articulated air traffic control and flow management actions more difficult to implement than in the US. Nevertheless, after the very heavy delays experienced in the 1980s, the states belonging to ECAC decided to create a European central flow management unit - the CFMU - to provide a centralised ATFM service for their airspace.

As noted, in Europe, congestion is felt not only at airports, as is mostly the case in the US, but also in the airspace at many of the fixes (junction points in the airspace). In addition, more emphasis has been put into planning several months ahead, than in the US and, consequently, ATFM concepts differ. The CFMU (EUROCONTROL, 1993), distinguishes three phases in ATFM:

- *Strategic* - takes place from six months until two days before the day of operation;
- *Pre-tactical* - takes place on the two days preceding the day of operation;
- *Tactical* - this phase, called strategic in the US, takes place on the day of operation prior to the departure of aircraft.

This research uses the European definitions and vocabulary, except when otherwise specified.

At pre-tactical and tactical levels, flow managers in Europe have been taking several types of actions to handle congestion problems such as: negotiating increases in capacity with ATC, slot allocation, and vertical or horizontal re-routings. Negotiations with the area control centres might involve a split of a sector into several sectors or extended opening times of certain sectors in order to increase the capacity of the system.

Slot allocation is, in practice, the same as ground-delay or ground-hold. A departure slot, usually at a later time than initially scheduled, is issued to flights heading to congested locations. These locations can be airports, air traffic control sectors or just airspace junction points. A slot allocation programme is called a regulation. It should be noted that, different to the US, a flight is frequently subject to several regulations. Re-routing measures consist of re-routing flights in order to by-pass certain congested locations. The idea behind them is to prevent or alleviate overloads.

The CFMU is equipped with a computer system (TACT) comprising a computer assisted system for slot allocation (CASA) in the tactical phase of ATFM. TACT is linked to an automatic system for flight plan processing (IFPS), which provides updated and detailed information on predicted demand. As in the US one of the problems faced in Europe is the lack of accurate traffic data to support planning, especially at the strategic and pre-tactical levels.

At a more structural level of planning, CFMU has the possibility of ordering simulation studies from the experimental centre of the European Organisation for the Safety of Air Navigation (EUROCONTROL). These studies usually range from the evaluation of new flow control procedures to the testing of contingency routing schemes.

For all other flow management measures described above, there are almost no support tools available. Most decisions are still taken by looking at maps and by building charts and tables by hand, or summing up figures which flow managers obtain from different sources. The problem is even more acute at present because all the new flow managers hired by the CFMU have had little experience on the job.

The EUROCONTROL Experimental Centre in 1995 started a research project aimed at developing a prototype of a re-routing decision support tool, CARAT - Computer Aided Route Allocation Tools, which was finished by the end of 1997. This project draws partly on the Re-routing project described in this thesis which took place between October 1994 and April 1995, at the CFMU (see Chapter 3). The CFMU is now introducing some of the results of CARAT, namely a function which provides a choice of routes to support re-routing of individual flights at the tactical level.

2.6 Air Traffic Flow Management in the OR and DSS Literature

It is possible to distinguish three major modelling approaches to air traffic flow management problems, which are not necessarily alternatives (but tend to be so in the literature): mathematical programming, simulation and artificial intelligence.

2.6.1 Mathematical Programming

Optimisation appears to be the favoured approach of ATFM policy-makers. After safety, the main objective of ATFM is to optimise the flows of air traffic. However, despite this emphasis on optimisation, optimisation models do not appear to have been implemented in practice. Some reasons for this are discussed further in this section.

Mathematical programming literature on ATFM is already significant, the major stream of literature in mathematical programming is concerned with ground-delay policies. Odoni (1987) provided the first problem statement based on the US situation. Several papers, addressing the case of a single congested airport have followed (Andreatta and Romanin-Jacur, 1987; Richetta and Odoni, 1993; Terrab and Odoni, 1993). The problem has been formulated in the following way: if demand is expected to be above capacity, at one or more airports, or in airspace for a certain (significant) period of time, generate a plan of delay assignments so that the cost (or other criterion) is minimised (maximised), subject to all airport and airspace constraints (Odoni, 1994).

Mathematical programming models for the allocation of ground-delays have been mainly integer programming and network models. Lindsay *et al.* (1993) and Tošic and Babic (1995) provide a detailed survey of literature on the optimisation of ground-delays. The progress of these models in terms of the cases they cover has been quite steady. Andreatta and Romanin-Jacur, in 1987, address the case of one airport where congestion lasts for a single period of time. Terrab and Odoni (1993), present an exact solution method for a case with one airport, several periods and deterministic capacity. In 1993, Richetta and Odoni provide a linear programming solution method to a multi-period single airport case where capacity is stochastic, and Vranas *et al.* (1994a) present integer formulations for a network of airports, taking into account the interdependency between operations at different airports. More recently, formulations have been developed to deal with dynamic situations, when information on capacity changes over time (Richetta, 1995; Vranas *et al.*, 1994b). Most of these formulations are meant for the US where congestion is mostly felt at airports or terminal areas, so it is assumed that there is no congestion in sectors en-route.

In recent years, the case where congestion is also experienced in en-route sectors has received more attention in the literature. Helme (1992) describes a multicommodity network flow formulation of this case. Glockner (1996) also presents a network modelling framework but with multiple scenarios to deal with capacity uncertainty. Lindsay *et al.* (1993) provide a binary programming formulation of this case. There is also a reference to a paper to be published in the US (Bertsimas and Stock, 1995) where the multi-airport case is formulated considering also capacities en-route. Vranas (1996) draws on these formulations to build a model for optimal slot allocation in the European airspace. Tošic *et al.* (1995a) formulate the problem of allocating ground-holds in a situation where both airports and en-route sectors can be congested as an integer problem with solution methods based on linear programming relaxation and bottleneck heuristics.

The solution methods suggested so far, depending on the version of the problem, range from minimum cost flow to standard integer linear programming algorithms. Most of the experimental work reported has been done using off-the-shelf software and some heuristic methods. More recently, research on the US case looks into ways of improving solution times so that optimisation models could be used in practice. To this end, Bertsimas and Stock (1995) and Andreatta and Brunetta (1998) propose new integer formulations of the ground-holding problem, which reportedly provide shorter solution times (for a comparison, see Andreatta and Brunetta, 1998).

There has also been some research reported on the use of heuristics: Andreatta *et al.* (1994) describe a heuristic for the allocation of delays which is based on priority rules. Heuristics are not only less time-consuming than exact methods, but are also easier to grasp by the users, who often regard optimisation methods with suspicion, possibly because they view its mathematical content as rather obscure.

With research focusing on improving solution methods for the large-scale integer models required in practice, OPTIFLOW's (see section 2.5.1) approach is based on a linear relaxation of the multi-airport formulation proposed in the literature. Decision variables regarding flights, or their departures are assumed to be continuous. The underlying reason for this simplification is the availability of efficient algorithms and software to solve the linear continuous model (Booth, 1994). In support of this approach, there has been some experimental work reported where it is shown that with certain integer formulations of the multi-airport ground-holding problem, the linear relaxation provides an integer solution for most instances of the problem (Andreatta *et al.*, 1994).

Re-routing flights has received practically no attention in the literature to date: Bertsimas presented some integer models for en-route re-routing in the US airspace at an INFORMS conference in the US (Los Angeles, 1995). Tošic *et al.* (1995b) describe an integer model for the allocation of delays where the possibility of choosing between alternative routes is considered. The model was tested on traffic overflying Serbia and does not appear to be entirely grounded in European ATFM reality (see Chapter 7 for detailed discussion).

An important issue in modelling air traffic flow management problems is how to deal with uncertainty: the capacity of an airport or other element of the airspace can vary suddenly and significantly, for instance due to weather changes. Traffic demand is also significantly uncertain until a few hours before the departure of the flights. Qiao *et al.* (1996) derive equations to calculate expectations and probabilities of delay of aircraft requesting take-off. The authors argue that these equations can be used in real-time to calculate ground-delay of aircraft heading to congested elements of the airspace. Andrews (1993) presents the results of a study into the impact of weather uncertainty on optimal ground-holding strategies. The study indicates that uncertainty in the delay prediction (related to uncertainty in capacity prediction) should be taken into account in allocating delay to an individual flight. Some of the optimisation models developed for ground-holds consider stochastic capacity (Richetta and Odoni, 1993). A shortcoming of these models is that they tend to be larger and harder to solve than the deterministic ones. In ATFM practice, the development and increasing use of very powerful data gathering systems that update information on traffic demand and capacity almost continuously, has proved to be an effective way of dealing with uncertainty. As a result of these data gathering systems the development of stochastic models may not be worthwhile for very short planning horizons such as tactical ATFM.

There is exploratory research which addresses ATFM problems in a more global way, including various types of control measures or that approaches ATFM within the scope of a broader ATC problem. A global modelling approach to air traffic flow management problems, which covers the whole range of ATFM measures, is described within an automation programme in the US (Wang, 1991). It addresses the case where one wants to generate, evaluate and select strategies to resolve all congestion problems detected at the time, but from a 'local' point of view. The problem consists of optimally combining a number of local strategies to prevent occurrences of congestion while considering the interdependencies between congestion problems. It is formulated in network terms and a solution algorithm based on a standard shortest path algorithm is applied. Nevertheless, this algorithmic approach proved to be unfeasible, taking too long to reach a solution. It requires exponential time relative to the number of congestion problems. The amount of effort required to build the local strategies and determine interdependencies between congestion occurrences could also be significant. Bielli *et al.* (1982), Zenios (1991), and Bianco and Bielli (1993) propose different network models for air traffic control which include flow control measures both before and after flight departure, ranging from ground-delays to queues at holding points. There has been no follow-up to this work.

In assessing the applicability of mathematical programming approaches to ATFM a key question is why none of the models proposed in the literature for the allocation of ground-delays has been or is being implemented in a system for use in practice. Several research projects commissioned by the FAA or EUROCONTROL have looked at optimisation approaches but they have not got beyond the prototype stage. The following reasons for not using optimisation models have been given (Andreatta *et al.*, 1994; Odoni, 1987, 1994):

- the difficulty in defining an aggregate optimisation function that will satisfy all the stakeholders;
- the long execution time of the optimisation models. It should be noted that most of these models are integer, and, therefore, very time-consuming to solve to optimality. However, this problem can be mitigated by using approximate methods (i.e., methods that provide a reasonably good solution in substantially less time).

Another reason can be added:

- some of the models proposed in the literature do not appear to be grounded in reality.

However, Odoni (1996) supports the use of optimisation approaches for two reasons: 1) they provide 'benchmarks' against which the performance of a current system can be compared, and thus address questions such as whether there is ample or little room for improvement over current practice; and 2) optimisation algorithms can lead to the identification of generic types of ATFM strategies and eventually to the development of easier-to-understand and more user-friendly heuristic algorithms implementing these strategies.

As discussed in section 2.2., OR applications require research into the context. Issues such as the stakeholders are, who the users of the model are, when are they going to use the model, to what effect is it used, and the availability of data for the model, have to be clarified. If optimisation models are aimed at a scenario different from the present, an ideal scenario or a probable future scenario, then the perceived differences between that scenario and the present environment have to be stated. Odoni (1987, 1994) structures US ATFM decision support needs and formulates an ATFM optimisation problem. No similar ground-clearing work for European ATFM exists.

2.6.2 Simulation

Simulation may well be the most used approach in air traffic management practice. It is a powerful tool for representing and delving into complex systems such as the air traffic system. Simulation models are well-suited to the representation of uncertain and highly dynamic environments, and the interaction between capacity and demand. Further, if as it is often the case in air traffic management, the chance of experimenting on the real-world system cannot be taken, simulation provides a model where several policies and analyses of the 'what if' type can be explored.

The literature on simulation approaches to ATFM results mostly from systems under development or systems that are already used in practice. There are references to simulation systems whose main functions are: i) to represent and predict capacity and demand of the air traffic system and highlight congestion problems (EUROCONTROL, 1997a; Frolow and Sinnott, 1989; Medeiros, 1989; Winer, 1993); and ii) to explore different strategies and system improvements (Adams *et al.*, 1996; DeArmon and Lacher, 1996; EUROCONTROL, 1997a; Flynn *et al.*, 1994; Frolow and Sinnott, 1989; Hörmann, 1987; Mazé, 1994;

Zellweger, 1993). Mazé (1994) developed a simulation demonstrator to be used in pre-tactical ATFM at the CFMU. There has been no follow-up to this work. Most of the literature under category ii) is concerned with long term strategies (e.g. to study the impact of building a new airport or perform sensitivity analysis of changes in traffic control procedures) or the analysis of flow management policies at a pre-feasibility stage. It is not concerned with producing and evaluating specific congestion-relieving strategies on a daily basis. For instance, simulation has been used to test new optimisation models (Lindsay *et al.*, 1993) and, in Europe, it was used to test the feasibility of the CASA algorithm (Flynn *et al.*, 1994).

In the broader field of air traffic management two types of simulation are used: real-time simulation and fast-time simulation. Real-time simulation represents part of an air traffic control centre operations including the aircraft under control and involves validated air traffic controllers. It is usually used to test new procedures (e.g. new separation rules), a different organisation of the airspace (e.g. breaking-up an ATC sector into two sectors) or the introduction of a new computer tool (e.g. EUROCONTROL has used it to test new tools in the context of their research programmes). Fast-time simulation is computer-based simulation frequently used before reaching the stage of real-time simulation to evaluate the pre-feasibility of new concepts, organisations of the airspace or other investments in airspace capacity (e.g. building a new runway).

2.6.3 Artificial Intelligence

Artificial intelligence literature on ATFM is based mostly on commissioned research projects. Research in this field is still at an experimental stage. Most literature concentrates on the application of knowledge-based systems. Research on the application of knowledge-based systems has been reported at the FAA in the US by Kornecki (1995) and Winer (1993) who describe the development of a knowledge-based system prototype for traffic flow management called SMARTFLO. Weigang *et al.* (1997) describe two expert system prototypes for air traffic flow management in Brazil: one reschedules airline timetables to smooth traffic peaks at airports during rush-hours and another predicts congestion and proposes mitigative actions.

Bayles and Das (1994) describe a prototype system for ATFM which is based on the use of case-based reasoning. Case-based reasoning involves the storage of old problems and solutions thus providing information to help solve future problems. Each time a new problem arises, old problem(s) with similar features are automatically retrieved from the case-base. If the new problem differs from the retrieved problem(s) the solutions may need to be revised generally, through human intervention. The 'case' (problem and solution) that has been developed for the new problem is retained in the case-base, so that it can be accessed in the future. The authors justify the use of this technique on the grounds that ATFM problems tend to have similar features over time.

Teodorovic and Babic (1993) present an optimisation model where fuzzy logic is used in the allocation of ground-delays. EUROCONTROL (1997b) use a constraint programming solver, ILOG, to develop algorithms which allocate ground-delays using various decision criteria such as minimisation of delay per flight, minimisation of overall delay and minimisation of a cost function in which each flight has a different weight. The use of these algorithms in a static environment is shown to be possible. The authors want to test them in a dynamic environment.

Several authors highlight potential applications of artificial intelligence to the broader field of ATM (Delahaye *et al.*; 1996; Kodratoff and Vrain, 1993; Planchon *et al.*, 1993; Scardina *et al.*, 1989). Delahaye *et al.* (1996), describe an exploratory application of genetic algorithms to air traffic assignment, that is the assignment of traffic between origin-destination pairs taking into account extra route distance and sector workloads.

The above applications draw attention to the input that some of the artificial intelligence techniques, such as approximate reasoning, fuzzy logic and heuristic search have brought to the so called 'conventional' approaches of OR. Along the same line of thought, but from an artificial intelligence stance, Gosling

(1987) stresses the close relation between artificial intelligence and conventional approaches. He suggests that, artificial intelligence should not be seen as being radically different from conventional approaches, but more as a framework for a set of techniques some of which are also part of conventional approaches. On the issue of potential interfaces between artificial intelligence and mathematical programming, McBride and O'Leary (1993) carried out a survey of the state-of-the-art. They found a considerable number of examples, in various fields, of systems coupling mathematical programming with artificial intelligence. Examples of applications which combine artificial intelligence with simulation are provided in Doukidis and Paul (1992b).

2.7 Conclusions

This chapter provided a review of the literature in three areas: what constitutes OR and DSS, ATFM in practice and ATFM in the OR/DSS literature.

For the purpose of this research OR is seen as a social discipline with its own methods of research aimed at improving problematic situations faced by organisations. OR in practice is more than a collection of mathematical techniques and it is as much about problem or issue structuring as about problem solving. OR interventions can be seen as social processes, where the interactions between the actors in the intervention, including the OR practitioner play a vital role. OR interventions require situation-specific approaches methods, but general (meta) models of OR interventions can be outlined. The more recent discussions of this method emphasise the importance of researching the context and structuring the issues in a situation. The importance of knowing the context is also stressed in the few papers which address the nature of research in applied OR. It can be concluded that research in applied OR has to be grounded in reality, use real data and include a discussion of the assumptions made.

The survey of literature on decision support systems shows that they are well-suited to support the solution of complex problems, to provide fast response to unexpected situations that result in changed conditions and to support 'what if' analyses. In addition, DSS can provide new insights and learning of the decision process, cost savings and more consistency in decision-making. The three main components of DSS, user interface, data and models are introduced and the relation between them emphasised. The interface between OR and DSS is discussed and it is concluded that the models to be developed within the scope of this research have to take into account users needs, the user interface and the data requirements of a DSS for ATFM.

The review of ATFM in practice highlighted the following: European ATFM differs from US ATFM in the decision-making process and the timescale. European ATFM has a longer timescale and a more complex process of decision-making than US ATFM, where a single national body is in charge of Air Traffic Services. ATFM decision support tools are almost non-existent despite the widespread and urgent need for them at the different levels of planning.

Two gaps are highlighted in the OR and systems literature: the lack of ground-clearing work for European ATFM and the lack of research into models to support re-routing of flights. The urgent need for decision support tools identified in ATFM practice shows the practical importance of filling these gaps. They constitute the focus of this research. Having identified the focus of this research, the next chapter formulates the research objectives and substantiates the choice of method to attain those objectives.

Chapter 3

Research Approach

3.1 Introduction

This chapter discusses the research contribution based on the gaps identified in the literature review and characterises the approach taken to achieve that contribution. The research approach is identified drawing on the research approaches used in the social sciences and the approaches used to model-building in OR. The research approach discussed in this chapter is a result of several iterations. An important iteration took place during the fieldwork. The chapter describes the fieldwork process, how it modified the researcher's view of OR and, as a result, how it re-oriented the research.

3.2 Research Contribution

Drawing on Chapter 2 the following needs in ATFM research can be identified:

1. To date no ground-clearing research has been done on European ATFM and its decision support needs: there is some literature exploring the application of OR and systems to US ATFM but the differences in organisation, content and decision-making between the US and Europe are substantial, calling for specific research on European ATFM.
2. European ATFM needs tools to support its control measures. Re-routing flights is one of these.
3. The optimisation models for ATFM available in the literature are either not intended for, or not grounded, in European ATFM reality.

Therefore, this research contributes by:

1. providing a description of the European ATFM field and identifying the decision support needs;

2. defining the problems involved in the re-routing of flights in Europe and providing an initial framework for the development of re-routing decision support systems;
3. investigating the usefulness of optimisation approaches to the re-routing of flights in Europe including the development and testing of optimisation models.

3.3 Research Approach

Given the social context and content of OR, research approaches used in the social sciences may be relevant in defining an approach for this research. Therefore, this section characterises the approach to this research based on the research approaches used in social sciences. In addition, at a more operational level, it discusses the approach to be used to build the decision support models for European ATFM.

3.3.1 Research Approaches in the Social Sciences

The range of research approaches used in social sciences has been addressed in a number of books and papers (for instance, Hakim, 1987; Bryman, 1988; Allan and Skinner, 1991; and Galliers, 1992). Galliers discusses research approaches available for information systems research covering the spectrum used in social sciences. He divides the approaches into two categories, scientific and interpretivist approaches. Scientific approaches are those characterised by repeatability, reductionism and refutability (as defined by Checkland, 1981) and which assume that the phenomena under investigation can be observed objectively and rigorously. Interpretivist approaches are those arguing that the science ethos does not apply to social scientific enquiry because of:

> '- the possibility of many different interpretations of social phenomena.
>
> - the impact of the scientist on the social system being studied.
>
> - the problems associated with forecasting events concerned with human ...activity [given that] there will always be a mixture of intended and

> unintended effects and... the danger of self-fulfilling prophecies or the opposite.' (p.148)

Galliers (1992) classifies research approaches according to these categories and describes them as follows:

Scientific approaches

- Laboratory experiments: identification of precise relationships between chosen variables via a designed laboratory situation, using quantitative analytical techniques, with a view to making generalisable statements applicable to real-life situations.
- Field experiments: extension of laboratory experiments into the real-life situations of organisations and/or society.
- Surveys: obtaining snap shots of practices, situations or views at a particular point in time (via questionnaires or interviews) from which inferences are made (using quantitative analytical techniques) regarding the relationships that exist in the past, present and future.
- Case studies: an attempt at describing the relationships which exist in reality, usually within a single organisation or organisational grouping.
- Theorem proof: development and testing of theorems at the technical end of the socio-technical spectrum.

Approaches which can be classified as Scientific or Interpretivist

- Forecasting, futures research: use of such techniques as regression analysis and time series analysis, or the delphi method and change analysis to extrapolate/deduce likely/future possible events or impacts.
- Simulation, game/role playing: an attempt at copying the behaviour of a system which would otherwise be difficult/impossible to solve analytically, by the generation/introduction of random variables.

Interpretivist approaches

- Subjective, argumentative: creative research based more on opinion/speculation than observation, thereby placing greater emphasis on the role/perspective of the researcher. These can be applied to existing body of knowledge (reviews) as well as actual/past events/situations.
- Action research: applied research where there is an attempt to obtain results of practical value to groups with whom the researcher is allied, while at the same time adding to theoretical knowledge.

The applied nature of this research grounded in providing support for ATFM suggests that 'action research' is the most suitable approach. The concept of 'action research' arises in the behavioural sciences and its core idea is that the researcher is not an observer external to the subject of research but a participant in the relevant human group. Therefore, in action research the roles of 'researcher' and 'subject' are sometimes switched and the researcher is also part of the field of study. Checkland (1981) explains that in action research 'the researcher becomes a participant in the action, and the process of change itself becomes the subject of research' (p.152).

As explained by Galliers (1992), action research has the advantages of 1) resulting in practical suggestions for improvements to the organisation and 2) the fact that the researcher's biases are made known. It has the disadvantages of providing the potential for a very subjective interpretations of events, and of placing considerable responsibility on the researcher when his or her work is at odds with other stakeholders in the organisation. Another disadvantage is the fact that its application is usually restricted to a single organisation or event, making generalisations problematic.

Checkland (1981) draws attention to the fact that action research 'cannot be wholly planned and directed down particular paths' because 'when the phenomena under study are social interactions the researcher will find it almost impossible to stay outside them' (p.153). Therefore, the researcher may formulate research aims but cannot expect that they will remain unchanged, the researcher has to be prepared to react to whatever happens in the research situation.

Action research is particularly useful in defining the degree of involvement of the researcher with the organisation being researched. Chapter 2 concluded that research in applied OR requires research into the field of application, a grounding in the real world and the use of real data. To fulfil these requirements access to the CFMU to observe flow managers at work and collect real data is fundamental. Two degrees of involvement with the CFMU could be envisaged: one where the researcher goes to the CFMU to observe flow controllers at work, to collect data and finally to present the results of the research and another where the researcher is based at the CFMU working on a project of use to the organisation, learning 'by doing'. The second type of involvement is similar to the one described above as 'action research'. This involvement with the organisation is particularly suitable for research in applied OR, since it provides inside information on context and decision-making and enables the researcher to learn how operations are conducted. At later stages of this research, it became apparent that the placement at the CFMU provided important information that would not have been obtained had the research been confined to external observation.

While 'action research' is useful in defining the degree of involvement of the researcher with the organisation being researched, observer versus participant, it is partly a tautology, since 'obtaining results of practical value' is the objective of research in applied OR. The approach used to obtain the results of practical value can be further defined. The next section defines the approach used to build the decision support models for European ATFM.

3.3.2 Model-Building Approaches

Reisman and Kirschnick (1994, 1995), emphasising the model-building nature of OR, distinguish seven process categories among OR research strategies:

1. Ripple: a process which extends earlier work incrementally. for example by eliminating a simplifying assumption or addressing the n+1st dimension of an n-dimensional problem.
2. Embedding: a process in which two or more models are embedded in a more general formulation or a broader model.
3. Bridging: a process that 'involves tying two or more known models together into a more general theory that includes and expands both'. The models may come from different disciplines and this process usually results in the growth of all of its contributing disciplines.
4. Transfer of technology: a process that consists of transferring a model or knowledge from one context or discipline to another. This process differs from the bridging process since it usually does not contribute to the growth of the source discipline.
5. Creative application: a process that applies directly, not by analogy, a known methodology, such as linear programming, integer programming or parallel processing, to a problem or research question which had not been addressed using that method. This process is similar to the transfer-of-technology process, but usually it results in the redevelopment or redesigning of existing methodologies.
6. Structuring: a process that is used when a new situation presents phenomena not previously observed and documented thus requiring the creation of an intellectual structure that addresses what is observed.
7. Statistical Modelling: a process that is used when the models emerge from analyses of data obtained empirically.

The authors analyse a sample of the contents of the papers in the 1992 issues of Operations Research, Management Science, and Interfaces to ascertain how often OR/MS workers use these processes and in which circumstances. They conclude that the ripple process is mainly used in theoretical research whereas the transfer-of-technology process is the one most frequently used in applications. The authors stress these processes are not necessarily exclusive nor complete and that the distinction between them is not always straightforward. They also add that it is natural that the research process used will change if it is not providing good results.

This taxonomy of research strategies concentrates on the phase of model-building, it does not take into account the other phases of an OR research project. It does not cover issues such as how the information necessary to build the models is to be obtained, the degree of involvement of the researcher with the organisations which provide this information or, in other words, the type of fieldwork.

However, looking exclusively at the model-building phase of this research it is possible to draw some useful conclusions. Given the objectives of this research, statistical modelling and structuring processes are excluded from the fold of possible approaches. Since there is no early published research into the context of European ATFM and on the development of re-routing decision support models for European ATFM, ripple and embedding research processes are also excluded. In fact, the main processes driving this research are likely to be transfer-of-technology or creative application. However, the exploratory nature of the research suggests the need for a research process closer to creative application than to transfer-of-technology. In addition, at a secondary level, the bridging process may also be used for the parts of this research that draw on the fields of OR and Air Traffic Management, link them and may result in the growth of both.

3.3.3 Research Approach - Conclusions

The approach to this research can be defined at two inter-related levels:

- Degree of involvement with the client organisation: 'action research', with the researcher being based at the CFMU, learning 'by doing' on a project of practical interest to the CFMU. This involvement results in two embedded levels of research and corresponding methods: 1) the research into decision support models for European ATFM, and 2) the research into the OR intervention carried out at the CFMU which provided information and knowledge for level 1. The research method for the first level is explained below. The method for the OR intervention is discussed in the next section.

- Model-building: creative application, applying existing methodologies, directly, on a problem which has not been addressed before using those methodologies.

3.4 The Fieldwork Process- A Change of Paradigm

The fieldwork for this research was mainly carried out in Brussels, at the CFMU, from October 1994 to April 1995 and in May 1996. The researcher obtained a placement at the CFMU as a secondee, a university student of a subject relevant to EUROCONTROL, who engages there in a project of interest to both EUROCONTROL and the secondee. The secondment was based at the User Requirements' Section (URS), under the supervision of its head, Francis Gainche. The URS is concerned with the conception and design of new systems for flow management and the improvement of existing ones. It was the URS who produced the user specifications and designed the TACT, one of the main computer systems supporting CFMU activities. They have also played a key role in testing new CFMU systems.

The URS is part of the Flight Data Operations Division which handles everything related to flights operations and environment data. An important function of this division is to centralise the reception, checking and distribution of flight plans in the area of the 36 European states taking part in the CFMU project. However, at the launching stage of CFMU, during most of the secondment, the URS reported directly to the CFMU project manager, Pierre Jeannet.

The placement at the URS proved very useful. The URS, due to the scope of its functions, has close links with a wide range of units within CFMU, especially with users (flow managers) and software developers. This provided a privileged point of view and a mobility that would not have been achieved if the secondment had been based in a different unit. In addition, as the main thrust of

URS activity is to look forward to new systems, concepts and developments in ATFM, integration there was easier.

In establishing the objectives of the project the researcher had to find common ground between the priorities of her research and those of CFMU. The first priority of the research was to learn as much as possible about European ATFM practice, and at the same time collect data and information which could be used for model building and model testing. The second priority was to use the knowledge and data thus acquired to assess how operational research could be of use in the development of decision support models for European ATFM. The CFMU, as understood by the researcher at the time, wanted a report and also a software programme in a subject which could be of use to them.

In the initial contacts with the CFMU and their systems, it became apparent that in the tactical computer system they were developing, TACT, there was practically no support for re-routing of flights, a rather complex and commonly used ATFM control action. The selection of alternative routes for flights, taking into account distance and capacities of en-route sectors is not a straightforward task, especially if re-routing of whole flows of traffic is being contemplated. There was also no literature on decision support models for the re-routing of flights. Therefore, the researcher proposed that the project would concentrate on identifying and developing optimisation methods for re-routing flights. Optimisation appeared to be a relevant approach given that the optimisation of air traffic flow is one of the main objectives of ATC. The CFMU agreed to the researcher's proposal.

At the outset of the project the researcher's OR methodological framework was the traditional one, along the lines of the Ackoff and Sasieni (1968). Based on this method, the project was organised onto three modules:

1st Module: Specifications (formulation of the problem)

2nd Module: Modelling the problem (constructing a mathematical model to represent the system under study, deriving a solution and testing the model)

3rd Module: Computer Implementation and Validation (implementing the solution)

The initial timetable allocated 1 month to the first module, 3 months to the second module 2 months to the third module, extending over 6 months. In practice, the project lasted 9 months, from October 1994 to June 1995 and the contents and duration of the modules had to be reviewed. Initially, the researcher thought the first step, formulating the problem would be completed in a matter of days. However, soon after the beginning of the project it became obvious that there was a lot of ground-clearing work to do before reaching the stage of building models and specifying computer programs. For a start, the researcher's knowledge of the air transportation system was limited to the literature and an intensive learning process had to take place. Then, came the realisation that re-routing control measures can be controversial and are far from being a clear-cut issue, especially in an environment that was still at the launching stage such as CFMU. Flow managers' experience on re-routing measures for the whole ECAC airspace (36 European countries) was still scarce. European centralised ATFM was a relatively new concept requiring procedures and tools that were in many ways completely new.

Not surprisingly, the views on re-routing decision support needs were different among flow managers, staff of URS and other actors. The concept of theories, proposals and action programmes and of the importance of language in OR interventions (Boothroyd, 1978), became relevant at this point. The researcher realised that the traditional OR method (Chapter 2) was insufficient to deal with the situation faced at the CFMU because it did not acknowledge the importance of understanding the context, structuring the issues and interacting with the actors in the situation.

Updating the traditional OR method has been discussed in the literature. Chapman (1992), recognising that the traditional OR method does not explicitly consider the phase of describing and structuring the issues in a situation suggests an OR method model definition as follows:

1. describe the problems or issues;
2. formulate models of the problems or issues;
3. solve, resolve or dissolve any problems;
4. test any solutions;
5. implement any solutions.

He states: '*Issues* includes alternative perspectives and any other relevant feature of a situation which are not *problems* in the traditional sense.' (p.650). The models formulated are not necessarily mathematical, they can be verbal or graphical models. In Chapman's view, this method model incorporates the traditional OR method, all relevant scientific methods and all relevant issue structuring methods (problem structuring methods in Rosenhead's terminology). He states that the method moves from description to implementation, iteratively, with 'jump-backs' and 'work-backs'. He views this method model as a broad method and stresses the need to develop situation and model specific methods.

More recently, Ormerod (1996a) proposes a more general method for OR interventions which considers, in a more explicit way, the social and human interaction dimensions of OR interventions. The steps are as follows:

1. to research into the context: to begin to understand, through observation and possibly through more formal research methods, the client organisation and its environment;
2. to negotiate the issues: to structure, define scope and identify the outcomes required:
3. to design an intervention process: to identify the tasks required to achieve the desired outcomes, specifying the methods and the involvement of the different parties;

4. to analyse the issues: this could be to engage in debate with the participants using the chosen methods or may involve building and testing a mathematical model;
5. to advise on what could be done: to propose and assess ways of addressing the problem, in part based on the hypotheses, models and theorising. The advice will be framed in terms of the clients' expressed aims and preferences;
6. to assist with implementation: to help with the planning, training and operational introduction of the changes;
7. to reflect on the intervention: to articulate what has been learnt, how could it be improved.

Ormerod views this method more as a frame of reference than as a list of steps that have to be rigidly followed. Each step indicates 'that the focus of debate has moved on and new topics and activities have been introduced' (p.11) and the subject of each step can be revisited and revised throughout the intervention.

Applying this frame of reference, the first module of the project at CFMU focused on research of the context and on shaping the problem situation. Several tasks were performed during this period (17/10/94 to 18/11/94):

Task 1: Learn how TACT and its Re-routing editor worked.

Task 2: Identify the needs for re-routing methods and tools.

Task 3: Definition of decision criteria.

Both tasks 2 and 3 involved the following activities:

a) analysis of flow re-routing measures issued by the Central Executive Unit the main operational unit of CFMU. Most of these measures were taken to deal with contingency situations;
b) interviews with flow managers working for different flow management units in Europe (London, Madrid, Frankfurt and Paris);

c) interviews with flow managers working for the CFMU;

d) interviews with scheduled and charter aircraft operators: Sabena, British Airways, Eurobelgian Airlines and Air 2000;

e) visit to the EUROCONTROL Experimental Centre based in Bretigny-Sur-Orge in France;

f) visit to the London Flow Management Unit, to watch flow managers at work during two mornings.

Task 4: Identification of the main congestion problems in the European airspace.

Later on, during the project, other contacts and interviews were also held:

- interviews with staff of the EATCHIP, the European Air Traffic Control Harmonisation and Integration Programme, who are looking at redesigning the European air route network;
- interview at the Central Route Charges Office, the EUROCONTROL office which collects route charges on behalf of the member states;
- visit to the Lisbon Area Control Centre to watch air traffic controllers at work for one morning.

Though less intensively than during the first month, these activities were continued throughout the remainder of the project. This was because there was still much more to learn and during the project, a big step forward in the functions of the CFMU was made: up to April 1995, CFMU had mainly co-ordinating and longer term planning functions (strategic and pre-tactical); in April 1995 the tactical ATFM functions exercised by the five flow management units in Europe started being transferred to the CFMU, and TACT, the new computer system developed to support centralised ATFM, became fully operational. There was also a need to follow up some interviews to clarify opinions or obtain additional information.

At the end of the first month at the CFMU, the researcher wrote a report in which an attempt was made to draw the boundaries of re-routing control measures and redesign the project in what can be seen as the 'to negotiate the issues' and 'design the intervention' steps of the above OR method. The report addressed issues such as who the main parties involved in ATFM are, and where the authority for re-routing lies; it also outlined possible re-routing policies, and identified decision support needs. The report suggested that the final deliverable of the project be reviewed and scaled down from a re-routing programme to a re-routing demonstrator where different re-routing user functions, mainly intended for pre-tactical planning (Chapter 2), would be tested, and some exploratory examples shown. Development of the re-routing demonstrator had a two-fold objective:

1. to study the pre-feasibility of optimisation approaches to re-routing. Namely, conclude whether optimisation methods can be used and in what circumstances;
2. to develop a learning visual model to identify/elicit what the needs are in terms of re-routing decision support tools.

The user functions to be included in the demonstrator were based on the suggestions and views expressed by flow managers and from observation of current tasks. They ranged from the simple sorting of data, in terms of routes, to more complex functions which suggest which flows to re-route and onto which routes.

The report was well received within CFMU. It was reviewed by various CFMU senior managers namely the CFMU project manager, P. Jeannet and the director of CFMU, D. Duytschaever. The new project plan and the development of the re-routing demonstrator were approved and the project moved to the next step, developing models and software in, what can be seen in the above OR method, as the 'to analyse the issues' step. Initially, it was planned to incorporate some optimisation algorithms in the demonstrator, but it became clear that it would not be worthwhile to do so for two reasons: 1) most of the algorithms were already available in standard optimisation packages, and 2) the timescale was too short. Therefore, a standard optimisation package, GAMS/LAMPS, was used. The optimisation algorithms were applied to a bottleneck case based on data from three contiguous upper airspace sectors of Southern France: UM, H1H2 and N1N2, with the traffic which entered these sectors on 7/04/95 between 08.00 and 12.00 (for more details see Appendix C).

In June 1995, the researcher presented the results and conclusions to the CFMU, and handed in a final report together with the re-routing demonstrator. The report contained a rationale and description of the re-routing demonstrator functions. It also included an explanation of the models and algorithms that could be used to support each demonstrator function. Some of the functions needed just data sorting algorithms, others required the use of optimisation models. Results from the test of the models and algorithms using the above example were reported and discussed. The report concluded that 'optimisation methods can be of use in re-routing flights and can provide significant savings in delays' and identified the cases for which optimisation approaches were better suited. The re-routing demonstrator was a user interface, developed in Visual Basic, with a script, providing a visual image of different possibilities in terms of re-routing decision support (see Appendix A). Feedback from the flow managers was obtained. Given the exploratory nature and short duration of the project there was not an implementation phase. This marked the end of the intervention at the CFMU.

Reflecting on the intervention, it is clear that it succeeded in laying the foundations for the development of re-routing decision support tools and the use of optimisation approaches in re-routings. A shortcoming of the intervention was the lack of involvement in and commitment to the project of the users and other parties. However, considering the nature of the project and the context, this was difficult, if not impossible, to achieve. This was a secondee's project to be carried out exclusively by the researcher at a time when CFMU was launching their main computer system and people had little time to spare for other projects.

The management of expectations was also difficult. The researcher's expectations, to learn how European ATFM works in practice, to collect data, and to do exploratory work on the application of OR models to the re-routing of flights were fulfilled. However, at the CFMU, expectations of the research varied both from person to person and throughout the duration of the project. To start with the prevailing expectation appeared to be that this project, being a student secondment, was not going to produce anything of great significance to the CFMU. Later, and perhaps as communication lessened and anticipation built, over-expectations were engendered, and the researcher realised that it was expected she would produce a prototype of an operational computer programme for pre-tactical and tactical re-routings. This over-expectation can also be explained by the mounting pressure from the airlines who want the CFMU to offer re-routing of flights on a routine basis.

However, by the end of the project in June 1995, URS were happy with the achievements of the project. They intend to use the re-routing demonstrator in the production of the user requirements for a re-routing decision support tool. The project reports defining the issues and problems involved in re-routing control measures and in the use of optimisation models constituted an initial contribution to a research project at the EUROCONTROL Experimental Centre in France. This research project, which started in May 1995, with a team of nine people, and finished by December 1997, was aimed at producing a prototype of a decision support tool for pre-tactical and tactical re-routings. The project led to the development of a function illustrated in the re-routing demonstrator, a function to support re-routing of individual flights. The function uses the optimisation approach which was then recommended by the researcher.

The intervention at the CFMU prompted two interrelated questions for further research: 1) what would be the suitable level of automation of a re-routing DSS and how would the optimisation models fit in it; and 2) the optimisation models for re-routing flows (the most complex case) when applied to the three sector case were solved quickly; how would they behave when applied to a larger, more realistic airspace and air traffic.

To address the first question literature on DSS and automation was reviewed and the material collected during the intervention at the CFMU was analysed to identify the different views on automation and draw possible scenarios for the future of European ATFM. The optimisation results were also taken into account to ascertain how optimisation models would fit in a re-routing DSS.

To address the second question, the research focused first on the improvement and further development of the optimisation models and second on extending the models to the whole French upper airspace. The models initially developed at the CFMU were reformulated in order to become clearer and more efficient, both in terms of size and execution time. In addition, a more detailed model was developed. In May 1996, the researcher spent some days at the CFMU collecting French airspace maps and traffic data. The traffic data provided by all the flights which crossed French upper airspace on 25/04/96 between 04:00h and 22:00h was gathered. Preparation of the data for the optimisation, which involved the identification of sectors, routes, costs and the sorting of flights took approximately 5 months (Chapter 8 discusses this in more detail). The models were tested in January and February 1997. The analysis and discussion of the results prompted several extensions to the models. With the illustration and formulation of some of these extensions the core work under this line of research was concluded.

3.5 Conclusions

This chapter identifies the research contribution and defines the approach taken to attain it. The definition of a research approach is based on the literature survey of the nature of OR in Chapter 2, on the research approaches used in the social sciences and on the OR literature on model-building approaches. It defines the research approach on two interrelated levels: the degree of involvement with the CFMU and the research approach taken to build the decision support models. Given the exploratory and applied nature of the research and the favoured degree of involvement with the CFMU the research can best be described as 'action research', meaning a type of research where the researcher is based at the organisation obtaining results of practical interest to the organisation. The approach defined for the level of building decision support models stems also from the exploratory nature of this research: creative application, that is using existing methods (for instance, integer programming, linear programming) directly to address problems that have not been tackled before using those methods.

The fieldwork process and the OR intervention it comprises are described along with a change of OR paradigm from an 'OR as scientific techniques' view to an 'OR as socio-technical discipline' view. This change of paradigm resulted also in the need to use a different OR method which acknowledges the importance of understanding the context before structuring the OR intervention. That is the subject of the next chapter: to understand the context of European ATFM. This understanding is not only a necessary stage in an OR intervention but enables the structuring of decision problems and the development of decision support models for European ATFM.

Chapter 4

Understanding the Context of European Air Traffic Flow Management

4.1 Introduction

This chapter discusses the context of European ATFM. It responds to the need for research into the European ATFM context highlighted in Chapter 2. In addition, it provides the basis for defining the problems faced in re-routing control measures. In so doing, it also explores possibilities for the application of OR to European ATFM. It is based on fieldwork carried out in 1995 and 1996.

The next section provides a description of the origins and the making of EUROCONTROL and the CFMU. Section 3 explains how European ATFM works and identifies opportunities for the application of operational research. Section 4 describes the stakeholders in European ATFM and section 5 addresses the issues of authority and centralisation of European ATFM.

4.2 The EUROCONTROL Central Flow Management Unit

4.2.1 Historical Background

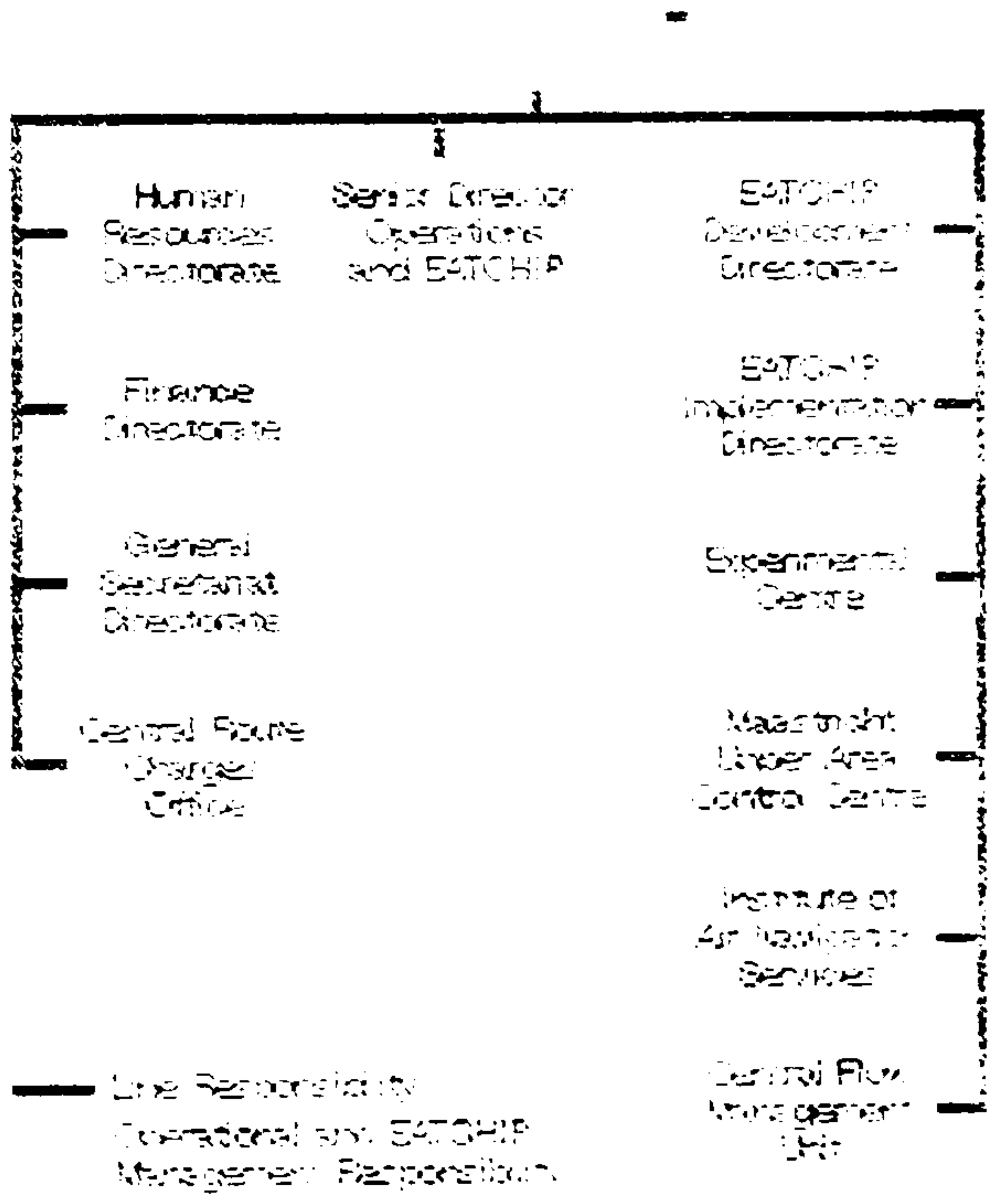
The CFMU is a directorate of EUROCONTROL,an European organisation which was founded by six European States (France, West Germany, UK, Belgium, Luxembourg and the Netherlands). The initial idea behind its creation was to reorganise the airspace into control sectors, not based on national criteria, which allowed for a better management of traffic. This would involve the creation of transnational control centres, which in a first phase would control the upper airspace of the member states (Mazé, 1994).

The EUROCONTROL control centre of Maastricht was created within this framework in 1972. It supervises the upper airspace of Belgium, Luxembourg, Netherlands and West Germany. This emphasis on European air traffic control integration was later, in 1981, softened because of the obstacles raised by the member-states in relinquishing control of their airspace to EUROCONTROL. The aim of integration of ATC systems has not been dropped but EUROCONTROL's role as supervisor of upper airspace is restricted to the area controlled by the Maastricht Centre.

At present, EUROCONTROL has a planning and co-ordinating role in European air traffic management. Its main objectives are:

- to plan European air traffic management to meet future needs;
- to optimise the use of airspace by matching capacity to demand.

In addition, as Duytschaever, the director of CFMU, puts it: 'EUROCONTROL provides expertise together with operational, experimental and training facilities to assist in the increase of ATC capacity to cope with the growth in air traffic.' (1993, p.343). The internal structure of EUROCONTROL is shown in Figure 4.2-1.



Source: www.eurocontrol.be

Figure 4.2-1: Internal Structure of EUROCONTROL

EUROCONTROL is engaged in other activities as well as flow management: For instance, EATCHIP, The European Air Traffic Control Harmonisation and Integration Programme, is a co-operative programme of the states belonging to the ECAC aimed at the integration of ATC procedures and systems in the ECAC area. A second example is the Experimental Centre. which undertakes studies for the member states and other units within EUROCONTROL. Studies undertaken range from real-time simulation exercises to test the effect of restructuring a control area on controllers workload to the use of model simulation to test the effectiveness of air traffic flow management algorithms. A third example is the Institute of Air Navigation Services which trains air traffic controllers and other professionals in the air traffic services. A final example is the Central Route Charges Office, which collects air traffic control charges on behalf of the EUROCONTROL member states.

The roots of European ATFM, and the CFMU, can be traced back to the late sixties, when the air traffic control system showed the first signs of congestion. Several steps were then taken, both by airlines and air traffic control services, in order to co-ordinate schedules, but they proved insufficient to cope with the increasing congestion. The first flow management units, as such, were created in France in 1972 and Germany in 1975. In the following years 12 flow management units became operational throughout Europe. Each flow management unit did the planning and issued flow control measures for the area control centres it covered.

It soon became clear that flow control measures could not be taken at a national level irrespective of the consequences they would have on the ATC systems of other states. Philipp and Gainche (1994) describe the situation created: 'This large number of national and sub-regional ATFM units has resulted in an unmanageable situation, as well as in severe communication and co-operation problems. The imposition of uncoordinated restrictions by the 12 units has detrimentally affected the overall ATFM service and has proved to be counter-productive. Local ATFM decisions were not based on a homogeneous. regional assessment of expected air traffic demand. Many delays have been caused by inadequacies of the ATFM service and not by the lack of ATC capacity' (p.5-5) and 'It had become clear that any permanent solution to the problems encountered could only be found on a region-wide scale and through concerted and concentrated efforts from all states and users concerned' (p.5-3).

A cornerstone in European ATFM was the International Civil Aviation Organisation (ICAO) special European Regional Air Navigation meeting, in June 1980, which recognised the need for a single integrated ATFM service in the European region, and established the main functions, concepts and elements of a standard ATFM service. The European ATFM of today is based on the model resulting from that meeting. Another important achievement of this ICAO meeting was the agreement to create an European Central Data Bank which would provide flight data and other information to all flow management units. This data bank was developed during the first half of the 1980s by EUROCONTROL, and became fully operational in 1987.

However, the very severe congestion problems and flight delays experienced in the 1980s appeared to have been the immediate events leading to the creation of centralised ATFM in Europe. ICAO in 1988, put forward a new concept for a centralised ATFM organisation. In brief, ICAO envisaged a European ATFM organisation comprising two Central Executive Units, covering Western and Eastern Europe respectively, and assisted by flow management positions (FMP) at every area control centre in Europe. The CFMU project is based on the ICAO centralised ATFM organisation concept corresponding to CFMU Central Executive Unit West. However, the political changes in East Europe and the delay in the launching of Central Executive Unit East, brought about an extension of the area of responsibility of the CFMU, which now also covers some East European Countries.

Also in 1988, the ministers of transport of the ECAC States entrusted EUROCONTROL with the development of a central flow management unit project. In July 1989, the creation of the CFMU was approved by the permanent commission of EUROCONTROL (formed by the civil aviation and defence ministers of EUROCONTROL member-states).

To ensure co-operation with all parties involved ATFM, a Flight Data and Flow Management group was created for the duration of CFMU implementation. This group was open to the civil aviation administrations of the ECAC states, the ICAO and representative aircraft operator organisations (e.g. International Air Transport Association, International Air Carrier Association, European Business Aviation Association). The CFMU met regularly with the Flight Data and Flow Management group to monitor and take decisions on future developments of the CFMU project. All members of the group had equal status.

In 1989, as an interim measure for the transition period, five core units were established in Frankfurt, London, Paris, Rome and Madrid. These flow management units worked together with the CFMU in order to provide a more integrated ATFM. The pre-tactical functions of these units were transferred to the CFMU during 1991/1992. The transfer of the tactical functions started in April 1995 with the closure of the Paris Flow Management Unit and finished in March 1996, when CFMU, assisted by the FMP, became the sole provider of ATFM in the ECAC area.

4.2.2 The Central Flow Management Unit Organisation and People

The functional organisation of CFMU (EUROCONTROL, 1993) is shown on Figure 4.2-2. CFMU has two main operational units:

1. The Central Executive Unit which is in charge of planning, co-ordinating, executing and monitoring ATFM measures;
2. The Flight Data Operations Division, which is in charge of the flight plan processing and of providing other data necessary for ATFM.

Both units are open 24 hours a day. The CFMU Central Executive Unit is assisted by the FMP located at the area control centres. They supply the CFMU Central Executive Unit with local information on capacity and the traffic situation and interface with the area control centre and the aircraft operators departing from the area. To work for the operational units of the CFMU, people have to have some background in the aviation world. To work as a flow manager for the

CFMU Central Executive Unit, a necessary condition is to have previous experience of work as an air traffic controller, experience in flow management is not necessary. Many flow managers had no experience of flow management when they joined the CFMU Central Executive Unit.

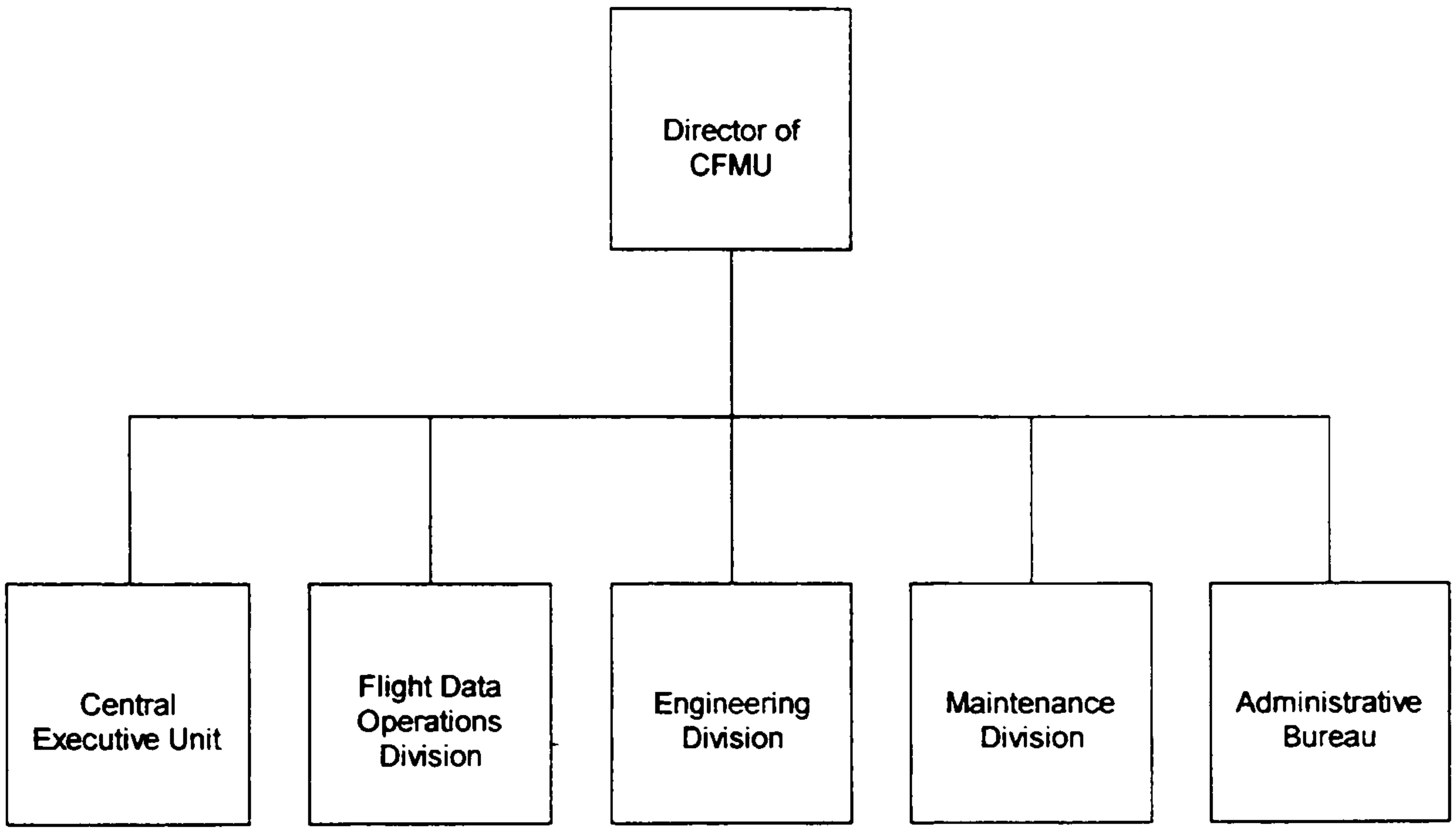


Figure 4.2-2: Organisation of CFMU

The Engineering Division is responsible for the development and operation of CFMU computer systems and other technical facilities and the Maintenance Division for its upkeep. The Administrative Bureau deals with personnel, finance and contract matters.

4.2.3 The Central Flow Management Unit Systems

The primary systems of CFMU are shown in Figure 4.2-3. The Strategic Database (STRAT) stores capacity and planned flight data up to six months in advance based on the information provided by the aircraft operators. It has been used for strategic and pre-tactical planning. The Initial Flight Plan Processing System (IFPS) takes in the flight plans filed by the aircraft operators, checks, corrects and distributes them to the ATC units involved in the flight. A copy of the processed flight plans is also sent to TACT. Flight plans which the computer system is unable to correct are edited by the flight data operations division staff working on shifts in the flight data operations room. For contingency reasons, the IFPS operations are shared between two units: one based in Brussels and one based in Bretigny (France).

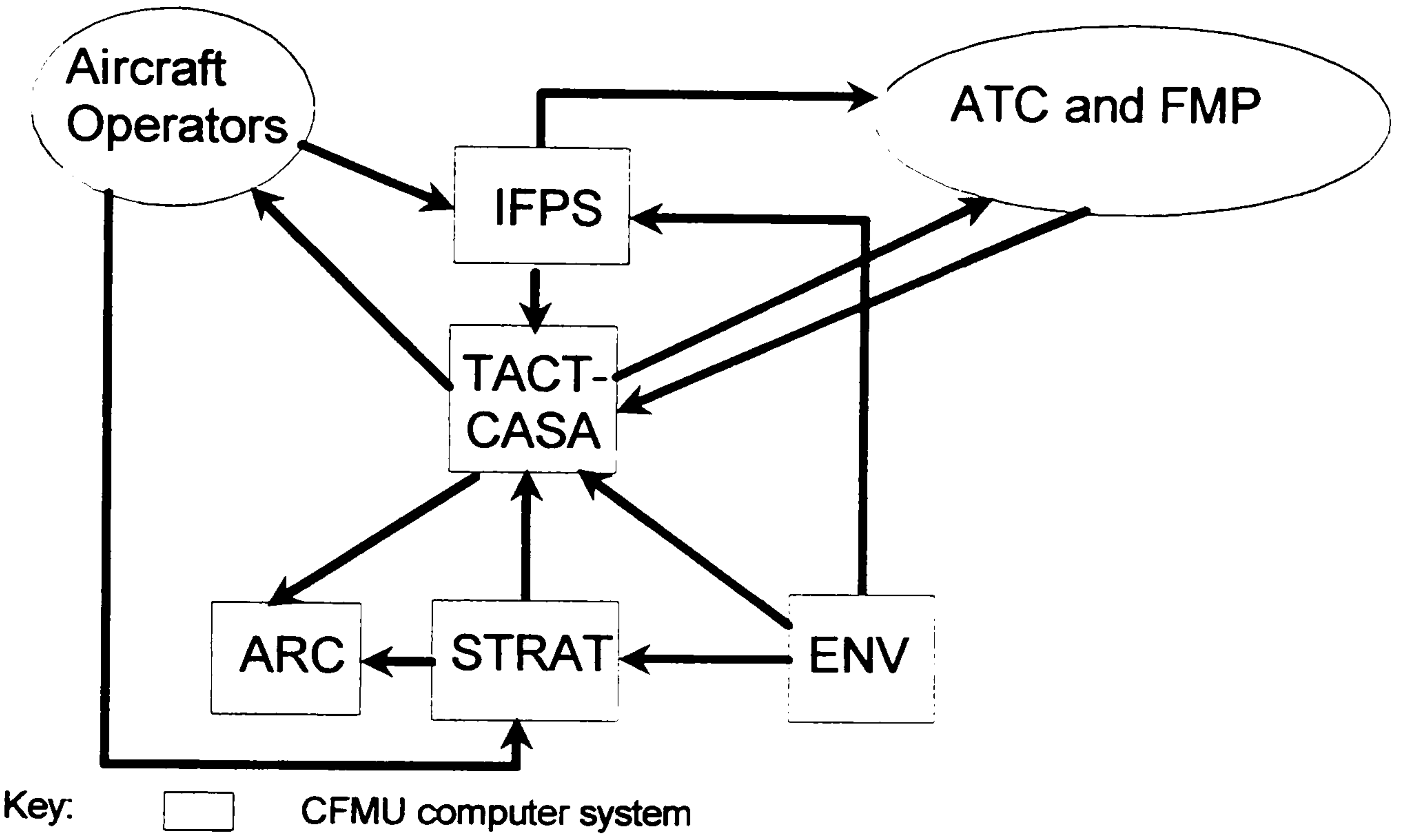


Figure 4.2-3: CFMU Systems

All the more permanent data necessary for ATFM, such as ATC units, aerodromes, air routes and other geographic data resides in the Environment Database (ENV). TACT is at the core of CFMU activities. It takes in the data supplied by the other systems and produces information and assistance for pre-tactical and tactical activities. It produces updated comparisons of traffic demand and capacity, it allows for the creation and monitoring of ATFM regulations and it automatically allocates departure slots to flights affected by regulations. The Archives System (ARC) is used for the provision of quality control statistics and for ATFM planning. It provides past traffic data for building more reliable traffic demand forecasts, to support strategic and pre-tactical planning.

A network is in place to connect CFMU systems with existing data communication facilities used by air traffic services and aircraft operators. An interface to CFMU systems is also available to be used by all FMP and aircraft operators who acquire the appropriate link (through British Telecom or the networks of the *Société Internationale de Télécommunication Aéronautiques*).

4.3 The Cycle of European Air Traffic Flow Management Activities

Three planning activities take place before a flight occurs: strategic (up to six months ahead), pre-tactical (2 days ahead) and tactical planning (on the day of the flight). Four main groups of stakeholders take part in these planning activities: aircraft operators, flow managers, air traffic controllers and, at a different level of decision national governments. Another group of stakeholders could be identified, the passengers, but they do not intervene directly nor as an organised group in air traffic flow management.

Aircraft operators can be considered the customers of ATFM since the CFMU is financed by the route charges they pay to EUROCONTROL Central Routes Charges Office. Flow managers are the main suppliers of ATFM control measures whose main purpose is to protect air traffic controllers from overloads. Therefore, many ATFM measures are negotiated with both aircraft operators and air traffic controllers. National governments influence many of the issues in ATC and ATFM but tend to intervene at a more strategic level.

4.3.1 Strategic Planning

The annual cycle of ATFM starts in the Autumn, after the Summer season (the Summer season goes from the end of April to the end of October). An ATFM co-ordination meeting, open to aircraft operators and flow managers throughout

Europe, is held to review the previous Summer season and lay the ground for the strategic planning of the next Summer season.

At this meeting, the CFMU Central Executive Unit presents a report where the performance of the ATFM service is assessed, the main problems experienced in the Summer are identified and actions to address them are suggested. Problems reported are usually major traffic bottlenecks in the European airspace, or problems encountered in the implementation of ATFM measures. The actions proposed to address bottlenecks range from re-routing of flows to the opening of air routes to some flows or increasing the capacity on certain key ATC sectors.

Following this meeting, a process of negotiations and planning activities starts to prepare the next Summer season. Aircraft operators send their planned flight operations to the CFMU where, at the Flight Data Operations Division, they are entered into STRAT. This, will provide traffic loads estimates for relevant points, sectors and aerodromes in the European airspace.

Then the Central Executive Unit, after consultation and discussions with aircraft operators and National Administrations, prepares what is called the Traffic Orientation Scheme (TOS). The TOS is a rule plan where routings for major traffic flows during the Summer season are laid down. It is aimed at getting a more balanced distribution of traffic in the European airspace. This has to be done in such a way that aircraft operators are not over-penalised with expensive detours from the best route and that there is fairness in the distribution of penalties.

In the TOS, flows are defined in terms of origin and destination areas. These areas can be a single airport, a pre-defined group of airports, a flight information region or a country. Flows can be further refined by adding an en-route point which flights overfly on their way to the destination area. Routings for a flow range from mandatory routes to the specification of no-go points. The TOS also contains off-load routes which can be activated whenever demand and capacity imbalances occur along the mandatory routes.

In February, another ATFM co-ordination meeting takes place to shape-up the strategic planning for that year. At this meeting the TOS for the coming Summer season is approved and will be later published by each state of the region. As a result, during the Summer peak periods defined in the TOS, all flights within Europe have to follow the mandatory routes specified in there unless changes are made at pre-tactical and tactical levels.

Along with the preparation of the TOS, other strategic planning activities take place, namely the co-ordination with airspace management. Airspace management has a longer term planning horizon than ATFM, and whereas ATFM focuses on getting the best use of a given capacity, airspace management concentrates on increasing the capacity of the air traffic system. Proposals from flow managers and aircraft operators are discussed with airspace management, ranging from the opening of new air routes or segments to a different organisation of ATC sectors.

Part of the contingency planning is also done within the framework of strategic planning. Contingency planning deals with events which result in serious disruptions of air traffic services and supporting services. These events might be sudden and unexpected such as a radar or computer system failure, or can be predicted sometime in advance, like a strike of air traffic controllers or the moving of an area control centre to new premises.

Contingency measures are usually temporary, lasting only for the duration of the disruption, until the air traffic services affected resume normal activities. However, some contingency measures in Europe have remained in effect for several years. Such is the case of the contingency arrangements prompted by the war in former Yugoslavia. There is a Contingency Routing Scheme in place which establishes mandatory routings in order to ease the severe traffic overloads resulting from the closure of parts of the airspace of former Yugoslavia. The annual review and preparation of the Contingency Routing Scheme follows the same stages as the TOS. Flights in flows affected by these measures have to follow the routes laid down in the Contingency Routing Scheme.

In the run up to and during the Summer season, alterations are made to the TOS and Contingency Routing Scheme, taking into account more recent information on ATC capacities and traffic demand. These alterations are usually discussed and co-ordinated with the parties concerned. The resulting measures are distributed in an ATFM information message or the daily ATFM notification message (ANM).

The staff who, on behalf of the CFMU Central Executive Unit attend these meetings, lead the negotiations and prepare the flow plans, are experienced flow managers, usually at the level of head or deputy head of operations. To prepare these plans they have practically no decision support tools. There is only the occasional simulation study done by the EUROCONTROL Experimental Centre (for instance, to test the impact of a specific routing). Therefore, decisions are made on the basis of their experience and some calculations using statistics of past traffic and the traffic forecasts provided by the Strategic Database.

The EUROCONTROL Experimental Centre simulation studies until recently relied on an adapted version of a simulator developed in the US: NASPAC - National Airspace System Performance Analysis Capability. This system was developed to support airspace planning helping in the analysis of capacity constraints and in evaluating potential solutions to airspace management problems. For example, NASPAC can simulate the system-wide effects of opening a new runway at a certain airport, changing airport procedures, or changing flow control restrictions (Frolow and Sinnott, 1989).

Recently, the Experimental Centre started using another simulator AMOC - ATFM MOdelling Capability. AMOC allows for the simulation of different configurations of ATC sectors, capacities and flight routes. It has been used in longer term ATM studies looking at European ATM in year 2006 (EUROCONTROL, 1997a) and in strategic planning at its interface with airspace management (EUROCONTROL, 1998): in the Winter 1997/98 it was used to estimate by how much capacity would need to grow in each of the ECAC area control centres in 1998 so as to maintain the 1997 levels of delay. Also recently, a more detailed simulator derived from the TACT test configuration, has become available at the Experimental Centre: TACOT - TACT Automated COmmand Tool. TACOT replays the operational log of TACT including all operator commands. Both these simulation tools have been mostly used to examine the feasibility of different ATFM policies or to access the impact of specific, one-off control measures rather than more routine planning.

A simple model outlining the reasoning behind the elaboration of a strategic flow plan is described below. It should be stressed that the steps described are not necessarily sequential and can take place more than once, throughout the preparation of the plan:

a) identify the major congestion problems;
b) investigate the reasons for these problems (e.g. inadequate scheduling, lack of ATC staff during peak time, major flows contributing to it);
c) identify obvious interdependencies between some of these problems, that is if decisions regarding one problem will affect other problems (e.g. Brest, Bordeaux and Marseilles, which are three adjacent control areas in Southern France). Group significantly interdependent problems;
d) devise routings of flows or other measures to alleviate or solve the problems;
e) assess the impact of the measures on the problems;
f) check for possible problems these measures could cause on other parts of the airspace and try to alleviate them.

It should be noted, that given the uncertainty of traffic forecasts a few months in advance, the tendency has been to move some of the planning from a few months to weeks or even days before the flights. For instance, some of the routings that had previously been defined in the TOS started being defined only weeks or days before the flights in plans sometimes called 'Mini-TOS'. In 1996, to address aircraft operators criticisms that the TOS was too rigid, and that in many circumstances mandatory routes were not needed. there were plans to replace the TOS by a more flexible scheme called Standard Routing Scheme (SRC). This scheme instead of pre-defining the daily periods of application of mandatory routes for the whole Summer season, would contain mandatory routes which would only be activated at the pre-tactical level to balance capacity with demand or at the tactical level if needed.

Potential Applications of Operational Research to Strategic Planning

The decisions at a strategic level, namely for the TOS, can be summarised in the following way: given a series of bottlenecks in the airspace how can they be alleviated to obtain a more balanced distribution of traffic while ensuring equity and avoiding over-penalising flights.

Potential applications of operational research are:

A. tools to produce **demand forecasts**, since the traffic demand forecasts available at present for strategic (and pre-tactical planning) do not provide a sufficiently accurate picture of the traffic demand. To obtain these forecasts two methods have been in use in ATFM practice: one based on traffic data of a similar day (called the reference day), another based on the planned flight data provided by the aircraft operators. Both methods have advantages and shortcomings:

  - The forecasts based solely on a similar day are not able to capture the variability of traffic demand; but given the periodicity of many flights can provide a workable estimate of how traffic is going to behave.
  - The forecasts based on planned flight data usually differ significantly from the actual traffic demand. This is due to all the cancellations, changes and new flights which are likely to be known only on the day of operations. To overcome this difference, uniform demand adjustment factors, based on empirical evidence are used. However, these factors do not appear to be enough to correct the deviations.

The case has been argued for a combination of both methods and for the improvement of the adjustment factor used. Whatever the direction taken, it is clear that, given the uncertainty of a significant part of the traffic demand, statistical methods have to be used.

B. **Simulation** to assess the impact of different measures on the congestion problems and the overall traffic situation. The simulation could be based on TACOT - TACT Automated COmmand Tool, with a user friendly interface, providing a visual image of relevant information such as bottlenecks, traffic loads on sectors and likely levels of ground-delay. The idea behind it would be to run, in fast time, a few *typical* Summer days of traffic trying different routings and comparing their impact on the traffic situation.

C. **Optimisation** to suggest which flows to allocate to which routes in order to get a more balanced distribution of traffic with minimum cost. Several modelling possibilities can be identified (see Chapter 7 for more details):

- **Network flow models** offer good insights into traffic flow management problems: the airspace can be modelled as a network, where the sources and sinks are airports or entry and exit points, the nodes are beacons and other navigational points, the arcs linking the nodes are air segments and the capacity is defined not on arcs but on sets of arcs, the ATC sectors. This model has to be expanded in order to take into account the time dimension of the problem.
- **Integer programming models** appear to be adequate to represent flow management problems, since the decisions to be made involve flights, that is discrete variables. Although integer models can be hard to solve, it should be noted that the level of

detail required to represent the decision problems in strategic planning is low and resolution time is not critical.

The optimisation models will work with a very simplified representation of the airspace. Therefore, one question arising is: given all the complex constraints and rules applying to the use of the airspace, will the routings obtained using the optimisation models be feasible in practice? To reply to this question a more detailed representation of the airspace will have to be considered. A possibility would be to combine the optimisation model with a more detailed simulation model that would enable flow managers to evaluate the feasibility of the routings.

Another possibility would be to use artificial intelligence techniques to capture rules and knowledge that cannot be incorporated into optimisation models. Several authors have explored the application of artificial intelligence techniques to air traffic control and air traffic flow management problems (see Chapter 2). Given the relevance of knowledge based on experience, expert systems appear to be adequate to diagnose and address strategic flow problems. The combined use of optimisation models and expert knowledge, is a possibility worth looking into.

4.3.2 Pre-tactical Planning

Pre-tactical planning takes place on the two days prior to the day of operations. It is an ATFM activity where methods and procedures are far from stabilised. In April 1995, TACT had just become operational and flow managers were still getting used to the system. Therefore, pre-tactical planning was a mixture of procedures from the time before TACT and a few tentative procedures which made some use of TACT. This section describes the operations as in April 1995 with additional comments on possible developments or foreseeable changes.

The main result of pre-tactical planning is the ATFM plan for the day of operations which is distributed to the aircraft operators and other air traffic services in the ANM. The preparation of the plan starts on day minus 2 counting from the day of operations. The first step is to identify possible congestion problems. To pinpoint these problems flow managers rely on the comments and requests for protection from the FMP, past knowledge on where congestion problems are likely to occur, and other information on events which might affect the traffic such as an international football match. The ATFM plan of the same day of the previous week constitutes also a good guide as to what to look for. Flow managers in the team doing the pre-tactical planning are assigned different problem areas to look at.

The ensuing comparison of ATC capacity with traffic demand is based on the forecasts provided by STRAT or statistics of the traffic recorded on the same day, the week before. Feedback from the FMP on previous plans is also considered. For instance, some area control centres might have experienced overloads, which were not forecast, and for which there was no protective measure in place. The capacities of the different ATC sectors are provided by the relevant area control centre, on the day or sometime in advance. The traffic demand forecasts, are obtained using one of two methods: one method is based on the planned flight data supplied by the aircraft operators, the other method relies on past data (see section 4.3.1).

Once potential overloads are identified, another phase, the preparation of preventive measures begins. Preventive measures range from negotiations with the area control centres/FMP to increase capacities or to open alternative routes for certain flows to slot allocation regulations. Increases in capacity are achieved by implementing or extending the opening time of different configurations of ATC sectors. A slot allocation regulation establishes a limit on the number of flights which can cross a certain element of the airspace, per period of time. At this stage no slots are allocated, the decision problems consist of deciding where to place regulations and which flows will be affected by the regulation. This is done by trying to assess the importance of each flow or by looking at similar past regulations. Experience-based rules laid down to assist in the preparation of regulations are also used. The regulations for the different areas are discussed with the FMP involved and when completed they are co-ordinated and put together, forming the ATFM plan.

On day minus 1, the ANM is prepared and the regulations are entered into TACT. TACT provides an estimate of the likely delays with the demand data then available, mostly planned flight data coming from STRAT. This demand data, is still going to undergo a lot of changes, and is treated cautiously. The ANM is organised by departure areas (i.e. flow management position area) and only those pages requested are sent to aircraft operators. For each departure area, validity date, day and time of release of the message, the restriction specific to departures from within that area, the flight levels affected and the time of validity of the restriction are provided. The ANM also includes the TACT estimates on likely delays and a list of restricted air routes which will be open on the day of the flights. Examples of restricted air routes, are routes in military airspace.

Pre-tactical planning is done by a team of around 8 to 10 flow managers in the CFMU Central Executive Unit operations room, where tactical ATFM also takes place. These teams work on shifts and do pre-tactical and tactical planning in turn. Each team has a supervisor, who usually is an experienced flow manager. The importance of having some experience in flow management is apparent at pre-tactical planning. Deciding where to place a regulation is not a straightforward task, especially if there are no simulation tools available. Redundant or inconsistent restrictions can create even more congestion in the system.

Many new developments are likely to occur in pre-tactical planning, namely in two areas: regulations and planning timescale.

Regulations

At present, flow managers are still strongly influenced by the work procedures and methods transferred from the different flow management units. Experienced flow managers, who used to work for these units, still think in terms of the flows and regulations they used to manage at the national level. However, as their knowledge of the European airspace as a whole widens, it is likely that new regulations making use of a European centralised ATFM will emerge.

Planning Timescale

As many ATFM regulations tend to remain the same for long periods of time, or follow a weekly pattern, it is possible to think of planning horizons other than two days before the day of operations. For example, provided capacities are known well in advance, and reliable traffic demand forecasts are available, pre-tactical planning could be done, say, on a weekly basis, with some fine-tuning on the day before the operations.

Potential Applications of Operational Research to Pre-tactical Planning

There are three layers of decisions at pre-tactical level:

1. What measures should be taken to prevent overloads: negotiation of increases in capacity with flow management position/area control centres, re-routing of flows, slot allocation regulations?
2. What flows to re-route onto what routes?
3. Where to place slot allocation regulations in order to: a) prevent overloads; b) minimise overall delay; and c) have a certain degree of fairness.

At pre-tactical level there is less uncertainty on the traffic demand and capacity than at strategic level but there is also less scope for changes in the orientation of traffic flows. ATFM cannot produce a whole new traffic orientation scheme for the European airspace everyday: there is insufficient time and it would not be worthwhile, since many of the congestion problems faced everyday are almost the same. Therefore, solutions tend to be more local and to follow a similar pattern.

The need for pre-tactical decision support tools is vast and urgent. As suggested for strategic planning, to re-route flows, both simulation and optimisation models appear to be useful. The optimisation problem consists of routing flows in order to minimise the cost of not taking the best routes and the cost of congestion. This problem is in some ways similar to the one defined for strategic routings, however, at pre-tactical level, decisions are defined more locally, for subsets of sectors, and tend to be more detailed in terms of time and airspace elements. Therefore, models for pre-tactical re-routings despite being more local than models for strategic planning, due to the level of detail, are likely to be larger.

It is possible to think of a stepwise approach to the development of tools to support the preparation of regulation plans. In a first stage, a simulation tool based almost directly on TACT, running with improved demand forecasts, where different regulation plans can be simulated. This tool has to have a strong visual component, for instance, showing on a map the traffic loads, levels of delay and the origins and destinations of traffic crossing the different airspace elements. The *Centre D'Etudes de La Navegation Aerienne* developed a tool to support pre-tactical planning in France, called SPORT, that had such a strong visual component (Planchon *et al.,* 1993). In a second stage, taking into account that many of the pre-tactical problems have a similar nature but are rarely identical, a case-based reasoning tool able to recognise 'similar' problems and to guide decision-making by looking at past situations could be developed. Bayles and Das (1994) showed that a case-based reasoning approach could be applied to ATFM in the US.

However, strategic and pre-tactical planning should not be thought of as two completely separate and unchanging levels of planning. As discussed some of the planning previously done at the strategic level is being moved towards pre-tactical level, and the timescale of pre-tactical level is likely to increase. Although the level of detail differs between strategic and pre-tactical planning, the concepts, objectives and logic are somewhat similar. Therefore, it is possible to have an integrated approach to the development of systems for both levels of planning. For example, the optimisation models outlined in section 4.3.1 could be aimed at both levels of planning with the in-built possibility of changing the level of detail in terms of time and space.

4.3.3 Tactical Planning

Tactical planning takes place on the day of the operations, until the departure of the flight. It is done 24 hours a day, in the main part of the CFMU Central Executive Unit operations room by teams of flow managers working on shifts. The operations room resembles an ATC operations room, with TACT screens instead of radar screens. Each TACT position is served by a phone and headphones are also available. The supervisors position, at the back of the other positions, is also served by a TACT terminal and a whole array of communications, such as a fax machine and Aeronautical Fixed Telecommunications Network and SITA terminals.

When the day starts, all regulations in place that day are already in TACT. These regulations will eventually result in the allocation of slots or ground-delays for the flights affected. The slot allocation is done automatically by CASA. Aircraft operators do not have to request a slot, the submission of the flight plan will be enough. In a situation where no regulations apply, flight plans have to be submitted up to one hour before departure. If there are regulations in place (announced in the ANM), flight plans will have to be filed three hours before departure. However, to know traffic demand in advance, CFMU has been urging the aircraft operators to file flight plans as soon as possible.

The CFMU Flight Data Operations Division has a system to process and save what are called repetitive flight plans, which are plans of regular flights that tend to have always the same key flight plan parameters. The Repetitive Flight Plans are sent to the CFMU by the aircraft operators, usually scheduled airlines, a few months before the season starts. This saves aircraft operators filing time and allows ATFM to have a better forecast of demand. Thus, if TACT on checking the flight plan route, identifies regulations affecting the flight, a departure slot for that flight will be issued automatically. Slots are allocated on a first-planned first-served basis. To ensure equity, some slots are put aside to cater for short-haul flights, which are usually planned later. If a flight is affected by more than one regulation it will be given the delay of the most penalising regulation. The departure slot is sent to the aircraft operator two hours before the scheduled departure. This slot might be improved later, for instance as a result of other flight cancellations. Aircraft operators can also request a modification to the slot if they cannot comply with it.

This fully automatic allocation of slots provided by CFMU is a new feature of European ATFM. For example, at the London Flow Management Unit, many slots were allocated by hand, using flight plan strips in the same fashion as in ATC operations rooms. For some exit points of the UK, software was developed, but only to help the flow manager to keep track of slots. The flow manager was responsible for allocating the slots.

At the CFMU Central Executive Unit, TACT allocates the slots and displays the traffic loads and delays for each control area. The main task of flow managers is to monitor the traffic in order, to prevent overloads and long delays. The supervisor distributes the regulations prepared at pre-tactical level among the flow managers in the team, usually according to area control centre or region. One of the more experienced flow managers is given a co-ordinating task, and two flow manager assistants staff the help desks, dealing with queries from aircraft operators, FMP and other air traffic services.

If overloads, not anticipated at the pre-tactical level, are in sight, the flow manager might either try to negotiate increases in capacity or create a new regulation, in co-ordination with the corresponding flow management position. If the overload is a backlog at the end of a regulation the flow manager might extend the time of the regulation. At times, regulations, which had been put in place at the pre-tactical level, turn out not to be needed, and are cancelled. If delays of a regulation are building up, flow managers might once again try to negotiate increases in capacity or co-ordinate re-routings with FMP/area control centres. The re-routing of a flight, in order to by-pass a regulated location, can reduce not only the delay of that flight but also the delays of the flights behind it in the slot queue.

The re-routing might involve a new horizontal route or it might be a vertical change. A vertical re-routing is done to avoid regulations that apply to certain altitudes. Typically, all flights request their optimum flight level, usually upper flight levels (above 24500 feet) even to fly short distances. This tends to overburden the upper airspace and gives rise to protective measures on these sectors. For short-haul flights taking the optimum flight level involves an ascent to the desired level and after a short while they start the descent. For ATC, flights climbing and descending are more difficult to handle than flights crossing a sector at a constant level. Therefore, vertical re-routings are frequently applied to short-haul flights.

The decision to re-route a flight is taken by aircraft operators. If they accept the re-routing, they have to cancel the flight plan on the old route and file a new flight plan. This has to be done very quickly as the new route, which a few moments before would mean a significantly shorter delay, might in a matter of minutes get new flights and the aircraft operator ends up with a longer delay than before the re-routing.

Despite its popularity among aircraft operators, the use of individual re-routings at the CFMU Central Executive Unit has been restricted. Most flow managers have little experience in re-routing, and TACT, for the time being, provides no support. Usually, only flow managers with previous experience at the flow management units feel confident enough to suggest re-routings.

An important part of tactical ATFM is communications, not only by computer links but also by phone. Flow managers spend a significant part of the time speaking to aircraft operators and the FMP. Aircraft operators often ring to ask for a better slot, or a re-routing, or just information on regulations. The FMP may phone to request protection, or ask for the extension of regulations.

Potential Applications of Operational Research to Tactical Planning

The decisions in tactical planning differ from the decisions in pre-tactical and strategic planning in the level of detail, timescale and volatility: tactical decisions apply to flights, take place a few hours before the flights in a very dynamic environment, where the traffic situation can change in a matter of minutes, whereas pre-tactical and strategic decisions apply to traffic flows and are taken days or months before the flights. Tactical decisions can be summarised as follows:

1. Given a set of regulations, how should ground-delays be allocated so that capacity constraints are not broken, delay is minimised and there is equity between flights?
2. How can a foreseeable overload be prevented: negotiating increases in capacity, extending or creating a regulation, re-routing flights?
3. How can the heavy delays of regulations be reduced: increasing capacity, re-routing flights?
4. How can the long delay of individual flights be reduced: increasing capacity, re-routing the flight?

CASA allocates ground-delays automatically on a first-planned-first-served rule. The allocation is done regulation by regulation, taking no account of the connections between flights. The research on optimisation models for the allocation of ground-delays is quite extensive, and mainly directed at the US case (see Chapter 2) but, as far as can be ascertained, it has not been applied in practice. This can be attributed partly to the realisation that using a cost objective function leads to inequity, that is favouring costlier flights in the allocation of ground-delays. In fact, the main difference between an optimisation model for each regulation and the CASA algorithm is not a reduction in total ground-delay but a different distribution of ground-delay among flights, according to cost.

However, it is likely that if the connections between flights were taken into account in the allocation of ground-delays, the total delay would be significantly reduced. Andreatta *et al.* (1994), present research on the use of priority rules based on connections between flights. The idea is to give a higher priority index, and therefore a shorter ground-delay to flights with more connections. Vranas (1994a, 1994b) present research on optimisation models for the allocation of ground-delays applying to a network of (congested) airports. Nevertheless, several difficulties will have to be looked into before going ahead with an algorithm of this type: 1) giving priority to flights with more connections raises again the problem of inequity between flights; 2) not all connections between flights are known in advance, since airlines have dynamic planning. The scheduling of resources changes during the day according to various factors, one of them being the ground-delays; and (3) an algorithm taking into account the connections between flights and regulations would be more time-consuming to run.

For decisions other than slot allocation, there is no computer support. Flow managers have been requesting a 'what if' possibility in TACT that would enable them to try out different re-routing and regulation measures (See Chapter 5 for more details).

At the tactical level, tools have to be sufficiently fast, detailed and flexible to be used in an operational environment, an environment where planning is very close to implementation. A case-based reasoning tool for typical contingency measures, such as the closure of an area control centre, could be useful. Simple optimisation methods combined with heuristics could also be applied to support the re-routing of individual flights. For instance, algorithms to find the *K-shortest* routes between two points could be combined with heuristics in order to identify quickly, in a regulation where delays are building up, which flights could be re-routed.

The operational research techniques often called soft OR, such as soft systems methodology, strategic choice, cognitive mapping or gaming can also be useful in European ATFM. European ATFM has many stakeholders with different views and often conflicting interests; it is still an open field, where many issues are far from defined. Soft OR can be particularly useful in the development of new systems to help structure and clarify problems, and to gain the commitment of the parties involved. For instance, it could be applied in the initial stages of the development of re-routing decision support tools in meetings involving the various stakeholders. These meetings would be aimed at defining issues such as the nature and functions of the re-routing tools and how to integrate them with existing systems and in the future European air traffic management environment.

4.4 Stakeholders in European Air Traffic Flow Management

Four main groups of stakeholders can be identified in European ATFM:

- aircraft operators;
- air traffic controllers;
- flow managers;

and at a different level of decision,

- national governments.

Another group of stakeholders could be identified, the passengers, but they do not intervene directly or as an organised group in air traffic flow management.

4.4.1 National Governments

National governments hold different views on air traffic flow management. There are governments who favour the integration of air traffic flow management in Europe, or going further down this path, integration of all air traffic control. Others express reservations, at least in specific areas. Control of the airspace is considered fundamental for the defence and economy of a nation. Some parallels can be drawn between the arguments raised for and against economic and political integration in Europe and the integration of air traffic flow management.

National governments influence many of the issues in air traffic control and/or air traffic flow management. Their priorities are in many situations prompted by factors beyond the scope of the air transportation system and are not easily negotiated. An extreme example of this is the war in former Yugoslavia which has generated more air traffic congestion in Europe.

4.4.2 Aircraft Operators

As noted, aircraft operators can be considered customers of ATFM since the CFMU is financed by the route charges they pay to the EUROCONTROL Central Routes Charges Office. Aircraft operators, where flight operations are concerned, want flights to proceed as scheduled, along the shortest route, at minimum cost. The weight given to each of these factors depends on the operator's policy: scheduled operators tend to put minimisation of ground delays, at the top of their priority list, whereas charter operators appear to give more importance to the minimisation of flight costs.

However, with the growth in the so-called ATC delays over recent years, and the difficulties involved in increasing the capacity of the ATC system, the reduction of delays appears to have moved up in priority for most aircraft operators. This move has generated some common ground with air traffic flow management: many aircraft operators are prepared to co-operate with air traffic flow management, at the expense of some flexibility as long as they think it will pay off in reduction of delays.

Aircraft operators have been involved in the CFMU project and appear to welcome the simplification of operations that centralised ATFM and TACT will provide. They were represented in a group which steered the implementation of the CFMU. There is also an Aircraft Operators liaison cell, with a permanent representation of International Air Transport Association and International Air Carrier Association, at the CFMU. However, some operators were concerned that the advisory tactical service provided by the flow management units would disappear when TACT and the CFMU became fully operational. The co-operative mood might also wane if aircraft operators do not see their delays being significantly reduced with TACT and/or if they do not understand the reason for regulations.

4.4.3 Air Traffic Controllers

Air traffic controllers have a more microscopic approach to traffic than flow managers: whereas flow managers have to ensure that the number of flights entering the various control sectors do not overload air traffic controllers, air traffic controllers' main job is to keep aircraft safely separated in the sector they are supervising.

To assess overloads, flow managers take into account reference values for capacity provided by the various air traffic control centres. However, capacity is a fuzzy variable, its definition varies from controller to controller, situation to situation. The capacity reference values provided to flow managers are of the type 'number of flights an ATC sector can accept per hour', and do not always take into account factors like the type of movements the controllers have to deal with, the changes of flight level or direction involved and the number of hours an air traffic controller has been working.

In addition, despite the fact that slot allocation tends to separate flights, there are still many instances of *bunching,* when a large number of the flights expected to cross a sector per hour, arrive within a few minutes of each other. These factors and the realisation that no matter how long flow managers spend planning, the number of flights crossing a sector in a certain period of time is bound to differ from the plan, create some tension between controllers and flow managers. As noted, the CFMU is assisted by FMP located at the area control centres to work as an interface with controllers. ATFM control measures are co-ordinated with the FMP.

4.4.4 Flow Managers

Flow managers tend to have different views on ATFM role according to whether they have worked at flow management units, doing the tactical planning, or at CEU doing the strategic and pre-tactical planning. Flow managers who have been doing tactical planning think more in terms of individual flights than in terms of flows or the global traffic situation. They tend to favour more flexible approaches to ATFM, where negotiations with airlines and ATC centres are common and the scheduling systems are usually manual. Some flow managers think that TACT will save time in co-ordination of air traffic flow management measures but are worried that it will be far more cumbersome and rigid, at tactical level, than the present de-centralised, manual system.

However, even within this group, there are also differences between the flow management units. Each flow management unit appears to have developed their own approach to air traffic flow management. At the London flow management unit there was practically no pre-tactical planning. They had a monthly flow management plan, where the main restrictions were defined and this plan was then adjusted on a daily basis, as needed. Their approach to tactical flow management, in the words of one of their flow managers, tended to be reactive, problems were solved as they happened, usually on an individual flight basis. One of the main objectives of the unit was to minimise the delay of each flight. Paris flow management unit, now closed, appeared to favour a more planned and systemic approach to problems. They tried to anticipate problems as much as possible, and take action to prevent them at pre-tactical level, on the two days before the flights take place.

Flow managers working for the CFMU, who have been concerned mostly with flows, and the global traffic situation in Europe, seem to favour more planned and integrated approaches to air traffic flow management. They also tend to support a more regulatory ATFM service: their reasoning is that if there is no authority behind ATFM control measures, these measures will not work: for example, aircraft operators will tend to fly the same congested shortest routes or try to arrive all at the same time at the same congested airport.

4.5 Authority and Organisation of Air Traffic Flow Management

A key issue in ATFM and its effectiveness is the authority of ATFM measures. At present, control measures such as the TOS, contingency routings and slot allocation are mandatory and usually complied with. Measures such as re-routing of flights are advisory and the decision is up to the aircraft operator.

However, there is an on-going debate on the adequacy of the present situation, and whether there should be more or less regulation. The argument against regulations basically contends that many regulations are unnecessary or bring too much rigidity into the system. For instance, some aircraft operators have criticised the TOS on that basis. If the routes in TOS become congested, the issuing of regulations on these routes faces more opposition from the airlines, who question the point of the mandatory routes. There has also been a tendency to use TOS extensively all year round: re-routings during off-peak periods have been known to be refused on the grounds that they do not comply with the TOS.

The underlying argument in favour of regulation can be depicted as follows: There is a need for a 'traffic regulator' in order to guarantee safety and a better and equitable use of the available system capacity. Without a 'regulator', airlines will tend to do what is best for them, and in so doing they increase overall congestion. For example, considering a flow re-routing decision: if airlines are not pressed into taking them, they will tend to fly the shortest route, sometimes even when risking long slot allocation delays. This happens either because they hope the situation will improve, for instance if others take the re-routing, and/or because they do not think the extra flying time will make the re-routing worthwhile. The problem is that by acting in this way, flights with some reasonable re-routing possibilities are delaying other flights with no alternative routes, thus worsening the overall traffic situation.

The extremes of this debate can be portrayed in two scenarios:

Hands-off Scenario: a scenario where ATFM has only an advisory and information-provider role. To address chronic congestion problems and balance traffic distribution, a variable pricing system, where airlines would have to pay more if flying on congested areas, could also be introduced.

Regulatory Scenario: in this scenario aircraft operators will just file the airports of departure and destination, type of aircraft, number of passengers and state their preferences. The ATFM service will provide the flight plan.

The present situation in Europe is somewhere in between, probably tending towards more regulation. It should be noted that ATFM authority will have to result from and rely on the co-operation of all stakeholders, especially aircraft operators.

Another important issue in ATFM and its effectiveness is the balance between centralised and local flow management. Given the complexity, uncertainty and volatility of the air traffic environment, not all decisions can be taken at the centralised top level. On the other hand, when de-centralising decision-making, adequate mechanisms have to be put in place to prevent mismanagement.

In Europe, there is some wariness of national-based flow management given the history of national-based obstacles to European co-ordinated flow control measures. The decision-making model is a centralised one, with practically all ATFM decisions taken at the CFMU Central Executive Unit in Brussels. The FMP located at the area control centres have mainly a consultative role. It is possible that, in time, some de-centralisation of decision-making will take place, so that the FMP may be able to take actions to handle local problems without the need for CFMU intervention.

4.6 Conclusions

This chapter describes of the European ATFM organisation, main activities and decisions, stakeholders and systems and identifies potential applications of operational research. ATFM is a planning service still in its early stages, aimed at preventing overloads and minimising overall delays by a balanced use of available capacity. The planning takes place at different points in time with a different timescope and level of detail. Accordingly, European ATFM activities are usually broken down into three phases of planning: Strategic, pre-tactical and tactical. Strategic planning takes place up to six months before the flights and is aimed at obtaining a balanced distribution of traffic in the European airspace. Pre-tactical planning takes place on the few days before the flights and its purpose is to prevent overloads. Tactical planning takes place on the day of the flights, a few hours before departures and in addition to preventing overloads it also tries to limit the extent of delays. However, these phases are not independent nor fixed, the distinction between strategic and pre-tactical planning can be blurred, especially with planning that takes place weeks before the flights. There has also been a tendency to move some of the plans previously done at strategic level to the pre-tactical level due to the uncertainty of traffic forecasts, a few months before the flights.

The creation of CFMU, in 1989, was brought about by the realisation that effective planning of air traffic, in Europe, could not be done on a national basis. CFMU manages traffic flows in the 36 European countries belonging to the ECAC area. The CFMU project has provided European ATFM with essential systems to assemble, store, process and display data. TACT, the core system, provides updated information on flights, traffic loads, regulations and delays. CFMU has also developed a computer tool for tactical planning, which allocates departure slots automatically, CASA. However, with European ATFM still lacking many decision support tools, operational research is barely used. Opportunities for the use of forecasting, simulation, optimisation and artificial intelligence techniques are identified.

This chapter provides a description of the European ATFM field and identifies potential applications for OR. Drawing on it, the next chapter moves to the next stage in this research: the problem setting for the re-routing of flights in Europe.

Chapter 5

Re-routing Flights in Europe - Problem Setting

5.1 Introduction

This chapter characterises re-routing control measures building upon the description of the context of European ATFM provided in Chapter 4 and bearing in mind the potential development of re-routing DSS. The chapter starts with a definition of the different types of re-routing control measures and then it looks into who has the authority in re-routing control measures. Given the uncertainty on how re-routing control measures and air traffic management at large are going to evolve, several scenarios in terms of authority are identified. Following this, the standpoints of the main stakeholders in a re-routing decision, aircraft operators and flow managers, are described covering the usage of re-routing control measures, the decision criteria used, the tools available and needed to support re-routing decisions. These views are complemented by a review of the decision criteria contained in the literature on optimisation models for the allocation of ground-delays. The review identifies decision criteria which can be transferred to re-routing decision support models.

5.2 Scope of Re-routing Control Measures

At present, re-routing control measures can be found at the three levels of planning in European ATFM, the strategic, the pre-tactical and the tactical levels. These control measures differ not only in timescale but in degrees of freedom and level of aggregation: At the strategic level the possibilities in terms of re-orientation of traffic flows are wider, but detailed data on individual flights is still scarce, therefore decisions are made for flows, sets of flights. At the pre-tactical level there is some scope for re-routing flows of traffic, but not major changes in orientation of traffic. At the tactical level, measures affect individual flights and unless there is a contingency situation there is no question of re-routing whole flows of traffic.

It should be stressed that re-routing control measures interact with slot allocation control measures: re-routing flights results in the airspace elements from the original route having less traffic, and the airspace elements crossed by the new route having more traffic. In brief, for airlines, re-routing their flights is a trade-off decision between the cost of not taking the best route and the cost of slot delays. For ATFM, re-routings constitute a means to: 1) ensure safety by protecting air traffic controllers from overloads; and 2) reduce overall delay by best use of the available capacity.

There are other re-routing measures which are not taken on a regular basis and are prompted by unusual events which result in severe losses of capacity or even closure of air traffic services: contingency re-routings.

At a more structural level another type of re-routing could be considered: (re)designing air routes and the associated air traffic control sectors in order to increase the capacity of the system. It is outside the scope of this research but cannot be ignored in the development of re-routing decision support systems.

5.3 Authority of Re-routing Control Measures

The issue of authority of ATFM measures is particularly relevant in the case of re-routings as the choice of a flight route is largely regarded as a commercial decision that is up to the aircraft operator. In November 1994, within the project at CFMU, three future scenarios, in terms of authority, were identified:

1. *Present Situation*: ATFM Routings are mandatory at strategic level and in contingency situations, at pre-tactical and tactical levels they are advisory. The decision is made by the aircraft operator This appears to be the scenario favoured by some aircraft operators and flow managers.
2. *Mandatory flow re-routings*: ATFM re-routings can be mandatory at strategic and pre-tactical level. That is, it will be possible to issue

mandatory routes for flights between a city-pair or any two points, a few days before the flights take place.

3. *Routes defined by ATFM:* in this scenario, aircraft operators will just file airport of departure, airport of destination, type of aircraft, number of passengers and state their preferences. The air traffic flow management system will provide the (mandatory) route. Some flow managers hold the view that ATFM should aim at this scenario.

The subsequent work on re-routings was carried out on the assumption that scenario 2 would come to pass. Recent developments in the direction of scenario 2 have confirmed this assumption. In the Summer of 1995, mandatory re-routings prepared with the co-operation of airlines were expected to be issued on a weekly basis to deal with congestion in Southern France. It should be stressed that the authority of re-routing measures will have to rely on the co-operation of all parties involved, in particular the aircraft operators.

5.4 Viewpoints on Re-routing Control Measures and Re-routing Decision Support Needs

This section describes the viewpoints of the main stakeholders in re-routing decisions: aircraft operators and flow managers. In addition, it defines the constraints imposed by other stakeholders in re-routing decisions: national administrations and air traffic controllers. This section results from observation of flow managers at work and interviews with flow managers and aircraft operators held during November 1994 and April 1995.

The observation of flow managers took place at the London Flow Management Unit and at the CFMU Central Executive Unit. The observation at the London Flow Management Unit consisted of shadowing a team of flow managers for two morning shifts in November 1994. The morning shifts were chosen because it is the time at which the North Atlantic traffic enters the British airspace, giving rise to re-routing control measures. The observation at the CFMU Central Executive Unit took place in November 1994, when the CFMU was still only responsible for the strategic and pre-tactical planning, and in April

1995, a few weeks after the CFMU started doing part of the tactical planning in the European airspace. In November, the observation consisted of shadowing a team of controllers doing the pre-tactical planning for two days. In April, a team of controllers was shadowed for four consecutive shifts doing the tactical and pre-tactical planning. The observation was complemented with interviews of senior flow managers at the CFMU Central Executive Unit and of flow managers working for the London, Paris, Frankfurt and Madrid Flow Management Units (these flow management units are now closed).

The following aircraft operators were interviewed in November and December 1994:

1. charter airlines: Air 2000 and Eurobelgian airlines;
2. scheduled airlines: British Airways and Sabena.

These interviews were later complemented with an interview at the EUROCONTROL Central Route Charges Office to learn how the route charges are calculated.

The observation and interviews sought the following information:

a) *Use of re-routing measures*: views on the usefulness of re-routing control measures: re-routing of flows and re-routing of individual flights, how often and in which circumstances flights are re-routed.

b) *Decision criteria and constraints*: the criteria used in re-routing decisions and the constraints applying to those decisions.

c) *Re-routing decision support tools*: the tools they have and would like to have to support re-routing decisions.

5.4.1 Use of Re-routings by Aircraft Operators

Flight re-routings, a few hours before the departure of the flight are frequently used by aircraft operators, specially the ones who have a well-organised operations service. Sabena, Eurobelgian Airlines and British Airways reckoned that on busy days 5 to 10% of their flights are re-routed, Air 2000 mentioned 15 to 20%.

In many situations, it is the aircraft operator who first suggests the re-routing, but they are happy to take up re-routings suggested by ATFM. The reductions in delay are usually substantial: at Sabena there were several examples of re-routings where, by avoiding a regulation, departure delays were reduced from 50 to 0 min, with approximately an extra 5 to 10 min of flying time.

As to views on flow re-routing measures, at pre-tactical and strategic levels, these airlines accept the necessity of the Traffic Orientation and Contingency Routing Schemes. They also think that mandatory re-routings are usually reasonable. This attitude suggests that mandatory flow re-routings at pre-tactical level, within certain limits, can be endorsed by airlines, if they think the re-routings are fair and delays can be significantly reduced.

5.4.2 Use of Re-routing Control Measures by Flow Managers

Flow managers tend to hold different views on re-routings according to their past experience and background. Many flow managers had no previous experience in re-routings when they joined the CFMU Central Executive Unit, others had experience gained at one of the European flow management units.

Flow managers at the flow management units did mostly re-routing of individual flights at tactical level whereas experienced flow managers at the CFMU Central Executive Unit have been mainly organising and co-ordinating flow re-routings at strategic and pre-tactical levels. This situation is changing as the different flow management units in Europe closed and their tactical responsibilities were transferred to the Central Executive Unit throughout 1995 and 1996. Viewpoints on flight re-routings appeared to vary between flow management units. The London flow management unit emphasised the role of flight re-routings as an advisory service they provide to flights with long slot allocation delay, whereas at the Paris flow management unit individual re-routings were usually avoided because they were seen as interfering with the overall planning and risk causing congestion problems not anticipated.

5.4.3 Aircraft Operators: Re-routing Decision Criteria and Constraints

Decision criteria in re-routings vary amongst aircraft operators: scheduled airlines such as Sabena and British Airways have on time departure as their main criterion. British Airways estimates that the cost of being late is very high and outweighs by far the cost of extra mileage or extra route charges incurred in a re-routing. Therefore, British Airways can sometimes take considerably longer routes to depart on time. The arrival delay which could result from these longer routes can be partially absorbed by increasing the speed of the flight. It should be noted that airlines do not disclose information on the concrete costs of re-routing and ground-delaying particular flights. The figures which are divulged are the total cost over a certain period.

Charter operators appear to have a different order of priorities. Their chief priority is to minimise operational costs. Therefore, route charges and extra fuel costs do bear a weight in any re-routing decision. Departure delay becomes a problem when it starts disrupting operations. This happens frequently during the Summer season when fleets are used in very tight schedules. Thus, charter operators when considering a re-routing balance the additional operational costs incurred with the re-routing against the reduction in slot allocation delay. Reportedly at Air 2000, for an additional flight, if route charges remain unchanged, it would take a 2 hour slot delay to make a 25 minute longer route attractive.

Air 2000 stresses the importance of route charges in a re-routing decision. They claim the ratio route charges/fuel costs has increased significantly over the past years. In fact, the extra route charges incurred in a re-routing are not proportional to the extra-mileage. At present, the EUROCONTROL Central Route Charges Office charges aircraft operators for standard routes between city-pairs not the routes actually flown by the flights. This standard route is statistically the most frequently used route (MFUR) between that city-pair during the previous year. Thus, if a flight is re-routed onto a route that is not the MFUR and crosses airspace of non-members of EUROCONTROL, airlines are overcharged for that part of the route. The extra-route charge will then depend on the length of the part of the route not in the MFUR nor in EUROCONTROL airspace. Airlines have been known to refuse re-routings due to this reason. However, as more countries join EUROCONTROL, this overcharging will tend to decrease. The number of EUROCONTROL member states increased from 18 in 1995 to 27 in 1998.

In arranging a re-routing, timing is crucial: the lag between the moment the enquiry about a route is made and the new flight plan is filed has to be as short as possible, otherwise the traffic situation might have already changed and flights end up with a slot allocation delay longer than before the re-routing.

In conclusion, the criterion to decide on the re-routing of a flight appears to be the reduction in ground-delay cost minus the cost of not taking the best route. The cost of not taking the best route includes the fuel cost, additional route charges and other operational costs caused by the re-routing. Fuel cost can be assumed to be proportional to distance at cruising speed. Route charges, as explained above, are not proportional to distance. The ground-delay cost of a flight can be affected by a wide range of factors such as:

1. the aircraft operator has a policy of departing on time;
2. the flight is a connection to other flights (e.g. London-Rome-Naples);
3. the aircraft used in the flight will be needed for other flights;
4. the flight is affected by constraints on crew assignments or working times.

Considering the above factors, the ground-delay cost function of a flight does not appear to be linear nor continuous. Given the *slacks*, or time intervals, airlines have in their scheduling and the psychological limits of certain waiting times for the passengers, a possibly better approximation to the cost function would be an interval function such as the one represented in Figure 5.4-1.

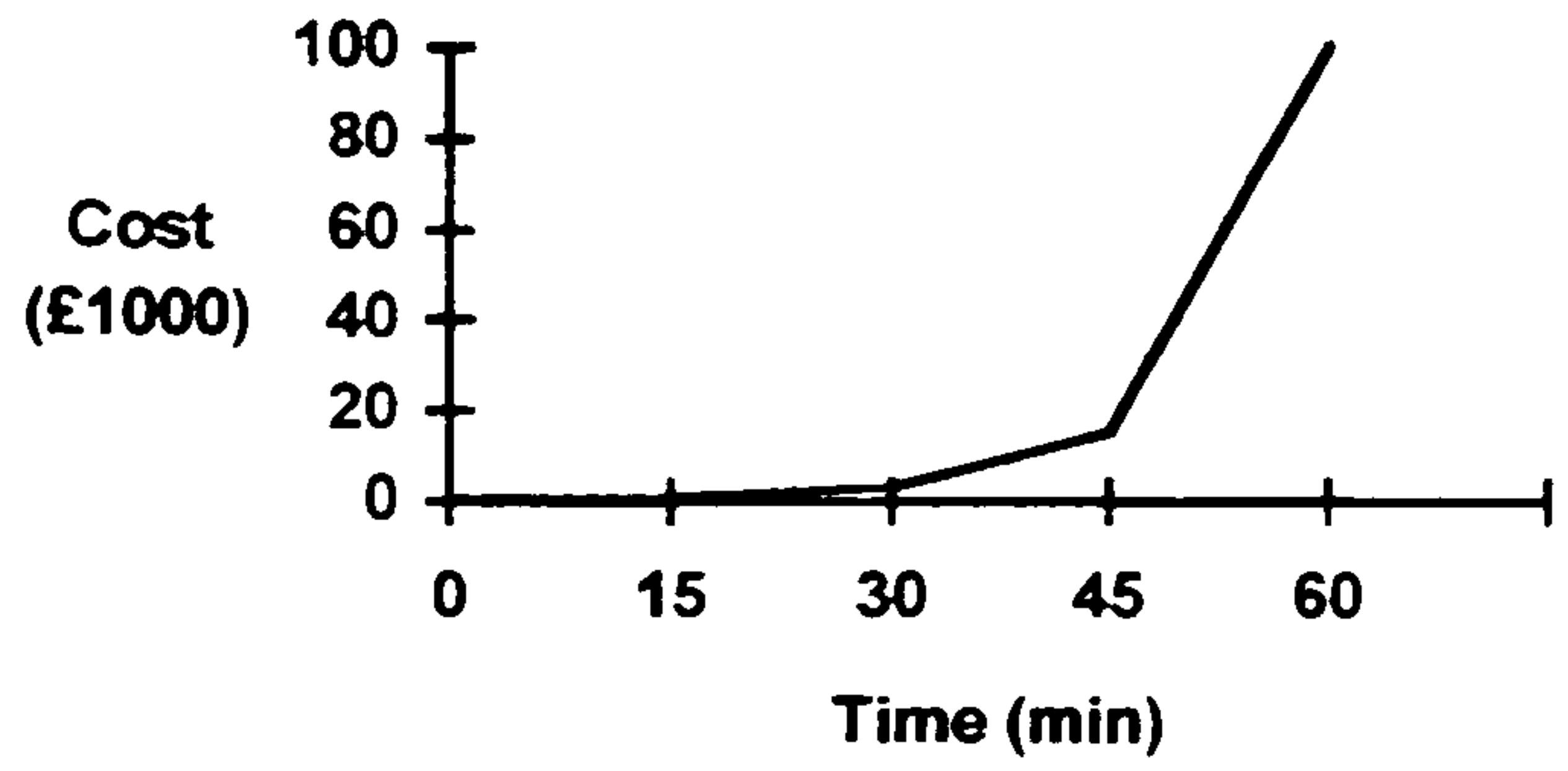


Figure 5.4-1: A Possible Ground-delay Cost Function

However, as noted above, these costs vary with the aircraft operator, the circumstances of that flight, and consequently are very difficult to calculate for each flight. Aircraft operators appear to approve the criterion used for slot allocation in European ATFM: flights are ordered on a first come first served basis.

5.4.4 Flow Managers: Re-routing Decision Criteria and Constraints

The re-routing decision criteria used by flow managers can be divided into two groups: criteria for re-routing individual flights and criteria for re-routing flows of traffic.

5.4.4.1 Re-routing Flights

Re-routing flights is typically a measure taken at tactical level, a few hours before the flights, when slot allocation delays are known. The re-routing can be first suggested by ATFM or the aircraft operator but, at present, the final decision to re-route a flight rests with the aircraft operator.

For a flight re-routing to become attractive to the aircraft operator the flight must have been allocated a significant slot delay. As explained above, what can be considered a significant slot delay is relative, it varies among airlines and from situation to situation. Some airlines interviewed mentioned delays of 30 minutes as a frequent threshold to start considering re-routings. On the ATFM side, thresholds for re-routings are also relative. Given that re-routing proposals are produced manually by flow managers, thresholds depend on how busy flow managers are, and on the delay situation. At the London flow management unit, on a quiet Winter day, flow managers proposed re-routings for flights with slot delays above 20 minutes, but on a busy day, the threshold would rise up to 60 minutes.

From ATFM point of view re-routing flights goes beyond the reduction in the slot delay of those flights, since they can also help to reduce overloads and improve traffic distribution. In ATFM practice, the first criterion used to select flights is the slot delay. Only flights with significant slot delays are considered for re-routings. It should be stressed, that if ATFM was only concerned with the overall delay situation, flights with short slot delays but with good alternative routes could also be considered for re-routing. However, for an airline to accept the inconvenience of a re-routing, the flight has to have been allocated a significant slot delay. For each flight selected, flow managers try to identify alternative routes. They are identified considering the approximate flying time and the slot delay the flight is likely to have on that route. Only flights whose reduction in slot delay is significantly greater than the extra-flying time caused by the re-routing are considered for re-routings. However, before suggesting a flight re-routing, the effect of each re-routing on the delays of the alternative route has to be assessed. A cautious policy, frequently used by flow managers, is to re-route flights only onto routes with no regulations, where there is capacity to accommodate them.

5.4.4.2 Re-routing Flows

These measures typically take place a few days before the flights, at pre-tactical level, when accurate traffic data is still not available. The definition of decision criteria for re-routing flows has further complications:

1. flows are formed by different flights with different priorities and costs;
2. decisions on re-routing of flows strongly interact with decisions on slot delays. Therefore, some measure or *proxy* of slot delay has to be included in the decision criterion;

3. re-routing decisions have to ensure equity between airspace users.

In ATFM practice, the approach taken can be explained as follows: first, identify what flows have acceptable alternative routes and then, within that set, decide which flows are to be re-routed. To identify alternative routes for a flow (step 1), the decision criterion is distance or an estimate of flying time. For example, for some of the contingency re-routings caused by the strike of air traffic controllers at the Marseilles centre, in the Summer of 1994, alternative routes were considered adequate if they did not imply a detour of more than approximately 10 minutes. The decision on which flows to re-route (step 2) is made on the basis of the routes available for each flow and the need to balance traffic distribution. This is an iterative decision process since the re-routing of a flow onto a certain route might require the re-routing of another flow in order to prevent overloads on the new route and the re-routings have to be agreed with the airlines' representatives and area control centres affected.

5.4.5 Aircraft Operators: Re-routing Decision Support Tools

Aircraft operators will be the ones paying, through the route charges, for the development of re-routing tools, and are directly affected by re-routing decisions. Airlines have flight planning systems which given a certain set of routes and weather forecasts provide the best route for a flight. The more sophisticated flight planning systems can provide a set of alternative routes from scratch. Air 2000 has even developed an in-house system to support re-routing decisions which rates routes according to what they call their variable cost. Variable cost is the difference between the route charges on the route and the route charges on EUROCONTROL MFUR.

Aircraft operators with a well equipped operations service know what the alternative routes are, the information they expect to get from ATFM is the delay situation on the different routes. Aircraft operators with fewer facilities expect to get information on both alternative routes and delay situation from the CFMU. All aircraft operators interviewed would like, and expect, the CFMU to have a re-routing function available to support tactical re-routings.

The aircraft operators interviewed do not oppose the development of tools to support pre-tactical and strategic re-routings. As explained in section 5.4.1, aircraft operators may endorse the development of these tools if they think the re-routings are fair and their delays are significantly reduced.

5.4.6 Flow Managers: Re-routing Decision Support Tools

Flow managers are the users of re-routing decision-support tools and the ones interacting with aircraft operators and area control centre/FMP whenever re-routings are being considered.

At the London flow management unit, where during the Summer season, the number of re-routings ranged from 20 to 90, flow managers evaluated flight re-routings manually. If there was a route on the air route chart which did not imply a long detour nor a long slot allocation delay and by-passed the regulation delaying the flight, they suggested it to the airline. Some flow managers with experience in flight re-routings do not appear to think there is a need for tools to support individual re-routings, whereas flow managers with no experience in re-routings would welcome a tool which could suggest to them alternative routes or even which flights to re-route. Flow managers preparing flow re-routings, at strategic and pre-tactical levels, have been insisting they urgently need simulation and decision aids to support re-routing control measures.

5.4.7 Air Traffic Controllers and National Governments Constraints on Re-routing Control Measures

National governments and air traffic controllers also influence re-routing decisions, especially at strategic and pre-tactical levels, when deciding on opening up new routes or on re-routing of significant flows.

For air traffic controllers what matters in a re-routing is not only the additional flights. The direction flights come from and take when crossing the sector, whether flights are climbing or descending or are going to make complicated or unusual turns are also important. An air traffic control team will find it comparatively more difficult to supervise a flow of traffic coming from an unusual direction than the same number of flights following a more usual route. Therefore, when considering re-routing measures, flow managers have to take into account, not only the capacity reference values supplied by the area control centre/flow management positions, but also the type of movements the re-routings might require. Because of this, flow re-routings are usually co-ordinated with the area control centre/flow management positions affected.

Beyond the intervention at the strategic level, national governments can indirectly affect re-routing decisions. For instance, to cross a certain airspace, airlines have to obtain diplomatic clearance from the national government and there are situations where airlines from some countries cannot cross the airspace of certain states for political reasons.

5.5 Decision Criteria in the Literature on Optimisation of Ground-delays

The definition of criteria for ATFM decision support models is not straightforward, given the diversity and large number of stakeholders and the difficulty in measuring the costs of delays. Decisions on re-routings can be even more complicated, since they affect slot delays and involve both costs of slot delays and routes. A survey of the decision criteria used in the literature on the optimisation of ground-delays follows.

Two factors have to be considered when assessing the feasibility of criteria to be used in decision support tools:

1. whether the criteria are accepted by the main stakeholders in the decision. In this case, the aircraft operators and the flow managers are the main stakeholders. A major factor in aircraft operators' acceptance is the existence of equity between aircraft operators.
2. whether there is information available and it is technically feasible to implement the criteria.

Authors developing optimisation models for ATFM have been considering a single aggregate cost criterion in optimisation models for the allocation of ground-delays. Various cost functions have been proposed, frequently associated with the type of optimisation model used: they range from a cost defined for each flight and period of delay reflecting the operational costs associated with that flight (Lindsay *et al.*, 1993; Vranas *et al.*, 1994a, 1994b), to a cost which depends on the flow of traffic and the element of the airspace reflecting different priorities in the use of the airspace (Bianco and Bielli, 1993; Bielli *et al.*, 1982; Helme, 1992), or a cost defined in terms of the type of aircraft used in the flight (Richetta and Odoni, 1993; Terrab and Odoni, 1993).

One way of estimating the delay cost function of a flight is to work with average aircraft operational costs (i.e. the sum of fuel, aircraft depreciation, maintenance and crew costs). This approach is frequently found in the literature (Andreatta *et al.*, 1993; Richetta and Odoni, 1993; Terrab and Odoni, 1993), where flights are split into three broad cost categories, according to the type of aircraft: general aviation and small commercial aircraft, narrow-body jets and wide-body jets. The cost of ground-delay is usually assumed to be half or less than half of the cost of airborne delay and it is assumed to be a non-linear function of delay. These assumptions are based on what are considered to be typical airline operational costs. The cost being a non-linear function of delay reflects the explosive increase in market costs caused by customer dissatisfaction, along with the operational costs incurred with lost connections, crew re-scheduling - and others when delay grows.

Another aspect that has been discussed in the literature is whether ATFM, when deciding on preventive measures, should take account of *connections* between flights. When a ground-delay is assigned to a flight, other flights can be affected: the next flight that is going to use that aircraft, flights that are registered as a connection for that flight, flights that are going to need the crew of that flight etc. The delay of this particular flight can affect not only the next *connected* flights but all subsequent flights on the chain of *connections*. Therefore, flights with a long chain of *connections* will tend to have a higher cost of delay than flights with fewer *connections*. Some of the optimisation models developed for the allocation of ground-delays take *connections* into account (Andreatta and Brunetta, 1994; Vranas *et al.*, 1994a, 1994b).

Applying the above mentioned feasibility factors, it is clear that a cost criterion will not be easily accepted by aircraft operators on the grounds that. by favouring costly flights, it leads to inequity. The reasoning behind this type of inequity is that in a congested airspace flights using larger aircraft, carrying more passengers, and long-haul flights, should have priority. In ground-delay optimisation models, to avoid extremely unequal situations, limits have been imposed on the maximum ground-delay of flights (Vranas, 1996; Vranas *et al.*, 1994a, 1994b). However, at present, the principle of equity between airspace users appears to be too ingrained in the air traffic management system for cost criteria to be accepted by aircraft operators.

Assessing the technical feasibility of including *connections* in the optimisation models, in ATFM practice, it would be difficult to know, several hours in advance, all the *connections* of a flight. Official connections between flights (e.g.: Lisbon-Zurich-Helsinki) are known well in advance and tend to be permanent but aircraft and crew scheduling *connections* are adjusted dynamically by airlines, as needed. Some of the *connections* are even adjusted as a result of slot allocation regulations. Therefore, at present, in many situations, an airline does not know, several hours in advance, how much the delay of a particular flight will cost nor all its *connections*. Even if airlines have estimates of these variables it does not follow they will be willing to share them with ATFM. Airlines might consider the information as confidential and sensitive.

Another factor in the acceptance of decision criteria is that they have to be understood by flow managers and aircraft operators. As remarked in Chapter 2, mathematically complicated or obscure criteria will tend to be regarded with more suspicion. Addressing this issue, Andreatta *et al.* (1994) have proposed an heuristic approach to ground-delay problems which is based on what they call priority rules. A priority rule can be specified by a priority table with as many columns as types of flights and as many rows as the possible number of delay periods. Each flight has a priority index resulting from its type and the ground-delay it has already suffered. The authors present examples where flights are classified according to whether they have *successors*, that is connections with other flights, and priority is given to flights with more ground-delay periods and with *successors*. However, other priority rules could be used, such as, the number of flight passengers (EUROCONTROL, 1997b). While this approach would be more easily understood by the different stakeholders, it needs to be carefully investigated because it can also raise concerns about equity between aircraft operators.

In ATFM practice, equity between flights has prevailed over any other decision criterion. Both in the US and in Europe delays are allocated on a first come first served basis. In the re-routing demonstrator presented in Chapter 6 two types of criteria are illustrated: delay cost and delay time. The optimisation models for the re-routing of air traffic flows presented in Chapter 7 incorporate several possibilities in terms of ground-delay cost functions. Some of the functions used were adapted from (Richetta and Odoni, 1993). However, in order to insure that all flights are treated equally, all flights are assumed to have the same ground-delay and re-routing cost functions.

5.6 Conclusions

This chapter has provided a description of the problem setting for re-routing control measures in Europe, bearing in mind the development of re-routing decision support tools. The different types of re-routing control measures were identified at strategic (routing flows for the season), pre-tactical (re-routing flows to prevent overloads), tactical (re-routing flights) and contingency levels of European ATFM.

The development of re-routing decision support tools has to take into account not only the present environment but also the changes that are likely to take place within the next two to five years. One of the areas where there is considerable uncertainty is the authority flow managers at the CFMU are going to have in the implementation of re-routing control measures. Several scenarios were considered and the one which appeared to be more likely was selected:

scenario where pre-tactical and strategic flow re-routings will be mandatory and the re-routing of individual flights is decided by the aircraft operator.

Interviews were conducted with aircraft operators and flow managers in order to learn their views on re-routing control measures and re-routing decision support needs. The decision criteria used in the literature on ground-delay optimisation models were surveyed and their acceptance by stakeholders and their technical feasibility discussed.

The information collected in the interviews with flow managers and aircraft operators and in the observation of flow managers at work enables the identification of various decision support possibilities and models. The next chapter describes a re-routing demonstrator that, drawing on this chapter, illustrates different re-routing decision support functions.

Chapter 6

Initial Steps in the Design of Re-routing Decision Support Systems - A Re-routing Demonstrator

6.1 Introduction

This chapter focuses on the initial steps in the design re-routing of decision support systems. It is based on Chapter 5 which structured the problems faced in the re-routing of flights in Europe. The chapter provides a framework for the development of re-routing decision support systems and a basis for the decision models presented in Chapter 7.

The chapter starts by identifying the participants in re-routing DSS. The concept and need for a re-routing demonstrator are then explained bringing together literature on systems development and air traffic management. Following this, the re-routing demonstrator is discussed as a first step in the development of DSS. A re-routing demonstrator developed during the intervention at the CFMU is described. The feedback on the re-routing demonstrator obtained from users and other participants is then presented. Using the demonstrator functions, issues of automation and complexity of re-routing DSS are discussed. Finally, the integration of re-routing DSS in the future air traffic management system is briefly addressed.

6.2 Participants in Re-routing Decision Support Systems

The participants in the development and operation of a DSS have been defined in different ways. Turban (1990) considers the following:

1. The user, who is usually the decision-maker.

2. The intermediary, who helps the decision-maker to use the system or who manipulates the system on behalf of the decision maker. This role was more relevant in DSS early days, when systems were not very user-friendly. However, such 'chauffeured' use of systems is a feature of top management use of DSS.
3. The DSS builder.
4. The technical support person who assists in the development and maintains the system.
5. The toolsmith who provides tools that improve the efficiency and effectiveness of the DSS.

Alter (1980), in contrast, considers five roles: a user who communicates directly with the DSS in either an on-line or off-line mode, a decision-maker who makes decisions by using the output of the DSS, an intermediary who interprets the output of a DSS for the decision-maker and a maintainer who maintains the technical aspects of the DSS.

Bidgoli (1989) stresses the overlaps among these roles and how dependent they are on the scope of the problem under investigation. He considers three roles for the design, implementation and utilisation of a DSS:

- User - the individual, department, or other organisational unit for whom the DSS is designed. The DSS will have to address and meet the requirements of the user.
- Designer - this role may be further divided into two:
  - Managerial designer who defines the management issues related to a DSS.
  - Technical designer who is concerned with the technical issues related to the DSS design and use.
- Intermediary - who is the liaison between the user and the DSS. During the design phase the intermediary may explain the user's needs

to the designer of the system. At a later phase, the intermediary may explain the assumptions and limitations of the system to the user.

Bidgoli's definition of roles and distinction between decision-maker and user is useful for the context of European ATFM. Applying it to the European ATFM environment, the different participants in the development of Re-routing DSS can be identified as follows:

1. The users are the flow managers based at the CFMU in Brussels. As noted in Chapter 5, flow managers have differing levels of experience.
2. There are two groups of decision-makers in re-routing control measures: the flow managers and the airlines. In addition, there are other groups who can also influence re-routing decision-making: air traffic controllers and national administrations. Therefore, the re-routing DSS should support both decision-makers and take into account the constraints imposed by other groups.
3. The designer of a Re-routing DSS is, in a first stage, the EUROCONTROL Experimental Centre in France and, in a second stage, the software team in charge of the development of the system.
4. The intermediary is the CFMU User Requirements Section.

Taking into account the roles of the different participants, it is then possible to start to define the functions of a re-routing DSS. After canvassing the views on Re-routing DSS expressed by users, the airlines and URS staff it became clear that a re-routing demonstrator would be needed. That constitutes the focus of the next section.

6.3 The Need for a Re-routing Demonstrator

In this section, the need for a re-routing demonstrator is expanded bringing together the systems development and air traffic management literature on prototypes. The differences between the re-routing demonstrator and a prototype are also discussed.

A prototype of a system is a 'quick and dirty' version of that system. Turban describes two types of prototypes: the 'throwaway' and the 'evolutionary'. The 'throwaway' is a pilot test programme which is developed to achieve a better understanding of the system performance and users requirements. Once the pilot test is completed, the prototype is discarded and the design starts. The 'evolutionary' prototype, is a mini-system that is refined iteratively. over a long trial period. In practice, a prototype approach may have elements of both prototypes, some parts are discarded and redesigned, others are used in the design of the final system.

Turban (1990) considers there to be five distinct features of prototyping:

1. learning is explicitly integrated into the design process;
2. short intervals between iterations of the prototype;
3. involvement of users. The users provide the expertise and are key players in the successful implementation of the system;
4. initial prototype must be 'low cost';
5. prototyping by-passes the life-cycle stage of information requirements definition. It allows requirements to evolve as experience is gained.

Other authors also emphasise the learning role of prototypes. Avison and Fitzgerald (1988) see prototypes as learning models and aids to the design of systems and argue that with a prototype the users can discover what they want from the system and learn what is feasible. They add that prototyping can be an iterative process, by which users' suggestions and requirements are, step by step, incorporated into the prototype. They also identify the situations where prototypes are particularly useful:

- The application area is not well defined.

- The cost of rejection by users would be very high and it is essential to ensure that the final version has got users' needs right.

- There is a requirement to assess the impact of prospective information systems.' (Avison and Fitzgerald, 1988, p.40)

When compared with conventional feasibility studies prototypes have the advantages of: 1) being cheaper than a feasibility study; 2) moving the project forward in that a basic system is available for use and the logic and structure of the DSS already implemented; and 3) being concrete whereas the feasibility study is an abstraction (Keen, 1989).

However, several authors have also pointed out potential shortcomings of prototyping. Alter (1996) lists the following potential disadvantages of prototyping:

- It may encourage inadequate problem analysis. Prototypes may encourage the overlooking of the systems analysis stage of a project.
- Users may not give up the prototype, thinking that it is an adequate version of the final system. It may also generate confusion about whether or not the system is complete and maintainable.
- It may require 'superprogrammers', programmers who are able to work with different prototyping tools and programming languages.

To manage user expectations, Mallach (1994) recommends that developers must take time to point out to the users the missing features of a prototype and explain what would happen if they were skipped. Long (1989) adds that prototyping may require greater involvement of key users who are already busy with their work and that the shortcuts involved in prototytping sometimes undermine the final system's technical foundations. This last problem is also mentioned by McLeod (1990) who highlights that the emphasis on speed which is characteristic of prototyping may lead to inadequate controls in terms of cost and documentation. However, the author is of the opinion that proper project management and a policy of establishing and enforcing budget limits and documentation standards can prevent these problems. Prototyping can also extend the development schedule because of a tendency to make minute changes to the prototype which do not really improve the usability of the tool (Mallach, 1994).

The importance of prototyping is also well recognised in the air traffic management field. The director of the FAA Aviation Research (Zellweger, 1995) highlights the role of prototyping in reducing the risk of system development:

> 'Prototyping lets us explore how to best implement a new concept or how to build a system during all phases of system development - from early research to detailed design. It allows us to address and resolve many of the major risks in the early stages of a programme. In essence, we can study how a proposed system of people and machines will behave before we have to make firm design decisions that could be very difficult and costly to change later.' (p.9)

Other ATM researchers, for example, Hansman *et al.* (1995) present prototyping as one of the key elements in the integrated Human Centred systems approach. This is an approach where the human is considered 'as a functional component of the closed loop information system.' (Hansman *et al.*, 1995, p.1). They stress the role of a prototype in the exploration of different system options.

Another important function of prototyping is to encourage user participation in the design and development of the system, and, thereby, increase user commitment to the system. Hansman *et al.* (1995) write of *ownership* of a new system that a user community will have if involved early in the development of the system. However, there are different degrees of user participation in systems development: the user might just have a consultative role, with the systems analyst making the decisions and specifying the system, or the user might have a decision-making role with the systems analyst having more of a *facilitator* role. Avison and Fitzgerald (1988) identify two diverse views of systems development: the conventional versus the human-oriented:

> 'The conventional view specialises in aspects of technology, whereas the human-oriented view is more interested in the organisation as a whole and the user as a creator in that environment.' (p.38)

This view is also related to the socio-technical approach of the social sciences (Avison and Fitzgerald, 1988) which recognises the interaction of technology and people in any technical system and the need to optimise them jointly. In Avison and Fitzgerald's view this approach can lead to systems that are not necessarily the most efficient from a technical viewpoint but which work better in practice.

The re-routing demonstrator was conceived within this theoretical framework, as a learning tool to explore different function and levels of aid with the users, the flow managers. Its need stems from the following factors: 1) the users (flow managers) of a re-routing tool have differing levels of experience and, therefore, different needs in terms of decision support; 2) a new system, of centralised flow management, has been launched and the knowledge base for re-routing control measures is still being built; and 3) there are different views on the degree of automation and functions appropriate to a re-routing tool.

The re-routing demonstrator provides a visual image, on a computer screen, of different re-routing decision support possibilities. It follows a script based on a real traffic situation observed in Europe. It differs from a prototype in the following:

- It offers different decision support possibilities rather than a 'version 0' of a future re-routing DSS. The demonstrator functions may result in a separate re-routing DSS (for instance, a pre-tactical re-routings DSS and a tactical re-routings DSS).
- Only part of the algorithms behind the functions are embedded in the demonstrator.

However, the demonstrator has many features in common with the 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.

6.4 The Re-routing Demonstrator Functions

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

Routes

1. **Route Congestion.** This function answers a query where the flow manager, already knowing the routes, is interested in just getting updated information on the nature of the delays, at a certain time, on a certain route. Given a route, a departure time and a reference speed, the function provides an estimate of the slot delay on that route. If there are no regulations affecting the route, the function provides the capacity still available on that route, that is how many flights may be added onto the route.

2. **Alternative Routes.** This function addresses the situation where the flow manager needs to know the alternative routes from point A to point B avoiding certain (congested) airspace elements. The maximum number of alternative routes provided in the demonstrator is four. The routes are selected according to flying time and the user can specify maximum flying time.

Re-routing Flights - Tactical ATFM

3. **Routes for Flights.** This function addresses the situation in which the flow manager is trying to reduce the slot delay of a particular flight and needs to know alternative routes for that flight.

4. **Which Flights to Re-route.** This function addresses the situation in which, given a seriously congested traffic volume, flow managers need to identify quickly, which flights could be re-routed, that is, which have good alternative routes. The function provides a list of flights that could be re-routed.

Re-routing Flows - Pre-tactical ATFM

5. **Routes for Flows.** This function addresses the situation when the flow manager has already defined which flow(s) to re-route and needs to know to which routes to allocate these flows in order to minimise overall delay. Given an airspace region, and a set of flows to re-route, this function assigns a route to each flow.
6. **Which Flows to Re-route.** This function addresses a situation where flow managers need to know both which flows to re-route and onto which routes. Given an airspace region with serious congestion problems, this function provides a list of flows to re-route and the corresponding routes.
7. **Contingency Re-routings.** a function identical to 6) but prompted by a contingency situation, where the capacity of an airspace element is substantially reduced.

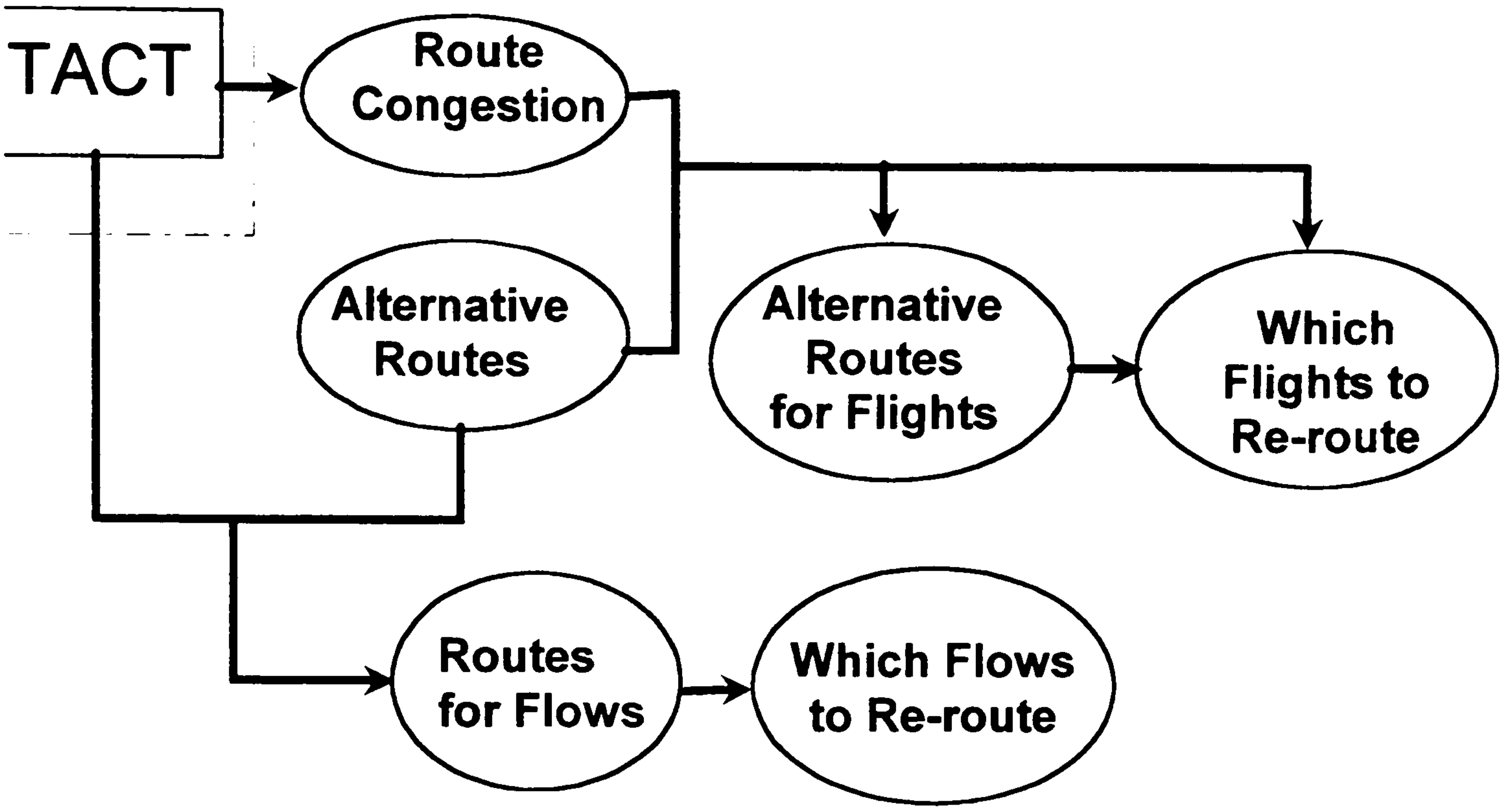


Figure 6.4-1: Structure of the Demonstrator

The demonstrator was developed using Visual Basic. Its main windows are shown in Appendix A. Figure 6.4-1 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 algorithms identified to support the functions providing information on routes and the functions for the re-routing of flights are outlined as follows:

1. **Route Congestion**: this is a sorting function which can be based entirely on data available within CFMU's computer system TACT:
    - If there are no regulations on the route, it takes the minimum available capacity of all the capacitated airspace elements crossed by the route.
    - If any of the airspace elements crossed by the route are regulated, it takes the delay of the most penalising regulation. It could be a 'what if' slot allocation or, if this is not possible, the

most recent estimate of the average or the maximum delay of the most penalising regulation can be used.

2. **Alternative Routes**: This function can be implemented using standard 'Shortest Route' algorithms which are efficient in terms of both execution time and storage space. In Appendix B, an outline of the model and algorithm identified for the re-routing demonstrator is provided. Two decision criteria were used in the demonstrator to select the routes: one based on flying time and the other on the cost of re-routing.

3. **Routes for Flights:** The routes are chosen using the following weighted time criterion:

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

where d_{i0} is the slot delay of flight i on the initial route, d_{ij} is the slot 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 slot delay and flying time. In the examples shown on the demonstrator $w1 = 0.5$ and $w2 = 1$. This function makes a combined use of the functions <Route Congestion> and <Alternative Routes>.

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

   - Flights whose slot delay is longer than 45 minutes.
   - Flights with alternative routes whose flying time is less than the maximum flying time specified.
   - Flights whose alternative routes have capacity to accommodate them on a first come first served basis.

For each flight filtered the best route is selected. The flights are then sorted by decreasing order using function (1).

The functions to re-route flows are more complex. Chapter 7 discusses different modelling approaches for these functions and provide three optimisation models developed to support them. It should be pointed out that these functions make use of the function <Alternative Routes> to identify routes for flows. Two decision criteria are used in the demonstrator:

- total flying time versus total slot delay;
- aggregate cost of re-routing versus aggregate cost of slot delay. It is assumed that all flights have the same unit cost of delay and the same unit cost of re-routing.

6.5 Feedback from Users and Other Participants

The demonstrator was shown to flow managers and to staff from the CFMU URS. The flow managers said they found all the demonstrator functions useful. As mentioned above two decision criteria were used in the demonstrator: time and cost. The flow managers, in practice, use only time as a re-routing decision criterion. Therefore, the flow managers who saw the demonstrator said they did not need a cost criterion nor information on costs.

Staff from the URS showed more interest in the pre-tactical functions. For tactical re-routings, it was thought that functions should be more detailed and take into account rules applying to the use of airspace (e.g. routes that are only open at certain times, the flight levels that can be used by aircraft on certain routes).

The URS in 1995 was planning to use the Re-routing demonstrator as a basis for specifying the user requirements for a re-routing decision support tool. In May 1996, a function of the type <Alternative Routes> had become available in TACT, the CFMU computer system. However, its use was limited because in many situations none of the routes proposed by the computer by-passed the regulation. The function obtained the routes from a limited database of routes. It did not have any algorithm to determine 'shortest routes'.

A project aimed at the development of a Re-routing DSS, CARAT, started at the EUROCONTROL Experimental Centre in 1995 and ended in 1997. The CFMU is now introducing a function that provides alternative routes for flights using an algorithm to calculate shortest routes.

The demonstrator functions have different levels of complexity and represent different levels of aid to the flow manager. The next section uses these functions to discuss the level of automation and complexity required of a re-routing DSS.

6.6 Automation and Complexity of Re-routing DSS

This section uses ATM and automatic control literature and the demonstrator functions as a basis for a discussion of the levels of automation for a re-routing DSS. Sheridan (1992) defines automation as 'the automatically controlled operation of an apparatus, a process, or a system by mechanical or electronic devices that take the place of human organs of observation, decision and effort' (p.3). The complexity of a problem can be defined in terms of how unstructured the problem is (see Chapter 2). A problem is complex if its procedures are not standardised, the objectives cannot be clearly defined, or the input and output cannot be clearly specified. The re-routing demonstrator functions can be mapped against a referential model of automation and complexity, as shown in Figure 6.6-2.

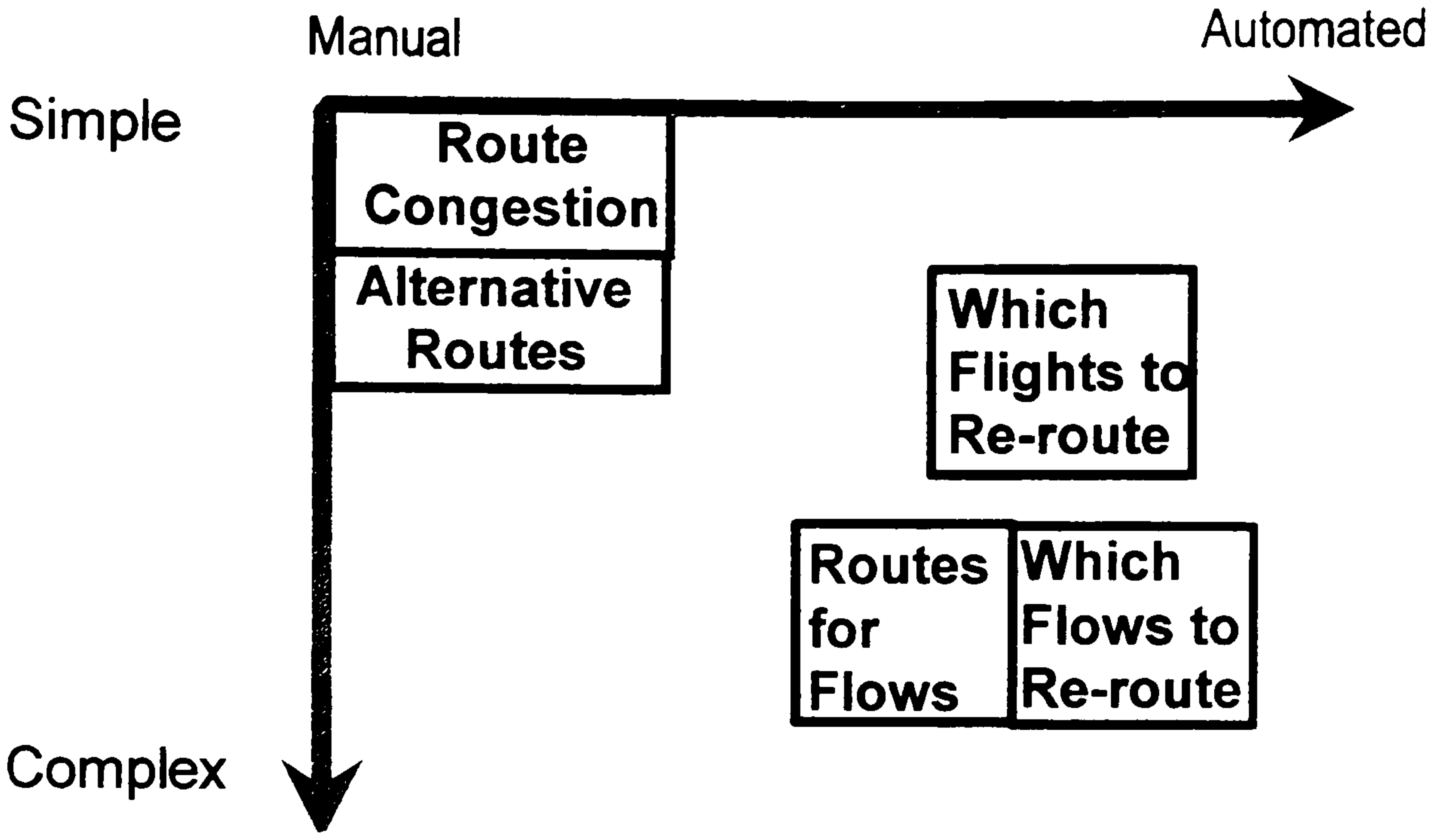


Figure 6.6-2: Complexity and Automation

For instance, the function <Which Flights to Re-route> is fairly structured in algorithmic terms but is substantial in terms of automation, whereas function <Routes for Flows> is more complex but it also requires more intervention from the flow manager.

Automation in air transport has been sought for a long time in order to achieve greater performance and reliability (Sheridan, 1992; Zellweger, 1995). However, because of the non repetitive and uncertain nature of many of the jobs, people are still very much involved. Even in highly automated environments such as piloting an aircraft, the human is still considered necessary for monitoring, detecting problems and intervening in a situation, if needed.

The term, supervisory control, describes the situation where there is a co-operative relation between human and machine (Sheridan, 1992). The machine has some decision or control capability, but it is supervised by the human. Sheridan (1992) provides an analogy between the supervisor's interaction with subordinate human staff members in a human organisation and a person's interaction with 'intelligent' automated subsystems. 'A supervisor of humans gives directives that are understood and translated into detailed actions by staff subordinates. In turn, subordinates collect detailed information about results and present it in summary form to the supervisor, who must then infer the state of the system and make decisions for further actions. Automation and semi-intelligent subsystems permit the same sort of interaction to occur between a human supervisor and the computer-mediated process.' (p.1)

According to Sheridan, in the strictest sense, supervisory control means that the computer is an autonomous controller for some variables at least some of the time. In a less strict sense, the computer transforms information 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 the term human-centred automation, where the human is considered the main element of the system (Hansman *et al.*, 1995; Zellweger, 1995). Human-centred systems development is not a straightforward process. Hansman *et al.* (1995) stress that unless the human is taken into account along the development process, the system performance after automation may be worse. This issue is also discussed in the DSS literature when referring to complementary intelligence (Young, 1989). As explained in Chapter 2, it is important that the process of decision making with the DSS makes best use of the user skills and the system skills.

Factors that can affect system performance in ATM (Hansman *et al.*, 1995) include:

- *Situation awareness and Attention limitation:* the ability to keep an adequate level of understanding of the situation. In a highly automated, complex and unstructured environment it is difficult to keep this understanding.
- *Information overload:* to prevent loss of situation awareness and of multi-tasking capability due to too much information, the quantity,

format and pre-processing of information to be provided to the flow manager has to be carefully assessed.

- *Human acceptance and understanding of the automation:* the flow manager has to be actively involved in the development of decision support tools and accept the decision criteria used.

An important issue to consider in the interaction between the human and the machine is the type of influence the human can have on machine-made decisions. In the context of the development of a computer system to support airport traffic management, Völkers and Böhme (1995) consider two types of human influence on an automatic planning system:

- direct influence - humans can modify or replace a computer-determined plan.
- indirect influence - humans can only change decision criteria or constraints, not computer determined plans.

Various factors have to be taken into account in deciding on the extent of human influence on a re-routing DSS:

- Whether sufficient knowledge and experience have been gathered to enable automation.
- The technical feasibility of the automation.
- How acceptable automation is to the stakeholders in re-routing decisions.
- How fast and frequently decisions have to be made.

In European ATFM, at tactical level, the environment is very volatile, and decisions have to be made continually and quickly, 24 hours a day. At pre-tactical level, one to two days before the flights, there is time to rethink and review decisions and the computer is not used to control the traffic situation. The demonstrator functions to support the re-routing of flights are reasonably simple or standard to implement. The functions to support the re-routing of flows require more complex algorithms and more expertise in defining the scope of the re-routings. Therefore, at this stage, a more automated DSS appears to be more useful and feasible for the re-routing of flights than the re-routing of flows.

In European ATFM, there is already some form of supervisory control at the tactical level. The CFMU computer system TACT, monitors the traffic situation and summarises the information to the flow managers. When flow managers, based on that information, issue a slot allocation regulation, TACT allocates slot delays automatically to the flights. The airlines receive slot allocation messages directly from TACT, without human intervention. The flow manager can only intervene in the slot allocation by changing the parameters of the slot allocation regulation (e.g. increasing the number of slots, blocking a slot for a flight) that is the human can only have an indirect influence on computer determined plans. This mode of supervisory control could also be adapted to the re-routing of individual flights, at tactical level, in the following way:

1. The flow manager activates the function <Which Flights to Re-route>
2. The re-routing system identifies the flights and sends a re-routing proposal to the airlines concerned, without human intervention.
3. The flow manager can change the parameters used in the re-routing function.

For the re-routing of flows, a DSS suggesting routing schemes which the flow manager can check, amend and replace, as needed, appears to be more useful and feasible.

The level of automation and complexity of a re-routing DSS is related to the approach taken in the development of the DSS. Turban (1990) presents a framework for DSS development issues devised by Sprague (1980), who identified three levels of technology:

1. *Specific DSS*: this is the 'final product' or, in other words, the finished DSS which is provided to the customer. It is used to support a specific

application. The Computer Assisted Slot Allocation System at the CFMU is an example of a specific DSS.

2. *DSS Generator*: This is a package of software that provides a set of capabilities to build a specific DSS quickly, inexpensively and easily. An example of a microcomputer based generator is Excel, which has capabilities ranging from modelling, report generation and graphical display to data management.
3. *DSS Tools*: These are software utilities or tools which facilitate the development of either a DSS generator or a specific DSS. Examples of these tools are programming systems or query systems.

Based on this framework and on Sprague and Carson (1982), Turban (1990) describes three approaches to the development of DSS:

- *Quick-hit*: according to this approach a specific DSS is constructed when there is a recognised need a high potential payoff, or a difficult problem to address. Costs and risks are low, the latest technology can be utilised, and the DSS can be constructed relatively quickly using commercially available generators.
- *Staged development*: according to this approach a specific DSS is constructed with some planning, so that part of the effort in developing the first system can be reused in a future DSS. This approach can lead to the development of an in-house DSS generator.
- *Complete DSS*: a full-service, large-scale DSS is constructed. It is a lengthy process which may result in very well integrated tools but has a higher risk of technological obsolescence.

Considering the uncertainty and infancy of re-routing control measures the staged development appears to be the most appropriate approach for the development of a re-routing DSS. The functions in the re-routing demonstrator can be amenable to a staged development (see Figure 6.6-3). For instance, in order to implement functions for re-routing flights and flows, there have to be functions providing alternative routes and information on delays or spare capacity of routes. This development approach could provide results earlier than if a fully automated system were to be developed from scratch, and it would be less risky.

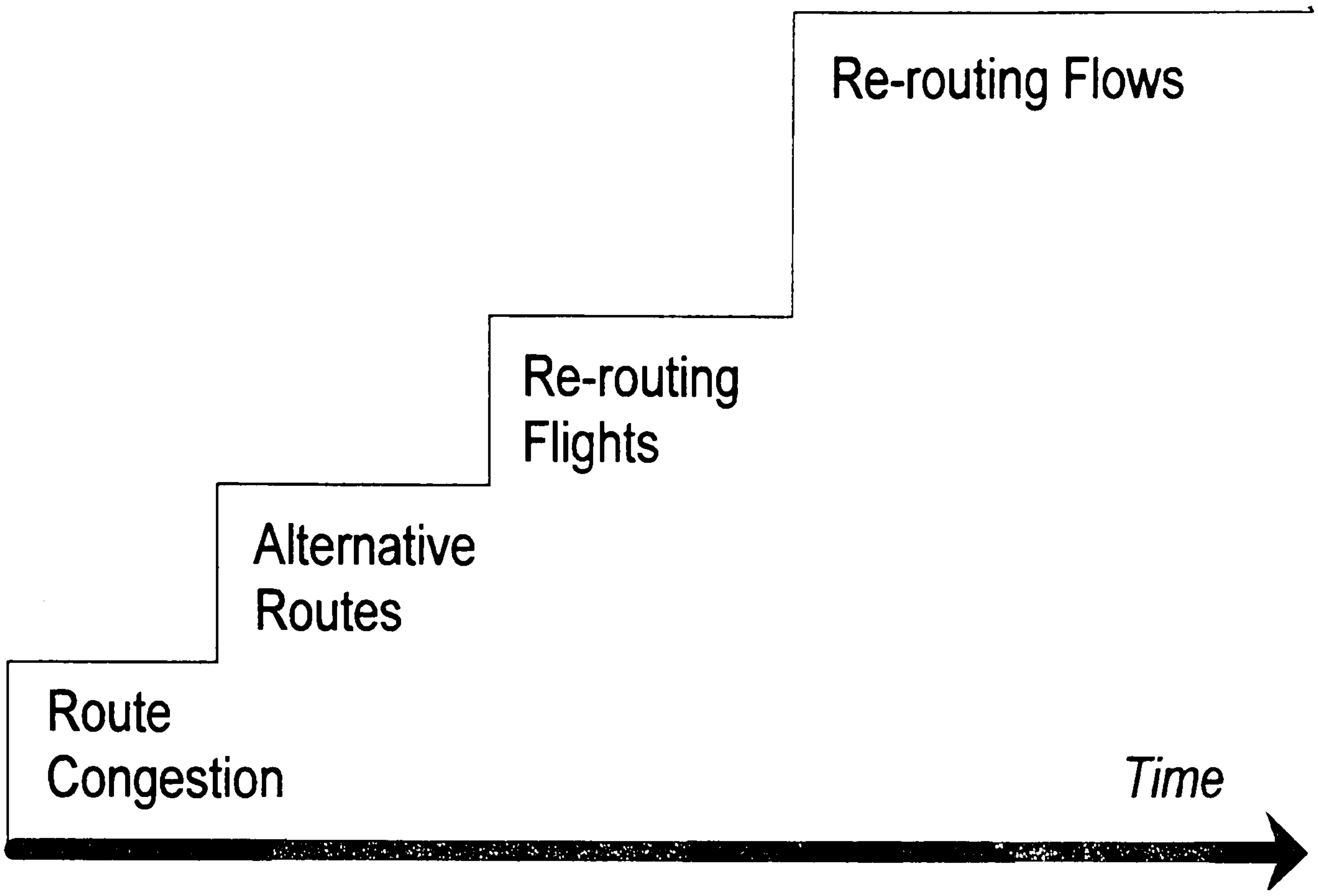


Figure 6.6-3: Implementation of Re-routing Functions

A further aspect which has to be taken into account in the development of DSS is how the tools will fit into the ATM environment at the time they are expected to become available. This is discussed in the next section.

6.7 Integration of Re-routing Decision Support Systems in the Future European Air Traffic Management Environment

The development of re-routing DSS cannot be seen in isolation: future developments in European and world ATM need to be taken into account. The underlying questions are: what is the ATM environment going to look like when the re-routing tools become available, possibly in the next 5 years, and how will they fit in that world? Re-routing tools should not be developed on the basis of present needs: considering the lead and building times of the systems the needs in 5 to 10 years must be anticipated.

Zellweger (1995) presents several examples of substantial investments made by the FAA in new systems that, when finally available, were not needed or outdated. The following examples illustrate how re-routing tools might become outdated before becoming available:

- Within the European ATC Harmonisation and Integration Programme-EATCHIP (see Chapter 4) there is a programme for route network development and associated airspace structure. This sub-programme is aimed at increasing European ATC capacity through the restructuring of the air route network and of the associated airspace sectorisation. This new air route network will be more flow-oriented and have far fewer junction points than the present one. The implementation of this network is expected to start in 1998. Therefore, the development of re-routing decision support tools will have to be undertaken bearing this in mind.
- With the progress in airlines' standard flight planning systems it is possible that in the future, even small airlines will be able to work out alternative routes for their flights without assistance from ATFM. The only information they will need from ATFM is the likely slot delay on a certain route. Therefore, it is possible that functions considered in the demonstrator to provide alternative routes for individual flights will not be needed.

Another key issue is how these re-routing tools will integrate with existing systems. Considering the functions in the demonstrator, they can be divided in two groups: functions for re-routing individual flights, at tactical level, and functions for re-routing flows. The degree of detail and the integration with TACT varies significantly between these two groups. Re-routing of flows addresses the distribution of traffic in a more aggregated way. The problem consists of routing sets of flights so that 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 therefore to interact often with CASA (see Figure 6.7-1).

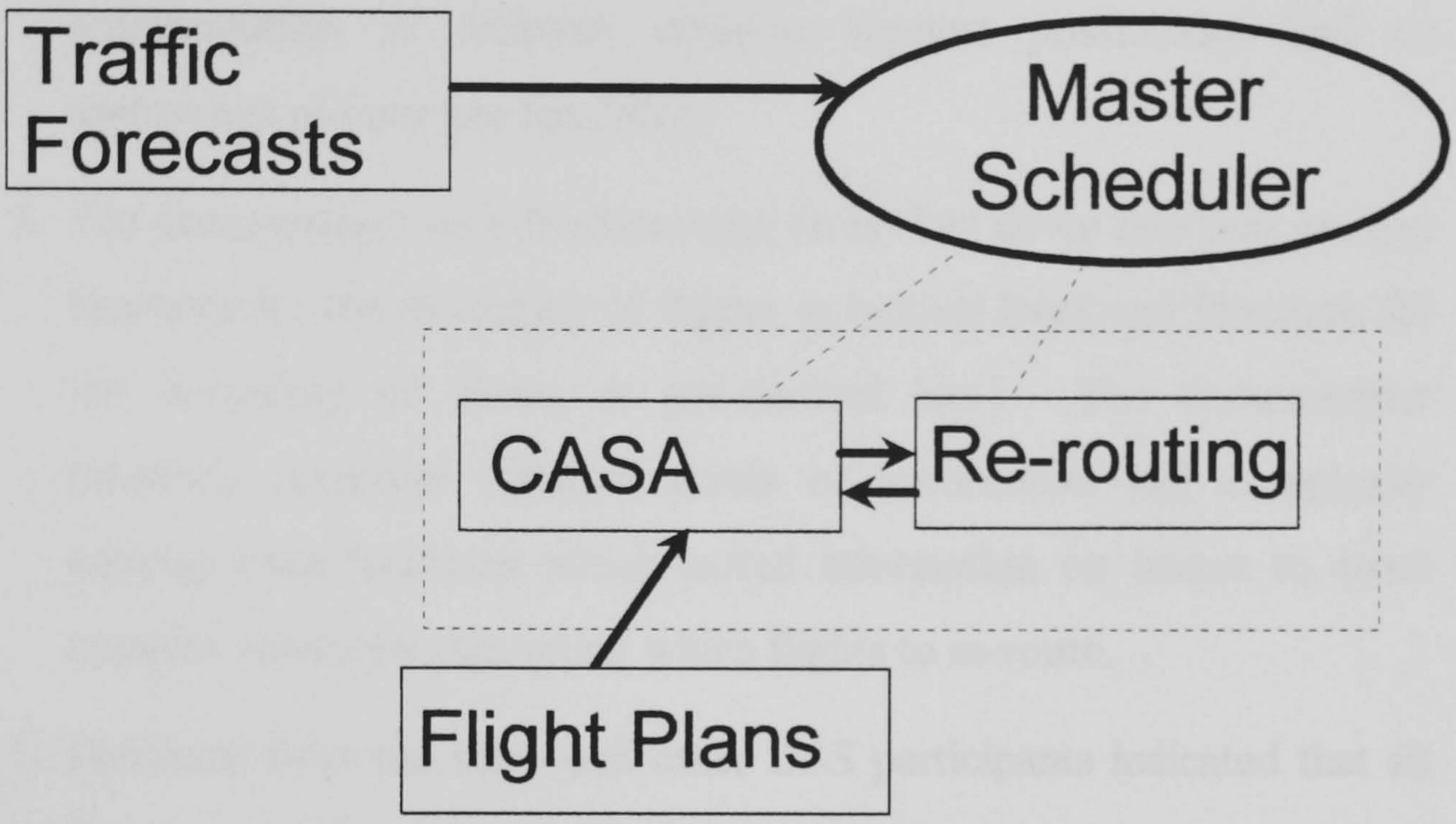


Figure 6.7-1: Integration CASA/Re-routing

6.8 Conclusions

This chapter concentrates on the initial steps of the development of a re-routing DSS. A re-routing demonstrator is discussed and described. The level of automation and complexity of re-routing DSS are debated based on the demonstrator functions. The conclusions are as follows:

1. DSS appear to be well-suited for the re-routing of flights in Europe because of their potential in responding quickly and consistently to complex problems. They can also provide training and support to less experienced staff.
2. The design of a DSS for the re-routing of flights has to take into account that the users of the tool, the flow managers, have different levels of experience and consequently, different decision support needs

and that there are different views on the degree of automation of a re-routing tool. It also has to consider that, given the novelty of centralised ATFM, the knowledge base for re-routing control measures is still being built.

3. A re-routing demonstrator was developed to provide a tangible representation of different decision support possibilities and an assessment of their pre-feasibility.

4. The demonstrator user functions can be broken down into two groups: functions for the re-routing of flights, at tactical level, and functions for the re-routing of flows, at pre-tactical level. The demonstrator functions represent different levels of automation and complexity ranging from functions which sorted information on routes to more complex functions suggesting which flights to re-route.

5. Feedback from the users and other DSS participants indicated that all functions in the demonstrator could be of use and suggested ways forward in the development of re-routing DSS.

6. The demonstrator functions providing information on routes and decision support for the re-routing of flights, at tactical level, use simple or standard algorithms. However, as the feedback from staff from the URS suggested, the database for the re-routing of flights will have to include detailed rules on the use of airspace.

7. The demonstrator functions to support pre-tactical re-routings are more complex than the functions to support re-routing of flights and require knowledge that is still in short supply.

8. Considering conclusions 2 and 3 and the different timescales for pre-tactical and tactical re-routings, a higher level of automation of DSS for tactical re-routings appears to be more useful and feasible than for pre-tactical re-routings. For tactical re-routings a form of supervisory control is suggested. For pre-tactical re-routings a form of manual control with the DSS providing advice is proposed.

9. Given the infancy of centralised European ATFM, the most appropriate approach to the development of a re-routing DSS appears to be a staged approach, starting with the simpler functions and step by step developing the more complicated ones.
10. 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 the changes to the air route network and associated airspace structure being decided in the context of EATCHIP and the progress in the airlines' standard flight planning systems.

In this chapter, several functions to support re-routing control measures were discussed. In the next chapter, optimisation models to support the most complex functions in the demonstrator, functions to support the re-routing of flows, are presented.

Chapter 7

Optimisation Models for Re-routing Air Traffic Flows

7.1 Introduction

This chapter explains the optimisation models developed for routing air traffic flows, in pre-tactical ATFM. They are intended for the most complex function illustrated in the re-routing demonstrator:<Which Flows to Re-route> (see Chapter 6). The chapter has two main sections. The first section explains the modelling process, covering aspects such as the identification of relevant models, pilot testing results together with the choices and trade-offs made. The second section describes the three models which resulted from the modelling process and were selected for further testing. Chapter 8 describes and discusses the testing of the models.

7.2 The Modelling Process

This section starts with the identification of relevant models for flow re-routings and discusses different modelling approaches. Following this, an account of the evolution of the models is provided to explain the work behind the models eventually adopted and the modelling decisions taken.

7.2.1 The Identification of Relevant Models

The identification of classes of optimisation models relevant to re-route flows was done mostly before and during the first contacts with the CFMU, but was revisited at later stages of this research. Models were identified taking into account the following: their appropriateness to represent the main features of the problem (see Chapter 5), the literature on models for air traffic management and the availability of off-the-shelf solution methods. The possibility of transferring models from the field of flow control of urban road networks was considered but, as pointed out in Odoni *et al.* (1987), there are significant differences between the two fields in terms of variables (e.g. continuous vs. discrete nature), decision criteria and constraints (e.g. types of control exercised). Two relevant types of models were identified: network flow models and integer models.

7.2.1.1 Network Flow Models

The European airspace can be represented as a directed network, where nodes are junction points between airways (called air routes in upper airspace), the arcs are segments of airways and the sources and sinks are either airports or connection points with non-European airspace. Each arc has a distance, crossing time, cost or any other *length* associated with it. Some of the models for ATC presented in the literature, represent the airspace in this way (Bianco and Bielli, 1993; Bielli *et al.,* 1982; Odoni, 1987; Zenios, 1991).

The multi-commodity network flow model, where different commodities have to be shipped through a capacitated network, with minimum cost, appears to be relevant to this case. Each commodity represents a flow of traffic defined in terms of a city-pair or origin/destination areas and the cost of an arc can vary according to the commodity. The network can be expanded in order to consider time: the period of time for which the re-routings apply is broken into time-windows, and traversal times are represented in terms of these windows. The network is then defined in a 3-dimensional (latitude, longitude and time) or 4-dimensional (adding altitude) space.

However, the re-routing problem differs from a standard multi-commodity network flow problem. One of the major differences is: whereas in the latter the capacities are on arcs, in an ATC environment capacities are on sectors, that is sets of arcs and nodes. A way of overcoming this difference is by changing the network. If in an initial stage a number of alternative routes is selected for each flow and each route is described in terms of the sectors they cross and the corresponding crossing times, then, in a second stage, the problem is amenable to a multi-commodity model with additional constraints. A reduced network can be built in the following way: all arcs and nodes of each sector are 'shrunk' into one arc; the first node of the arc represents the entry point into the sector, whatever the origin of flights, and the second node represents the exit point; the capacity of the arc is the capacity of the sector and instead of flows, commodities represent routes.

To illustrate this approach a very simple instance of a re-routing problem with two flows, three sectors and two routes for each flow is considered. Route 1 crosses sectors 1 and 3, route 2 sector 3, route 3 sectors 2 and 3, and route 4 sector 2. Time is ignored at present. A network model is shown in Figure 7.2-1.

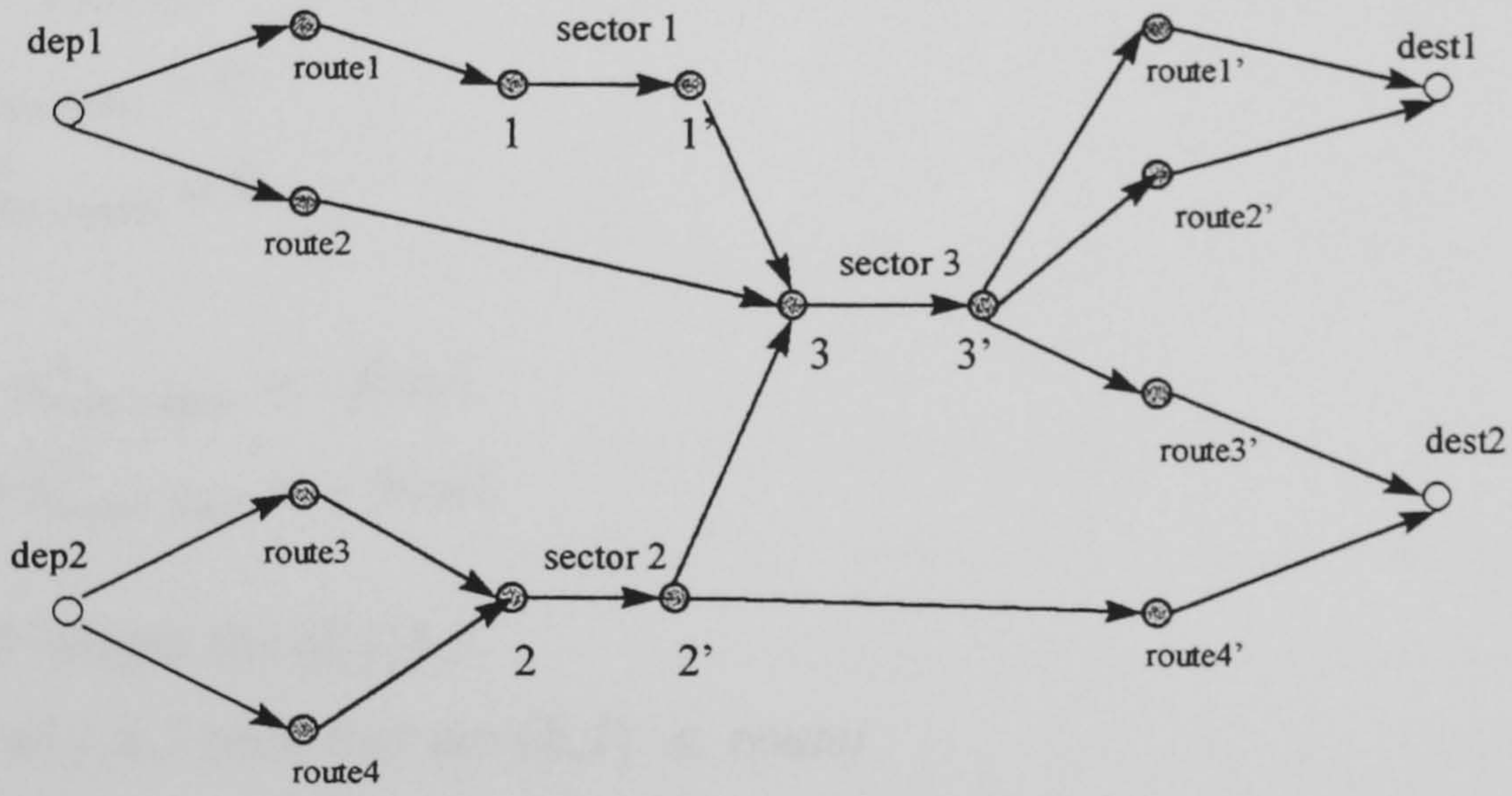


Figure 7.2-1: Example of a Network Model

The flow variables can be formulated as x_{kl}^{j}, representing the number of flights on route j going from node k to node l. These nodes represent the sectors or the sources and/or sinks of the routes. Following, is a possible network flow formulation of this instance:

$$Min\sum_{j=1}^{4}\sum_{k=1}^{18}\sum_{l=1}^{18}c_{kl}^{j}x_{kl}^{j}$$

subject to:

[sector capacity constraints]

sector 1: $x_{11'}^{1} \leq cap1$

sector 2: $x_{22'}^{3} + x_{22'}^{4} \leq cap2$

sector 3: $x_{33'}^{1} + x_{33'}^{2} + x_{33'}^{3} \leq cap3$

[flow constraints]

$x_{dep1,route1}^{1} + x_{dep1,route2}^{2} = flow1$

$x_{dep2,route3}^{3} + x_{dep2,route4}^{4} = flow2$

$x_{route1,1}^{1} - x_{dep1,route1}^{1} = 0$

$x_{route2,3}^{2} - x_{dep1,route2}^{2} = 0$

(...)

$x_{route1',dest1}^{1} + x_{route2',dest1}^{2} = -flow1$

$x_{route3',dest2}^{3} + x_{route4',dest2}^{4} = -flow2$

$x_{kl}^{j} \geq 0$ and integer for all j, k, l

$x_{kl}^{j} = 0$ for all j, k, l such that arc $(k, l) \notin routej$

where:

c_{kl}^{j} cost of arc (k, l) for a flight on route j

flowi number of flights in flow *i*, *i* = 1,2

capk capacity of sector *k*, *k* = 1,2,3

Introducing time into the problem, the approach would be essentially the same but expanded to another dimension (Ford and Fulkerson, 1962): time is broken down into time-windows, and for each time-window the traffic situation at the nodes of the network is computed. To illustrate this, consider route1 in the above instance with traversal times for every sector, say, of one time-window, and a period of four time-windows. The network in Figure 7.2-1 can be expanded as shown in Figure 7.2-2, for route 1.

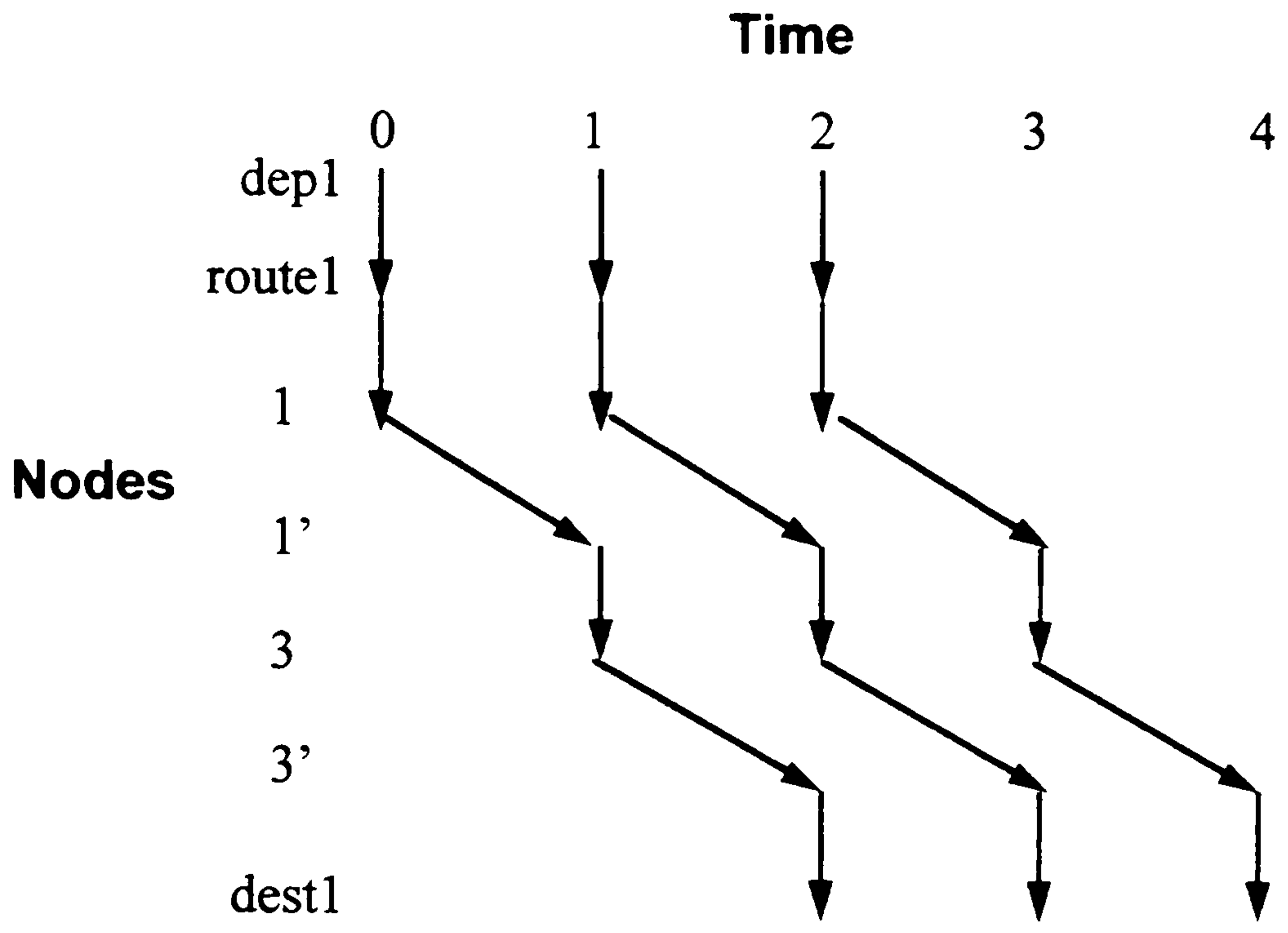


Figure 7.2-2: Example of a Time and Space Network Model

Ground-delays can also be represented in this model by arcs connecting the same departure point in sequential time-windows. The linear programming relaxation of this model, that is the model without the integrality constraints on the variables, is amenable to a multi-commodity network flow with side constraints for which specialisations of linear programming algorithms are presented in the literature (Kennington and Helgason, 1980). However, unlike the single-commodity network flow case, the solutions provided by the linear programming algorithm might not be integer. In which case, less efficient algorithms, such as branch-and-bound, will have to be used to find integer solutions. Powerful algorithms that address this problem, exploiting the network structure of the models, have been reported in the literature (Barnhart, 1993: Barnhart et al., 1995; Castro and Nabona, 1996; Crainic et al., 1993).

The use of multi-commmodity flow models is made more difficult by an unusual type of constraint on the activity of flow managers, mentioned in previous chapters: flow managers can only route flows of traffic for a pre-defined period of time, not individual flights. Therefore, each flow of traffic can only have one route (i.e. if flights of a flow are sent along one route, other flights of the same flow cannot be sent along a different route). This type of constraint suggests the use of another type of model: an integer model with binary variables representing the decision on the assignment of a route to each flow.

7.2.1.2 Integer Models

Integer models appear to be relevant to this problem because the decisions to be made are discrete: number of flights routed or delayed, assignment of a route to a flow. Integer models have been used in OR on ATC problems mostly to optimise the allocation of ground-delays to flights (see Chapter 2). What follows is a simple binary assignment model in which a route has to be assigned to each flow so that the capacity of ATC sectors is not exceeded and the total cost of re-routings is minimised:

$$Min \sum_{i=1}^{m} \sum_{j \in R_i} c_j x_{ij}$$

subject to

$$\sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} f_{kjt} x_{ij} \leq u_{kt} \quad (k = 1, \dots l; t = 1, \dots p)$$

$$\sum_{j \in R_i} x_{ij} = 1 \quad (i = 1, \dots, m)$$

$$x_{ij} \in \{0,1\} \quad (i = 1, \dots m; j \in R_i)$$

where i denotes flow, j route, k sector, and t time.

$$x_{ij} = \begin{cases} 1 \text{ if flow } i \text{ goes along route } j \\ 0 \text{ otherwise} \end{cases}$$

R_i set of routes that can be assigned to flow i

L_k set of routes that cross sector k

c_j is the cost of route j

f_{kjt} is the number of flights crossing sector k on route j, during interval t

u_{kt} is the capacity of sector k during interval t

This model is too simplistic, essentially, for two reasons: 1) it is often infeasible because many sectors in the European airspace tend to be congested; and 2) it does not take into account the cumulative effects of congestion, when flights are ground-delayed. The need to take into account congestion led to the definition of ground-delay variables, representing flights ground-delayed whenever the traffic demand exceeds the capacity of a sector. Models including these variables are described in the next section.

Integer models can be quite hard to solve, but the progress in solution methods has been remarkable and there are several off-the-shelf powerful solution methods widely available. Compared to network models, integer models allow for more flexible formulations and the inclusion of constraints such as 'one flow can only be assigned to one route'. For these reasons, the models developed for the remainder of the research are integer.

7.2.2 Authority of ATFM and Modelling Approaches

A key issue in determining the effectiveness of re-routing control actions, discussed in Chapter 5, is the degree of authority that flow managers at the CFMU can exercise. At present, only some of the routings at the strategic level, or those in contingencies or in severely congested situations are mandatory. All other re-routings tend to be advisory. Mandatory re-routing measures apply to flows, during certain periods and are usually negotiated beforehand with airline representatives and the area control centres involved, they cannot be imposed on an individual flight basis.

However, there is an on-going debate on the adequacy of the present situation, and whether there should be more or less regulation (see Chapter 5). Some stakeholders in flow management argue in favour of a firmer regulatory control, where responsibility for the provision of flight plans, including the flight route, lies with ATFM.

The nascent research on optimisation models for re-routing measures (Tošic *et al.*, 1995b; Loubieres, 1996) assumes that flow management do have the authority to route individual flights. The modelling approach taken in CARAT, the research project on re-routing aids taking place at the EUROCONTROL Experimental Centre, (Loubieres, 1996) works at the level of the individual flight:

European airspace is represented as a network model and the objective of the model is to minimise the sum of operational routing costs and of congestion costs. Congestion is measured by means of demand/capacity imbalances. The input to the model is the initial flight plans, and the output is the flight plans resulting from the optimisation. This approach may work if flow management has the authority to change flight plans and if efficient algorithms are developed to solve the very large optimisation models resulting from it.

In practice, at present, flow managers, when considering pre-tactical re-routing measures, group flights into main flows, according to origin/destination areas. They then identify alternative routes for the flows and compare capacity with demand for ATC sectors, in an iterative way. The alternative routes have to be acceptable to airlines, that is, they cannot be too long or too costly. The modelling approach taken here is based on this practice and assumes that flow managers have authority to issue re-routing measures applying to whole flows during a very well defined period, typically a day. Routes cannot be changed frequently nor be allocated on an individual flight basis.

Flights are grouped into flows according to their origin-destination, and the problem of re-routing air traffic flows is solved in two stages: 1) *Routes Problem*: identify acceptable and alternative routes for each flow; and 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. This approach results in smaller, easier to solve models but is less direct than the approach used in CARAT, as before reaching the optimisation phase flights have to be grouped into flows. However, it should be noted that if the flow variables are replaced by flight variables the models here presented can also be formulated in terms of individual flights.

7.2.3 Evolution of the Models

The different modelling approaches discussed above, were not this clear to start with. When the intervention at CFMU began, the knowledge of the problems to address was limited to the literature. The exploratory integer model described in section 7.2.1.2. was very soon deemed to be of little use because it did not deal with a common situation in European ATFM: a situation where traffic demand exceeds capacity even after the implementation of traffic re-routings, that is, a situation where flow re-routings redistribute congestion from more to less congested areas of the airspace.

The re-routing model developed after that, while at the CFMU, represents congestion by means of effects, that is, using ground-delay variables. These variables are activated whenever traffic demand exceeds capacity and are defined in terms of flow, route and time interval. The route index is needed because different routes have different crossing times and thus result in a different allocation of ground-delays. Therefore, the decision variables of this model are:

$$x_{ij} = \begin{cases} 1 & \text{if flow } i \text{ is assigned to route } j \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ijt} = \text{ number of flights of flow } i \text{ taking route } j \text{ ground - delayed at } t$$

To formulate the model, named M-CFMU, the following is assumed:

1. All flights have identical cost functions. This assumption ensures that there is equity between flights, but means that the model does not represent actual flight costs. Ground-delay and re-routing cost functions are in the model to account for different trade-offs between re-routing and ground-delaying flights and to compare various re-routing scenarios.
2. All flights in a flow, that is flights with the same origin-destination, fly the same route, at the same speed. The limitations of this assumption are attenuated by the fact that airlines tend to follow the same (cheapest) route and use the same type of aircraft for the same city-pairs. In addition, it should be noted that the time intervals considered are long and the models are not detailed to the point of providing exact times for individual flights.

3. The period of time for which flow re-routings are being considered is divided into p identical time intervals. These time intervals work as time units: the events 'Flight departure', 'Flight arrival', 'Flight Entry in Sector' are assumed to take place at the beginning of the corresponding time interval. Parameters like 'the time it takes to get to a certain sector on a certain route' are measured in 'number of time intervals'. If a flight crosses two sectors in the same time interval then the number of time intervals it takes to get to both sectors is the same and the crossing time for these sectors is 0 time intervals. This assumption is consistent with the way capacity of an air traffic control sector is defined for air traffic flow management purposes: 'number of flights per time interval'.

4. The capacity of sectors in time interval $p+1$, the time interval just after the end of the period during which the re-routing measures apply, is infinite. In practice, this means that in the time interval after the end of the re-routing the difference between capacity and demand will be sufficiently large to allow the backlog of flights ground-delayed to depart.

Model M-CFMU

[Min extra-cost of routes + cost of ground-delays]

$$Min\ w = \sum_{i=1}^{m} \sum_{j \in R_i} \sum_{t=1}^{p} (c_j f_{it} x_{ij} + g y_{ijt}) \qquad \textbf{(7.2.1)}$$

subject to:

[Capacity Constraints]

$$\sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{\tau_{jk}} (y_{ij,(t-t_{jk}-1)-r} + f_{i,(t-t_{jk})-r} x_{ij} - y_{ij,(t-t_{jk})-r}) \leq u_{kt} \qquad (t = 1,2,\ldots,p; k = 1,2,\ldots,l)$$

$$\textbf{(7.2.2)}$$

[One Flow→One Route]

$$\sum_{j \in R_i} x_{ij} = 1 \qquad (i = 1,2,\dots,m) \qquad \textbf{(7.2.3)}$$

[Total flights ground-delayed cannot be larger than total flights scheduled]

$$\sum_{j \in R_i} y_{ijt} \le \sum_{j \in R_i} y_{ij,t-1} + f_{it} \qquad (i = 1,\dots,m; t = 1,\dots,p) \qquad \textbf{(7.2.4)}$$

[A flight cannot be ground-delayed on a route the flow does not fly]

$$y_{ijt} \le Mx_{ij} \qquad (i = 1,\dots,m; j \in R_i; t = 1,\dots,p) \qquad \textbf{(7.2.5)}$$

$$x_{ij} \in \{0,1\} \qquad (i = 1,\dots m; j \in R_i)$$

$$y_{ijt} \ge 0 \text{ and integer} \qquad (i = 1,\dots,m; j \in R_i; t = 1,\dots,p)$$

Notation:

i	index for flows. $i = 1,\dots,m$
k	index for sectors. $k = 1,\dots,l$
R_i	set of routes admissible to flow i
j	index for routes. $j \in \left(\bigcup_i R_i \right)$ each route is defined by a sequence of sectors $k, k', k''\dots$ and a corresponding sequence of entry times $t_{jk}, t_{jk'}, t_{jk''}\dots$
L_k	set of routes that cross sector k
t	index for time interval. $t = 1,\dots,p$
t_{jk}	time intervals it takes to get from departure point to sector k on route j
τ_{jk}	time intervals it takes to cross sector k on route j excluding the entry time interval $\tau_{jk} = \max\{0, t_{jk'} - t_{jk} - 1\}$
u_{kt}	capacity of sector k during t
f_{it}	number of flights of flow i scheduled to depart at t
M	a constant large enough so that when $x_{ij} = 1$ then $y_{ijt} \le M$
c_j	additional cost of route j
g	cost of ground - delay per time interval

Expression (7.2.1) is the objective function, to minimise the aggregated cost of re-routing flights and the cost of ground delay. Expressions (7.2.2) establish that the flights crossing a sector during a certain period of time cannot exceed the capacity of the sector. The flights crossing a sector are calculated adding the flights scheduled to cross the sector during that period plus the flights ground-delayed during the previous period minus the flights ground-delayed during that period. The periods during which flights are counted in a sector depend on the route taken, and may be more than 1, if a flight takes longer than a time interval to cross a sector. Expressions (7.2.3) state that a flow is assigned to one and only one route and expressions (7.2.4) relate ground-delayed flights with scheduled flights. Expressions (7.2.5) establish that flights cannot be ground-delayed (or routed) on routes not assigned to their flow.

Expressions (7.2.2) can be simplified by crossing out symmetric terms:

$$\sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} (y_{ij,(t-t_{jk}-\tau_{jk}-1)} - y_{ij,(t-t_{jk})} + \sum_{r=0}^{\tau_{jk}} f_{i,,(t-t_{jk})-r} x_{ij}) \leq u_{kt} \qquad (t = 1,2,\ldots,p; k = 1,2,\ldots,l)$$

(7.2.6)

This model was tested on a set of test data based on the actual traffic crossing three contiguous air traffic control upper sectors of Southern France (see Appendix C). The traffic data totalled 261 flight plans, all the flights that entered these 3 sectors from 08.00 to 12.00h. This period was broken into equal time intervals of 15 min. Taking into account the pattern of traffic crossing the sectors, five flows with 2 alternative routes each, were considered. Four additional flows with no alternative route were defined to include the remaining flights. The size of the resulting integer model is shown in Table 7.2-1.

Table 7.2-1: Model M-CFMU - Example Size

Capacity constraints	48
Assignment constraints	5
Relation flights g. delayed/scheduled	144
Flow route constraints	224
Total constraints	421
Assignment variables	10

Ground-delay variables	224
Total variables	234

The model was optimised using GAMS/LAMPS version 2.25 in a UNIX time-sharing system. The server used in this pilot trial was not very powerful and the temporary space available to run the model was very limited. Therefore, despite its small size, many numerical instances of the model were not solved to optimality and feasible solutions sufficiently close to the optimum were adopted. However, the trial revealed some of the limitations of the model and prompted significant improvements. It also suggested the development of other models: a simpler model, and a more detailed model.

One of the limitations of the model is the lack of clarity of events, it is not clear when flights depart nor what is the role of ground-delays. To overcome it, departure variables were added to the model and the ground-delay variables were redefined just in terms of flows and time. The resulting variables are as follows:

d_{ijt} number of flights of flow i departing on route j at time interval t
y_{it} number of flights of flow i ground - delayed at time interval t

$$x_{ij} = \begin{cases} 1 \text{ if flow } i \text{ is assigned to route } j \\ 0 \text{ otherwise} \end{cases}$$

This change apparently increases the number of variables of the model, but in fact these variables are dependent. For instance:

$$d_{ijt} = (f_{it} + y_{i,t-1} - y_{it})x_{ij}$$

This formulation clarifies the role of ground-delay, as a measure of congestion to support the decision on flow re-routings (not to allocate actual ground-delays), and facilitates comparisons with other scenarios, for example, scenarios where flows are routed onto more than one route.

Another limitation of this model is the linear ground-delay costs. Ground-delay costs are very uncertain and vary according to the airline but typically, the cost tends to increase non-linearly with the length of the delay. However, if a non-linear cost function of the type $g(y_{it})$ is used the model becomes much more difficult to solve. To remain within the realm of linear programming, two possibilities were considered:

1. To define the decision variables in binary terms. For instance, the ground-delay variables become y_{zit}, and are equal to 1 if flight z of flow i is delayed at t and 0 otherwise. As a result, the cost of ground-delay can be function of z and t. However, this change increases substantially the size of the model: considering a plausible scenario with 20 time intervals, 150 flows each with 10 flights and two alternative routes the number of departure variables could reach 60,000 which is already a large integer model. This possibility was thus dropped.
2. To define the cost of delay in terms of the potential congestion in the airspace at a certain time interval and the contribution of a flow to it. The idea behind it is: in a congested situation the heavier a flow is the more acceptable it becomes to delay it. The following expression was used:

$$g(i,t) = a \cdot (1 + m(t) / \max(1, f_{it})) \qquad \textbf{(7.2.7)}$$

where a is a constant representing basic cost of delay and

$$m(t) = \sum_{k=1}^{1} \max(0, \sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{\tau_{jk}} f_{i,t-t_{jk}-r} - u(k,t)) \quad (t = 1, \ldots, p)$$

$$\textbf{(7.2.8)}$$

Another conclusion of this pilot trial is the importance of tightening the value of M, the large constant used in the constraints that force flights to take the route of the flow (see (7.2.5)). The slacker is the value of M, the less efficient the solution method. Initially, M was equal to the total of flights but, in order to tighten it, a constant equal to the total of flights in a flow was defined for each flow. At a later stage, these constants were tightened slightly more as a result of introducing upper bounds in the number of flights ground-delayed at each time interval. The model obtained after these alterations was renamed DELINT1.

The difficulty in running M-CFMU to optimality even with a small problem prompted the need to simplify it, in order to try to capture the relevant features of re-routing decisions in a model which is easier to solve (see Ward (1989) for arguments in support of the use of simple models). One of the aspects that complicates and increases the size of the model is the cumulative effect of congestion: whenever traffic demand exceeds capacity flights are delayed and build up, joining the traffic demand of the next period. If, instead of representing congestion by means of ground-delay, we use non-cumulative penalties activated whenever the traffic demand exceeds the capacity of an ATC sector, the model becomes substantially simpler. The value of the penalties can reflect, indirectly, the cost of ground-delays resulting from congestion. In this way, a simpler and smaller model, named BALDIST, was developed including the assignment variables x_{ij} and *congestion* variables defined as o_{kzt}, which equal 1 if there is a z*th* flight above capacity at t in sector k, and equal 0 otherwise. The flight index z is in the model to enable the use, in a linear objective function, of a cost function that varies with the number of flights exceeding capacity. This model has also the advantage of providing congestion information in terms of sectors (instead of flows).

A drawback of M-CFMU is that the length of delay affecting the flights is not taken into account. To overcome this drawback, variables can be defined in a more detailed way (this formulation draws on a ground-delay model presented in Vranas (1996)): $d_{ijtt'}$ representing the number of flights of flow i, on route j that are scheduled to depart at t and are departing at t'. This formulation results in larger models: for example, considering the scenario with 20 time intervals and 150 flows with two alternative routes each, the number of variables could reach 63,000 which is a large integer model. However, the size of the model can be considerably reduced if the number of delay time intervals is limited. For instance, if in the above scenario the length of ground-delay is limited to four time intervals the number of variables is reduced to 27,000, a more manageable size.

A model, DELINT2, was developed based on these variables. This model has the advantages of concentrating in the same variable both the departure and the ground-delay. It also results in a matrix of constraints that is closer to a network flow model type of matrix, that is with most coefficients equal to 1/-1. A good rule-of-thumb in obtaining integer models that are easier to solve using Branch-and-Bound methods is to formulate them as closely as possible to a network flow model. In fact, as it will be shown in Chapter 8, DELINT2, despite its larger size is easier to solve than DELINT1.

The three models obtained after the first trial, BALDIST, DELINT1 and DELINT2 were tested again using the same example but with the period of re-routing extended from 4 to 10 hours (the results are shown in Appendix D). It should be noted that, for this example, all the models were solved to optimality in very little time.

7.3 Description of the Models

The models described in this section assign a route to each traffic flow in order to minimise an aggregate measure of the cost of congestion and re-routings. Three integer programming models, resulting from different ways of measuring congestion, are presented:

> **BALDIST**- Congestion is measured by means of penalty variables that are activated whenever traffic demand is above the capacity of an ATC sector. The model minimises the sum of the estimated cost of congestion and the cost of re-routings subject to capacity constraints and constraints on the assignment of routes to flows.
>
> **DELINT1**- Congestion is measured using ground-delay variables of the type 'number of flights of flow *i* delayed at *t*'. The ground-delay variables are in the model to support the decision on re-routings, not to allocate ground-delays to individual flights. Therefore, unlike BALDIST, flights ground-delayed can build up over time. The model minimises the sum of the estimated cost of ground-delay plus the cost of re-routings subject to capacity and assignment constraints plus constraints defining and relating the two types of variables: assignment and ground-delay variables.

DELINT2- Congestion is measured using more detailed ground-delay variables than in DELINT1: number of flights of flow i scheduled to depart at t and departing at t'. Therefore, this model takes into account not only the number of flights ground-delayed but also the length of the delay affecting the flights.

As with model M-CFMU (see section 7.2) the following is assumed:

1. All flights have identical cost functions.
2. All flights in a flow, that is flights with the same origin-destination, fly the same route, at the same speed.
3. The period of time for which flow re-routings are being considered is divided into p identical time intervals.

The following notation is used:

Notation:

i	index for flows. $i = 1,\dots,m$
n	total number of flights
z	index for the *zth* flight above capacity. $z = 1,\dots, Z$
Z	maximum number of flights allowed to exceed capacity. $Z \le n$
N_i	set of flights in flow i. $\sum_{i=1}^{m} \lvert N_i \rvert = n$
k	index for sectors. $k = 1,\dots,l$
R_i	set of routes acceptable to flow i
j	index for routes. $j \in (\bigcup_{i} R_i)$
	each route is defined by a sequence of sectors $k, k', \dots$ and a corresponding sequence of entry times $t_{jk}, t_{jk'}, \dots$
L_k	set of routes that cross sector k
t	index for time interval. $t = 1,\dots,p+1$
t_{jk}	time intervals it takes to get from departure point to sector k on route j
τ_{jk}	time intervals it takes to cross sector k on route j
	excluding the entry time interval
	$\tau_{jk} = \max\{0, t_{jk'} - t_{jk} - 1\}$ where k' is the sector just after sector k in route j
$\overline{Y}$	limit on the number of flights ground - delayed
$\overline{q}$	maximum number of ground - delay periods allocated to a flight
u_{kt}	capacity of sector k during t
f_{it}	number of flights of flow i scheduled to depart at t. $\sum_{t=1}^{p} f_{it} = \lvert \mathrm{N}_i \rvert \quad (i = 1,\dots,m)$
M_{it}	a number large enough so that if $x_{ij} = 1,\ d_{ijt} \le M_{it}$
	$M_{it} = \min\{\lvert \mathrm{N}_i \rvert, f_{it} + \overline{Y}\},\ M_{i,p+1} = \lvert N_i \rvert$
c_j	additional cost of route j
g_{zk}	marginal cost of the *zth* flight above capacity in sector k
g_{it}	cost of ground - delay per time period and flow
$g(t)$	cost of t time periods of ground - delay
c_0 , α	constants in ground - delay cost function

Variables:

$$x_{ij} = \begin{cases} 1 & \text{if flow } i \text{ is assigned to route } j \\ 0 & \text{otherwise} \end{cases}$$

$$o_{ztk} = \begin{cases} 1 & \text{if there is a zth flight above capacity at } t \text{ in sector } k \\ 0 & \text{otherwise} \end{cases}$$

y_{it} number of flights of flow i ground - delayed at t

d_{ijt} number of flights of flow i departing on route j at t

$d_{ijtt'}$ number of flights of flow i on route j that were scheduled to depart at t and will depart at t'

7.3.1 Model BALDIST

For this model, a fourth assumption is added to the ones explained above:

4. The cost of the n*th* flight exceeding the capacity of an air traffic control sector is bigger than the cost of the (n-1)*th* flight.

$$\min w = \sum_{i=1}^{m} \sum_{j \in R_i} \sum_{t=1}^{p} c_j f_{it} x_{ij} + \sum_{z=1}^{\bar{Z}} \sum_{t=1}^{p} \sum_{k=1}^{l} g_{zk} o_{ztk} \qquad \textbf{(7.3.1)}$$

subject to

$$\sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{\tau_{jk}} f_{i,t-t_{jk}-r+1} x_{ij} - \sum_{z=1}^{\bar{Z}} o_{ztk} \leq u_{kt} \quad (k = 1,\ldots,l; t = 1,\ldots,p) \qquad \textbf{(7.3.2)}$$

$$\sum_{j \in R_i} x_{ij} = 1 \quad (i = 1,\ldots,m) \qquad \textbf{(7.3.3)}$$

$$x_{ij} \in \{0,1\} \quad (i = 1,\ldots,m; j \in \bigcup_{i} R_i) \qquad \textbf{(7.3.4)}$$

$$o_{ztk} \in \{0,1\} \qquad (z = 1,\ldots,\bar{Z}; t = 1,\ldots,p; k = 1,\ldots,l) \qquad \textbf{(7.3.5)}$$

Remarks:

1. another set of constraints could be considered:

$o_{ztk} \leq o_{(z-1),tk} \quad (z = 2,\dots,\bar{Z}; t = 1,\dots,p; k = 1,\dots,l)$

however as

$g_{zk} > g_{(z-1),k} \quad (z = 2,\dots,\bar{Z}; k = 1,\dots,l)$

these constraints will always be observed.

2. calculating the maximum difference between traffic demand and capacity, a tighter bound for Z can be obtained as follows:

$$\bar{Z} \leq \max_{(k,t)} \left\{ 0, \sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{t_{jk}} f_{i,t-t_{jk}-r} - u_{kt} \right\}$$

The objective of the model, represented in expression (7.3.1), is to minimise the total cost of re-routings and congestion. Expressions (7.3.2) are the capacity constraints affecting each ATC sector at each time interval and expressions (7.3.3) make sure that a flow is assigned to one and only one route.

7.3.2 Models with Ground-delays

For both the following models there is also an additional assumption:

4. The capacity of sectors in time interval $p+1$, the time interval just after the end of the period during which the re-routing measures apply, is infinite. In practice, this means that in the time period after the end of the re-routing the difference between capacity and demand will be sufficiently large to allow the backlog of flights ground-delayed to depart.

7.3.2.1 Model DELINT1

$$\min\ w = \sum_{i=1}^{m} \sum_{j \in R_i} \sum_{t=1}^{p} c_j f_{it} x_{ij} + \sum_{i=1}^{m} \sum_{t=1}^{p} g_{it} y_{it} \qquad \textbf{(7.3.6)}$$

subject to:

$$\sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{\tau_{jk}} d_{ij,t-t_{jk}-r+1} \leq u_{kt} \qquad (k = 1,\ldots,l; t = 1,\ldots,p) \qquad \textbf{(7.3.7)}$$

$$\sum_{j \in R_i} x_{ij} = 1 \qquad (i = 1,\ldots,m) \qquad \textbf{(7.3.8)}$$

$$d_{ijt} \leq M_{it} x_{ij} \qquad (i = 1,\ldots m; j \in R_i; t = 1,\ldots,p+1) \qquad \textbf{(7.3.9)}$$

$$\sum_{j \in R_i} d_{ijt} = f_{it} + y_{i,t-1} - y_{it} \qquad (i = 1,\ldots,m; t = 1,\ldots,p+1) \qquad \textbf{(7.3.10)}$$

$$x_{ij} \in \{0,1\} \qquad (i = 1,\ldots,m; j \in R_i) \qquad \textbf{(7.3.11)}$$

$$0 \leq y_{it} \leq \overline{Y} \text{ and integer} \qquad (i = 1,\ldots,m; t = 1,\ldots,p) \qquad \textbf{(7.3.12)}$$

$$y_{i0} = 0, y_{i,p+1} = 0 \qquad (i = 1,\ldots,m) \qquad \textbf{(7.3.13)}$$

$$d_{ijt} \geq 0 \text{ and integer} \qquad (i = 1,\ldots,m; j \in R_i; t = 1,\ldots,p+1) \qquad \textbf{(7.3.14)}$$

The objective of the model, represented in expression (7.3.6), is to minimise the total cost incurred in the re-routings plus the aggregated cost of ground-delays. The unit cost of ground-delays is assumed to be constant with the length of ground-delay. Expressions (7.3.7) make sure that all the flights present in a sector at a certain time interval do not exceed the capacity of that sector. Expressions (7.3.9), like expressions (7.2.5), ensure that flights do not depart on routes that have not been assigned to their flow. Expressions (7.3.10) state that the total flights of a flow departing at a time interval *t* equal the total flights of that flow scheduled to depart at *t* plus the flights ground-delayed at (*t-1*) minus the flights to be ground-delayed at *t*. Expressions (7.3.12) define the ground-delay variables as integer and impose an upper limit on the number of flights of a flow ground-delayed.

It should be noted that the number of constraints in expressions (7.3.9) could be reduced by replacing expressions (7.3.9) with the following constraints:

$$\sum_{t=1}^{p+1} d_{ijt} \le |N_i| x_{ij} \qquad (i = 1,\ldots m; j \in R_i)$$

However, the initial testing of the model revealed that the execution time decreases significantly when the numbers linking the departure and assignment constants are tightened, even if that means increasing the number of constraints of the problem.

7.3.2.2 Model DELINT2

$$\min\ w = \sum_{i=1}^{m} \sum_{j\in R_i} \sum_{t=1}^{p} c_j f_{it} x_{ij} + \sum_{i=1}^{m} \sum_{j\in R_i} \sum_{t=1}^{p} \sum_{t'=t+1}^{t+\bar{q}} g(t'-t) d_{ijtt'} \qquad \textbf{(7.3.15)}$$

subject to:

$$\sum_{i=1}^{m} \sum_{j\in(R_i\cap L_k)} \sum_{r=0}^{\tau_{jk}} \sum_{t=1}^{t'-t_{jk}-r+1} d_{ijt,t'-t_{jk}-r+1} \le u_{kt'} \qquad (k = 1,\ldots,l; t' = 1,\ldots,p) \qquad \textbf{(7.3.16)}$$

$$\sum_{j\in R_i} x_{ij} = 1 \qquad (i = 1,\ldots,m) \qquad \textbf{(7.3.17)}$$

$$\sum_{t'=t}^{t+\bar{q}} d_{ijtt'} \le M_{it} x_{ij} \qquad (i = 1,\ldots,m; j \in R_i; t = 1,\ldots p) \qquad \textbf{(7.3.18)}$$

$$\sum_{j\in R_i} \sum_{t'=t}^{t+\bar{q}} d_{ijtt'} = f_{it} \qquad (i = 1,\ldots,m; t = 1,\ldots,p) \qquad \textbf{(7.3.19)}$$

$$x_{ij} \in \{0,1\} \qquad (i = 1,\ldots,m; j \in R_i) \qquad \textbf{(7.3.20)}$$

$$d_{ijtt'} \ge 0 \text{ and integer} \qquad (i = 1,\ldots,m; j \in R_i; t = 1,\ldots,p; t' = t,\ldots,t+\bar{q} \le p+1) \qquad \textbf{(7.3.21)}$$

The objective of the model is, again, to minimise the cost incurred in the re-routings and the estimated cost of ground-delays but taking into account the length of delays. Expressions (7.3.16) and (7.3.17), as in the previous model, are, respectively, the capacity constraints on ATC sectors and the constraints on the assignment of routes to flows. Expressions (7.3.18) ensure that no flights depart on routes which their flows do not use and expressions (7.3.19) ensure that the number of flights departing equals the number of flights scheduled.

The number of constraints in expressions (7.3.18) could be reduced by replacing them with the following constraints:

$$\sum_{t=1}^{t'} \sum_{t'=t}^{p+1} d_{ijtt'} \leq |N_i| x_{ij} \qquad (i = 1,\ldots,m; j \in R_i)$$

However, as with DELINT1, initial testing showed that the execution time is significantly shorter with smaller numbers linking the above variables, even if the number of constraints is significantly increased.

The three models described in this section, BALDIST, DELINT1 and DELINT2, when applied to the 3 sector case described in Appendix D were solved to optimality in very little time. A natural question is how do they behave when extended to a larger airspace. To address this question, the next chapter describes and discusses the test of these models using data of traffic which crossed the whole French upper airspace on a day of 1996.

7.4 Conclusions

This chapter describes the modelling process behind the development of optimisation models for the re-routing of air traffic flows in Europe. It identifies two types of models relevant to the re-routing of flows: network flow models and integer models. Exploratory examples suggested that integer models would be preferable in terms of flexibility in the formulation and potential size of the problem. To define the decision variables, the authority of the CFMU in issuing re-routing control measures is debated. Considering the present situation and likely developments, it is assumed that the CFMU has the authority at the pre-tactical level to issue instructions to re-route flows of traffic for a very well defined period, but the decision to re-route a particular flight on the day of operations is made by the airline. The problem is then solved in two stages: in the first stage acceptable alternative routes (in terms of extra-flying time or additional cost) for each flow are determined; in the second stage, given the routes selected in the first stage and the capacity constraints affecting the ATC sectors, a route is assigned to each flow so that the total cost of congestion and re-routings is minimised.

The modelling trade-offs that can be made between the level of detail included, the execution time and the size of the model are debated and lead to the development of 3 different optimisation models BALDIST, DELINT1 and DELINT2. One area where these trade-offs have to be made is in the way congestion is represented in the model. At least, two possibilities can be considered: 1) use penalties whenever traffic demand exceeds the capacity of an ATC sector; or 2) use ground-delays to keep the demand within capacity. Possibility 2) is justified by the fact that congestion results in ground-delays, but it can lead to large-size integer problems. It should be stressed that at this level of planning, ground-delays are in the problem just to support the decision on the re-routing of flows. The actual allocation of ground-delays will be done by the CFMU computer system, TACT, on the day of the flights. Possibility 1) reduces substantially the size and execution time of the problem, but because it does not take into account the cumulative effect of capacity/demand imbalances over time it may underestimate congestion. Both possibilities are explored in this chapter: BALDIST is based on possibility 1) and DELINT1/2 are based on possibility 2).

Models with ground-delays have two types of decision variables: 1) variables assigning one route to each flow; and 2) variables assigning ground-delays (or departure time intervals) to flights. The first type of variable depends on the number of flows and the choice of routes available. The definition of the ground-delay variables, given the large number of flights involved, was not immediate. If a binary variable is defined for each flight in a flow, on each route and time interval, the number of variables easily reaches 100,000. Another possibility, used in DELINT1, is to model ground-delay variables in terms of 'number of flights delayed' which reduces the size of the problem but is less detailed and does not facilitate the use of non-linear ground-delay costs. To overcome these drawbacks, variables can be defined in a more detailed way: $d_{ijrt'}$

representing the number of flights of flow *i*, on route *j* that are scheduled to depart at *t* and are departing at *t*.

This formulation, used in DELINT2, results in larger models but still smaller than the binary models. It should be stressed that size and execution time are not necessarily linked. The execution time of some of the models tested can be reduced with alterations that increase the size of the models significantly and, for instance, initial results indicate that DELINT2 runs faster than DELINT1 despite being substantially larger.

Chapter 8 describes the testing of the models presented in this chapter and Chapter 9 discusses extensions to the models and how they can be embedded in actual re-routing decision support systems.

Chapter 8

Testing the Models

8.1 Introduction

This chapter describes the testing of the optimisation models presented in Chapter 7 using traffic data provided by the CFMU. Section 2 defines the input and output of models and section 3 describes the stages of data analysis, definition and sorting that took place to transform the flight plans into formatted input for the optimisation models, a process that took approximately 5 months. Following this, the results provided by the models BALDIST, DELINT1 and DELINT2 are analysed and compared and conclusions on the feasibility of the models are taken.

8.2 Input and Output of the Models

The following data is needed to run the models:

1. sectors (k);
2. flows of traffic (i);
3. routes admissible to each flow (R_i);
4. routes crossing each sector (L_k);
5. additional cost of each route (c_j);
6. BALDIST: marginal cost of the *zth* flight above capacity at each sector (g_{zk}). DELINT1: cost of ground-delaying a flight of flow i at t (g_{it}). DELINT2: cost of ground-delaying a flight for $(t'-t)$ time intervals ($g(t'-t)$);
7. period of time split into identical p time intervals;
8. capacity of every sector at each time interval (u_{kt});
9. number of flights of each flow scheduled to depart at each time interval (f_{it}).

Some of these data, such as the sectors, are typically permanent whereas others, such as the scheduled flights, are temporary, and changed on a daily basis. However, the flows and routes may vary monthly or even weekly, depending on the traffic situation.

BALDIST provides the following output:

1. route to be assigned to each flow (x_{ij});
2. flights above capacity at each sector and time interval ($o_{=tk}$);
3. estimate of cost of re-routings;
4. estimate of cost of congestion.

The output of DELINT1 is as follows:

1. route to be assigned to each flow (x_{ij});
2. number of flights of each flow ground-delayed at each time interval (y_{it});
3. number of flights of each flow departing at each time interval (d_{ijt});
4. estimate of cost incurred with the re-routings;
5. estimate of cost of ground-delays;
6. number of flights above capacity at each sector and time interval, provided by:

$$u_{kt} - \sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{\tau_{jk}} f_{i,t-t_{jk}-r+1} x_{ij}$$

It should be noted that DELINT1 does not provide an estimate of the number of time intervals for which flights are ground-delayed.

DELINT2 provides the following output:

1. route to be assigned to each flow (x_{ij}):

2. number of flights of each flow departing at each time interval ($d_{ytt'}$) and number of periods they have been ground-delayed $(t' - t)$;
3. estimate of cost incurred with the re-routings;
4. estimate of cost of ground-delays;
5. number of flights above capacity at each sector and time interval.

As noted, the estimates of cost of ground-delay and re-routings are calculated assuming that all flights have the same cost function, they do not represent actual costs. These estimates can be used to compare different scenarios such as a situation where all flights take the best route with a situation where flows are re-routed.

8.3 Preparation of the Data

The set of data used to test the models is based on the actual traffic crossing the French upper airspace on 25/04/96, from 03.00h to 22.00h, totalling 3582 flights. The French airspace was chosen because it is at the cross-roads of the European airspace, with approximately 25% of the whole of ECAC traffic, and many of its sectors are often congested. The period from 03:00h to 22.00h is similar to the periods to which some re-routing control measures apply.

The preparation of the data from the flight plans to a format able to run through the optimiser can be broken down into four interrelated stages: identification of ATC sectors and capacities, identification of flows, determination of routes and sorting of the flights.

8.3.1 Stage 1: Identification of Air Traffic Control Sectors and Capacities

Initially, the possibility of working with both upper and lower airspace was considered, but the lower airspace includes very short flights, terminal approaches and other local features that would require much more data analysis and preparation time. It was therefore excluded. The French controlled airspace is divided into five regions under the responsibility of five air traffic control centres: Aix, Bordeaux, Brest, Paris and Reims. For air traffic control purposes each region is, in turn, broken up into sectors. Sectors can have different configurations, for instance, two contiguous sectors can be merged for a certain period of the day if the traffic is expected to decrease or if there are less air traffic controllers on workshift. The set of possible configurations is pre-defined at strategic planning level; a few days before the actual flights, the ATC centres, taking into account traffic demand forecasts and personnel schedules, select the configurations for the day of operations. It should be noted that these multiple configurations and resulting variations in capacity are more common in the French airspace than in other parts of the European airspace, where sector configurations tend to remain the same. For the purpose of this test, a single configuration of sectors was adopted from 03.00 to 22.00h. The configuration chosen is the one with the largest capacity that was available on 25/4/96. The sectors considered, 41 in total, and corresponding capacities, are shown in Appendix E.

At present, ATC capacity for ATFM purposes is defined hourly. Therefore, hourly time intervals were used in this test. As a result of considering part of the airspace, an additional assumption is made: all other airspace elements not considered in the model (airports, lower airspace, neighbouring airports, etc.) do not have capacity constraints. The effect of this assumption is attenuated by the fact that the French airspace is one of the main bottlenecks of the European airspace.

8.3.2 Stage 2: Identification of Flows

The identification of flows took considerable time (approximately 1 month) and extensive analysis of the data. Different ways of defining flows were tested, with varying degrees of aggregation and, taking into account the availability of alternative routes. To start with, flows were defined according to the traffic orientation scheme, the plan where the main European flows crossing congested areas are routed for the Summer season. These flows, usually defined in very aggregate terms, were then refined. After that, the flight plans were analysed. This provided more significant flows. Some flows were altered, added and cancelled later in stage 3, when determining alternative routes, and also in stage 4, when sorting the flights (see below).

A flow is here defined as a set of flights departing from one airport or an airport area to another airport or airport area. The flows have a tree-like structure: many flows have very similar routes differing only in the extremities, that is the first and/or last segments of the route. It should also be noted that the larger the number of flows considered, the larger the possibility set for routing flows. Thus, the flexibility of ATFM is increased. The 138 flows identified are shown in Appendix E sorted by flow group. The flow groups are shown in Table 8.3-1. Flows belong to the same group if the portion of their routes crossing the French upper airspace is the same.

Another 41 artificial flows, one for each sector, were defined to group the remainder of the traffic, the flights that do not belong to any of the above flows. Each of these artificial flows includes all the flights that cross the corresponding sector. This method of grouping the rest of the flights, while counting the exact number of flights that cross each sector during a certain time interval, multiplies the total number of flights, because a flight will typically cross several sectors. In the models with ground-delays, DELINT1/2, it is implicitly assumed in the allocation of ground-delays that a flight crossing several sectors is a set of independent flights, one for each sector crossed. This simplifies the allocation of ground-delays because each of these flights is affected by a single capacity constraint and may have the effect of underestimating the total ground-delay. However, countering this effect it should be noted that part of these flights cannot be subject to ground-delays because they depart from airports outside the ECAC area.

8.3.3 Stage 3: Determination of Routes and Costs

The best route for each flow was obtained from the flight plans, selecting the most frequently filed route on that date. The alternative routes, depending on the choice of routes filed, were either obtained from the flight plans or determined by calculating the distance. The flying times were also obtained from the flight plans assuming that all flights were flying at the same speed of one of the flights in the flow. Only routes acceptable to airlines, that is routes whose flying time is not significantly larger than the flying time of the best route (extra flying time less than or equal to 30 minutes), were chosen. Given the large number of flows considered, this stage of data preparation took approximately two months to complete.

The cost of the alternative routes is an estimate of the fuel cost incurred with the re-routing, by flying longer or at a lower altitude. It is calculated in the following way for a route *j*:

$$c_j = 10.\ \alpha_j + \mu\Delta_j$$

$$\mu \ = \begin{cases} 10 \text{ if } \Delta_\mathrm{j} \le 15 \\ 100 \text{ if } 15 < \Delta_\mathrm{j} \le 30 \end{cases}$$

where the following notation is used:

α_j minutes flying in sectors lower than the sectors in best route

μ cost of a minute of extra - flying time

Δ_j additional flying time of route *j*

The routes chosen for each flow are described in Appendix E.

8.3.4 Stage 4: Sorting the Flights

The sorting of the flights by flows and departure time interval took also a long time (approximately two months). The flights considered for re-routings totalled 920 (approximately 26% of the traffic) and were easily sorted by the aerodrome code but had also to be sorted by departure time interval, which is more difficult to extract from the flight plan. The remainder of the flights, totalling 2662, had to be sorted by sectors they crossed, data which was also difficult to extract from the flight plan, and more error prone because sectors can be designated in different ways. The number of flights in each group of flows is shown in Table 8.3-1. The scheduled flights per flow and the time intervals are shown in Appendix E.

Table 8.3-1 Flights Considered for Re-routing

UK to Balearics, Barcelona and Alicante	33

Germany (exc. West) and Switzerland to Balearics and Barcelona	26
West Germany to Balearics and Barcelona	7
Barcelona and Balearics to West Germany	7
Barcelona and Alicante to Brussels and Amsterdam	17
Barcelona, Balearics and Alicante to Germany and Switzerland	32
Barcelona, Balearics and Alicante to UK	33
Madrid to Frankfurt and Stuttgart	8
Madrid to Southeast Germany and Switzerland	15
Madrid to West Germany	4
Athens and Rome to Lisbon and Madrid	11
North Italy to Lisbon and Madrid	14
Lisbon and Madrid to Athens and Rome	10
Lisbon and Madrid to North Italy	13
UK (exc. London), Brussels and Amsterdam to Switzerland	27
London to Switzerland	35
Switzerland to Brussels and Amsterdam	19
Geneva to UK	18
Zurich to UK	25
UK to Italy	54
Italy to UK	55
Paris to Italy	67
Italy to Paris	68
Paris to Toulouse	44
Paris to Marseilles and Nice	82
Toulouse to Paris (Charles de Gaulle and Orly)	41
Brussels, Amsterdam and West Germany to Madrid and Malaga	20
Germany (exc. West) to Madrid and Malaga	16
UK to Madrid and Malaga	46
South Germany to Canary Islands	9
Germany (exc. South) to Canary Islands	25
UK to Canary Islands	39
Total Flights Considered for Re-routing	920

8.4 The Results Using BALDIST

Before presenting the results, a few details on the objective function used in BALDIST are provided: the additional cost of a route is measured in terms of fuel cost as explained in section 8.3.3. For the cost of congestion two possibilities are considered:

1. $g_{zk} = c_0 \cdot z^2 \qquad (\forall k)$

2. $g_{zk} = c_0 \cdot (1+\alpha)^z \qquad (\forall k)$

Possibility 2 is adapted from (Terrab and Odoni, 1993). Three functions depicted in Figure 8.4-1 are experimented:

Function 1: $g_{zk} = 400 \cdot z^2 \qquad (\forall k)$

Function 2: $g_{zk} = 100 \cdot 2^z \qquad (\forall k)$

Function 3: $g_{zk} = 2 \cdot 4^z \qquad (\forall k)$

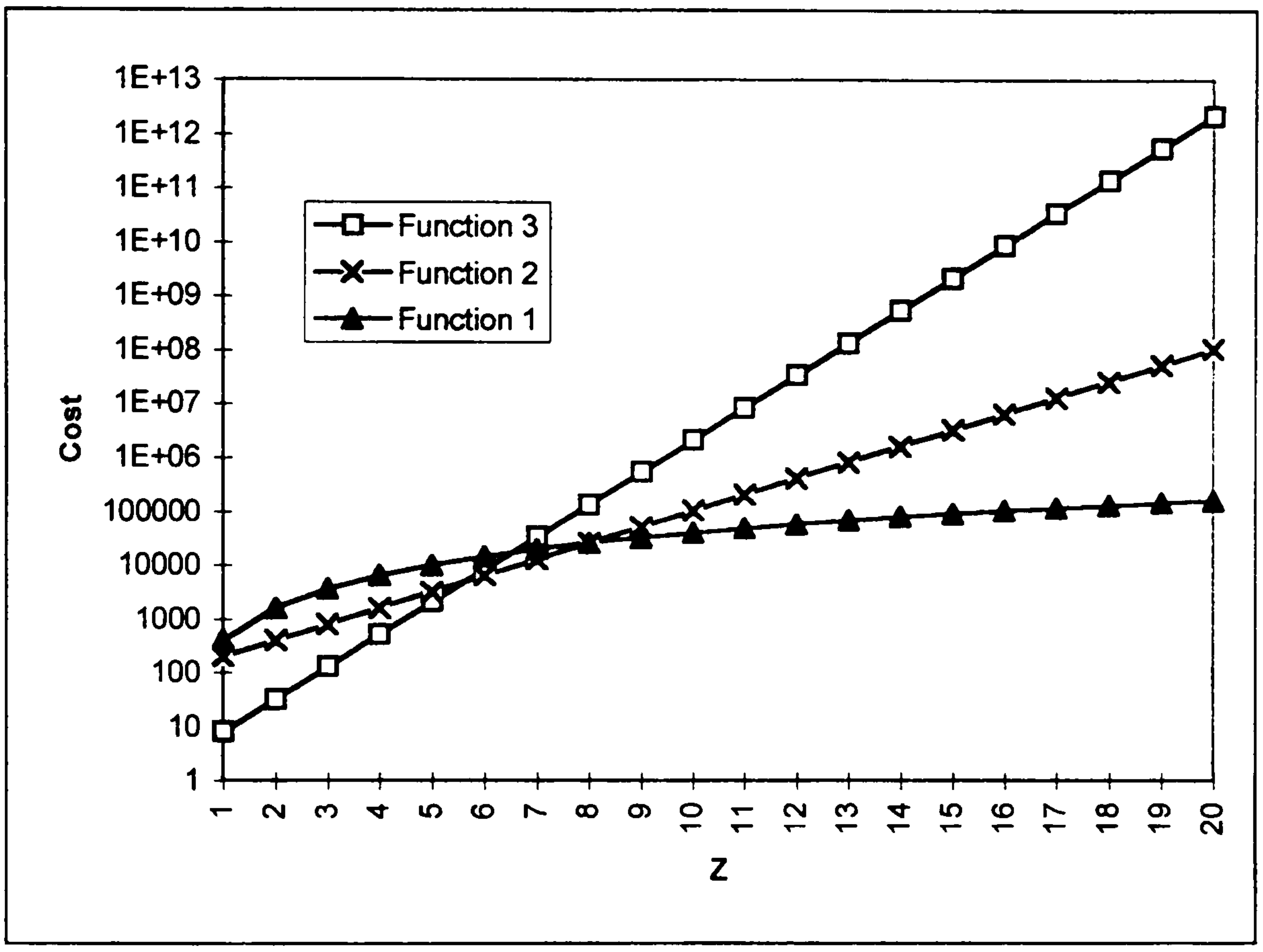


Figure 8.4-1: BALDIST - Congestion Cost Functions

The period from 03.00h to 22.00h is divided into 19 hourly time intervals. The model was solved using GAMS 2.25 modelling system coupled with a standard integer programming package LAMPS 1.66 on a SUN/SPARC workstation. The size of the problem is shown in Table 8.4-1 and the results in Table 8.4-2.

Table 8.4-1: BALDIST - Problem Size

Capacity constraints	779
Assignment constraints	138
Total constraints	917
Assignment variables	303
Congestion variables	14801

Total variables	15104

Note: $\bar{Z} = 19$

The difference in cost between the solutions with re-routings and the solutions obtained if all flights take the best route is substantial. However, it should be stressed that the situation 'All flights take best route' is an extreme situation: in a real environment not all flights take the best route and, if congestion is expected, flow managers and airlines take action dynamically to prevent congestion building-up. For instance, if ground-delays are mounting up on the best route a few airlines might decide to re-route some of their flights onto another route, thus alleviating congestion. Therefore, all comparisons between the situations 'all flights take best route' and 'with re-routings' have to be read remembering that what really happens is somewhere between the two situations but, probably, closer to the former.

The gap between the optimal value of the linear relaxation and the optimum (integer) value is in all cases very small. This might be due to the format of the constraints matrix, very close to a unimodular matrix, with most variables having coefficients 1 or -1 (see Winston, 1991). Consequently, the Branch-and-Bound (B&B) search (measured in number of B&B nodes) and the execution time are very short (see Table 8.4-2).

Table 8.4-2: BALDIST - Summary of Results

	Function 1	Function 2	Function 3
(1) Cost if all flights take best route	7834400	2326155200	202316774920448
(2) Optimum value	4086660	217152380	1102389427544
variation between (1) and (2)	-47.84%	-90.66%	-99.46%
(3) Linear relaxation-optimum value	4086036	217151805	1102389427279
variation between (3) and (2)	0.02%	0.00%	0.00%
Flows re-routed	35	35	29
Flights re-routed	346	342	251
CPU time (sec)	33	34	31

Number of B&B nodes	20	24	6

The models with functions 1 and 2 re-route more than 33% of the flights considered for re-routing control measures and the model with function 3 about 28%. The fact that function 3 only reaches functions 1 when $z=7$ and 2 when $z=5$ might explain this difference in number of flights re-routed (see Figure 8.4-1). However, the majority of the flows, 24 flows, are re-routed whatever the congestion cost function used (see Table 8.4-3). These recurrent re-routings are prompted by severely congested sectors, such as AO and UFXF. For instance, the London-Switzerland and Geneva-UK flows whose best route crosses sector AO, and have alternative routes by-passing it, are always re-routed.

Table 8.4-3: BALDIST - Flights Re-routed

Flow Group	Function 1	Function 2	Function 3
UK to Balearics, Barcelona and Alicante	0	0	12
Germany(exc. west) and Switz. to Balearics and Barcelona	2	2	2
W. Germany to Balearics and Barcelona	5	5	5
Barcelona and Alicante to Brussels and Amsterdam	8	8	10
Barcelona , Balearics and Alicante to Germany and Switz.	3	3	0
Barcelona , Balearics and Alicante to UK	12	12	1
Madrid to Frankfurt and Stuttgart	8	8	6
UK (exc. London), Brussels and Amsterdam to Switz.	15	15	15
London to Switz.	21	21	21
Geneva to UK	18	18	18
Zurich to UK	21	21	21
UK to Italy	4	4	6
Italy to UK	4	4	4
Paris to Italy	57	57	54
Italy to Paris	7	7	0
Paris to Marseilles and Nice	82	82	44
Toulouse to Paris	30	30	0
Brussels, Amsterdam and Wgermany to Madrid and Malaga	4	0	4
Germany (exc. West) to Madrid and Malaga	16	16	11
UK to Madrid and Malaga	29	29	17
Total Flights Re-routed	346	342	251

One of the advantages of BALDIST is the possibility of analysing congestion directly in terms of sectors:

Figure 8.4-3 and Figure 8.4-4 show expected congestion (here measured in terms of number of flights above capacity) in four situations: if all flights take best route, and if flights are re-routed using functions 1, 2 and 3. Sectors and time intervals for which there are no flights above capacity are not shown in the figures. As expected, flow re-routings smooth congestion peaks, with functions 1 and 2 reducing congestion more than function 3. However, sectors such as PV2 and AO are still significantly congested after the flow re-routings. This problem may be addressed by re-routing short-haul flights to the lower airspace (not considered in this test) or by increasing the capacity of these sectors, during the peak hours (Figure 8.4-2 shows the congestion peaks for sector AO).

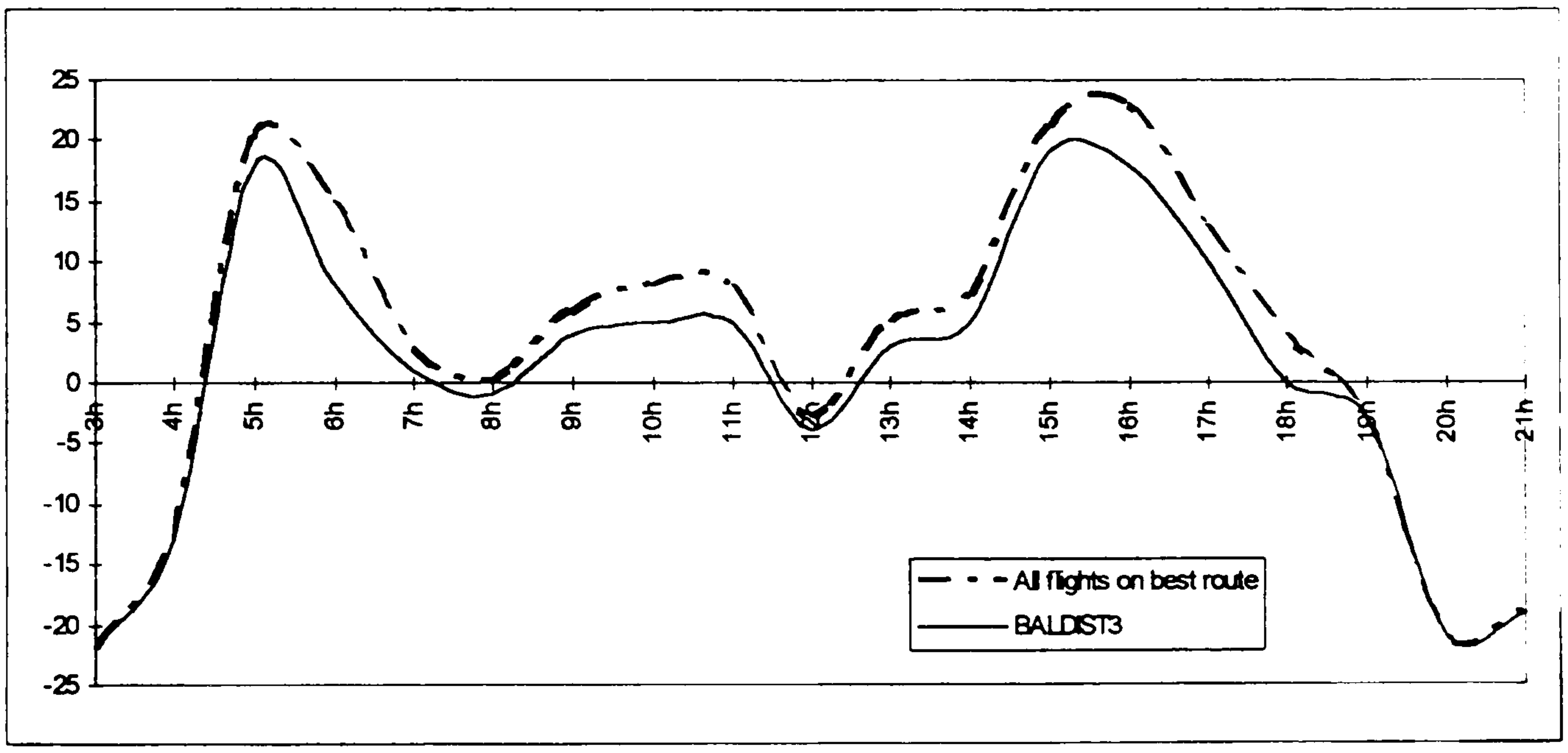


Figure 8.4-2: Sector AO - Traffic Demand minus Capacity

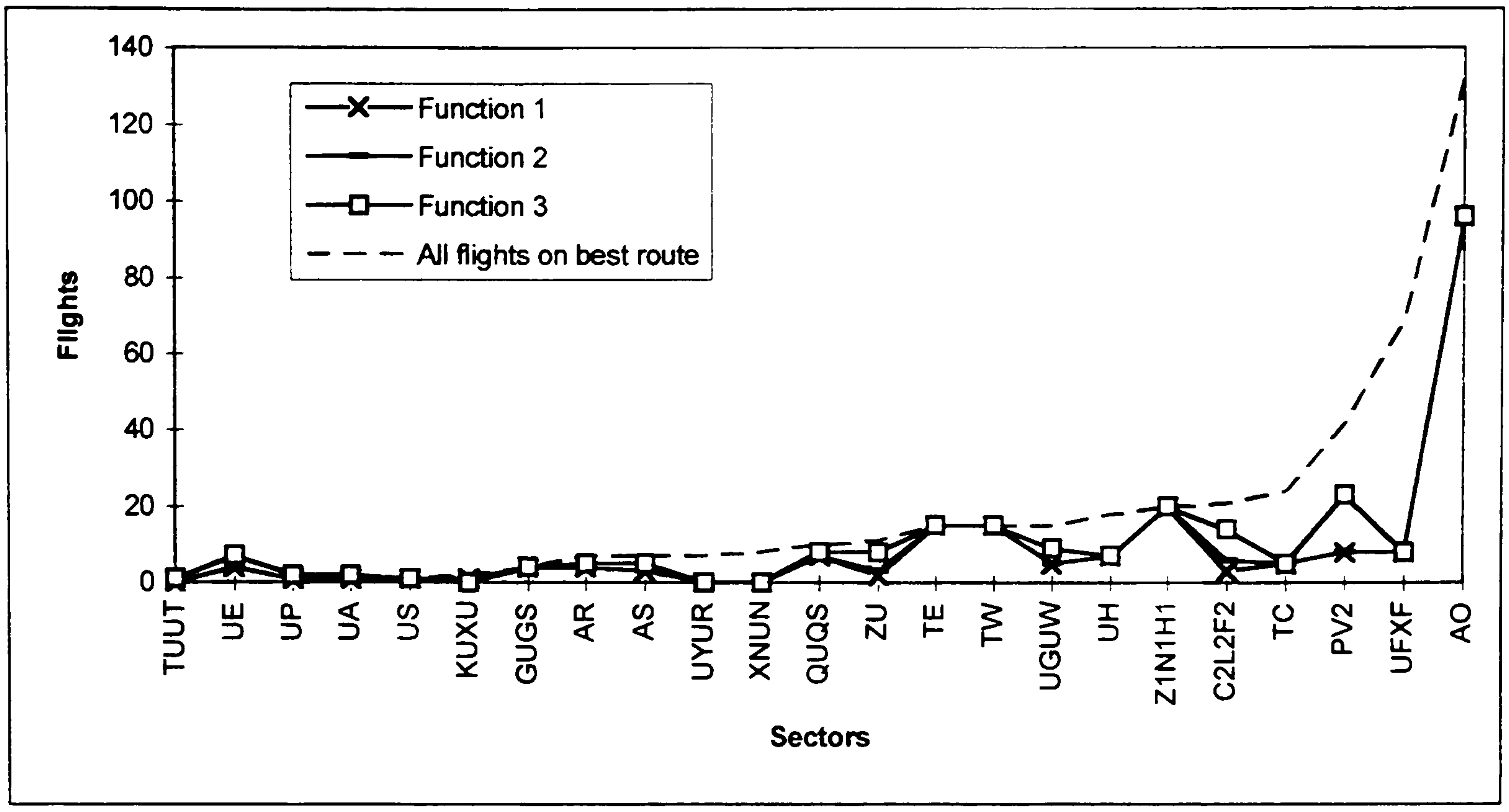


Figure 8.4-3: BALDIST - Flights Above Capacity by Sector

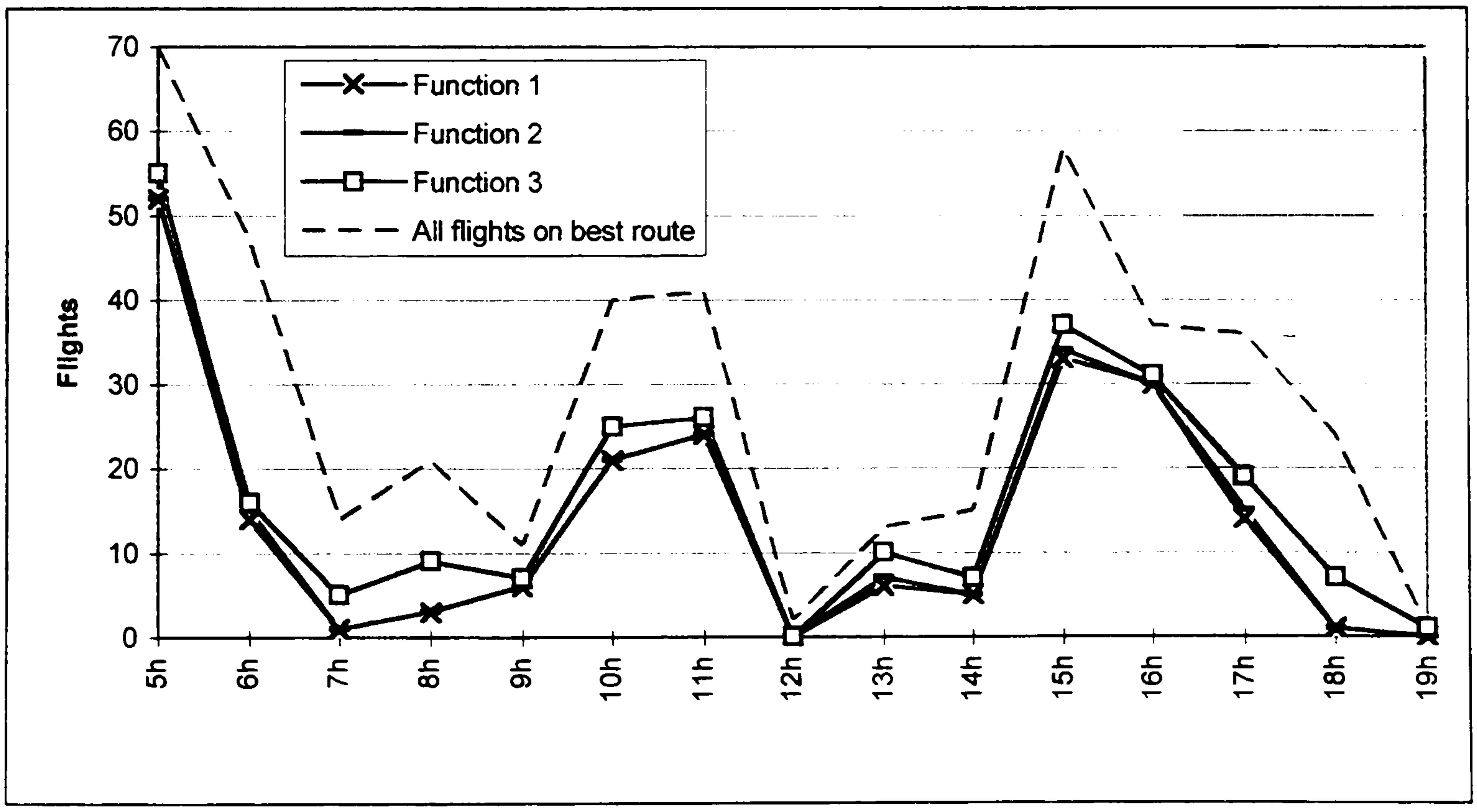


Figure 8.4-4: BALDIST - Flights Above Capacity by Time Interval

8.5 The Results Using DELINT1

The additional cost of routes is the same as for BALDIST, the cost of ground-delay varies with the time interval and flow and is calculated in the following way:

$$g(i,t) = a.(1 + m(t) / \max(1, f_{it})$$

Where a is a constant representing the basic cost of delay; the number used is a=147, approximately the same as the cost of 15 min of extra-flying time. Section 7.2.3 shows how *m(t)* is calculated (see expressions 7.2.8).

The time is again broken up into 19 hourly time intervals and an additional 20th interval to make sure all flights ground-delayed depart. The size of the problem is shown in Table 8.5-1 and the main results in Table 8.5-2. The first optimisation runs of this problem showed that it is hard to solve to optimality, therefore to limit the execution time, the best solution obtained after 10,000 iterations, corresponding to approximately 8 minutes of CPU time, was taken. However, the difference between the value of this solution and the lower bound provided by the linear relaxation of the model is very small: 0.71%, meaning that the value of this solution is, at most, 0.71% away from the optimum value. It should be noted that the solution obtained may well be the optimum solution, but the execution time required to ascertain it is too large.

Table 8.5-1: DELINT1 - Problem Size

Capacity constraints	779
Assignment constraints	138
Flights have to be routed onto flow route	6880
Relation flights g. delayed/departing	3580
Total constraints	11377
Assignment variables	303
Ground-delay variables	3401
Departure variables	6880
Total variables	10584

Table 8.5-2: DELINT1- Summary of Results

(1) Cost if all flights take best route	12323675
(2) Best value after 10,000 iterations	7181207
variation between (1) and (2)	-41.73%
Linear relaxation-optimum value	7130246
Maximum distance of (2) from optimum value	0.71%
Flows re-routed	34
Flights re-routed	312
(3) Flights g. delayed if all take best route	2154
(4) Flights g. delayed with re-routings	1011
variation between (3) and (4)	-53.06%
Total g. delay if all flights take best route (minutes)	129240
Total g. delay with re-routings	60660
CPU time (sec)	466
Number of B&B nodes	368

Table 8.5-3: DELINT1- Flights Re-routed

Flow Group	Flights
UK to Balearics, Barcelona and Alicante	6
Germany (exc. West) and Switzerland to Balearics and Barcelona	2
West Germany to Balearics and Barcelona	5
Barcelona and Balearics to West Germany	2
Barcelona and Alicante to Brussels and Amsterdam	9
Barcelona , Balearics and Alicante to UK	6
Madrid to Frankfurt and Stuttgart	2
London to Switzerland	21
Switzerland to Brussels and Amsterdam	6
Geneva to UK	18
UK to Italy	1
Italy to UK	4

Paris to Italy	67
Paris to Marseilles and Nice	82
Toulouse to Paris	30
Brussels, Amsterdam and Wgermany to Madrid and Malaga	6
Germany (exc. West) to Madrid and Malaga	16
UK to Madrid and Malaga	29
Total Flights Re-routed	312

Table 8.5-2 shows that re-routing only 312 flights, resulted in 1143 fewer flights being delayed. This represents 53.06% fewer delayed flights. Most of the flights benefiting from the reduction in ground-delay are the ones not considered for re-routing as seen in Figure 8.5-1. It should be noted that the ground-delay obtained using DELINT1 and DELINT2 is higher than it would be in a real situation. This may be explained by: 1) the difference between capacity and traffic demand and thus the ground-delay is calculated using hourly time units; and 2) the model is static. In a real situation, flow managers and aircraft operators usually take action to prevent or limit ground-delays.

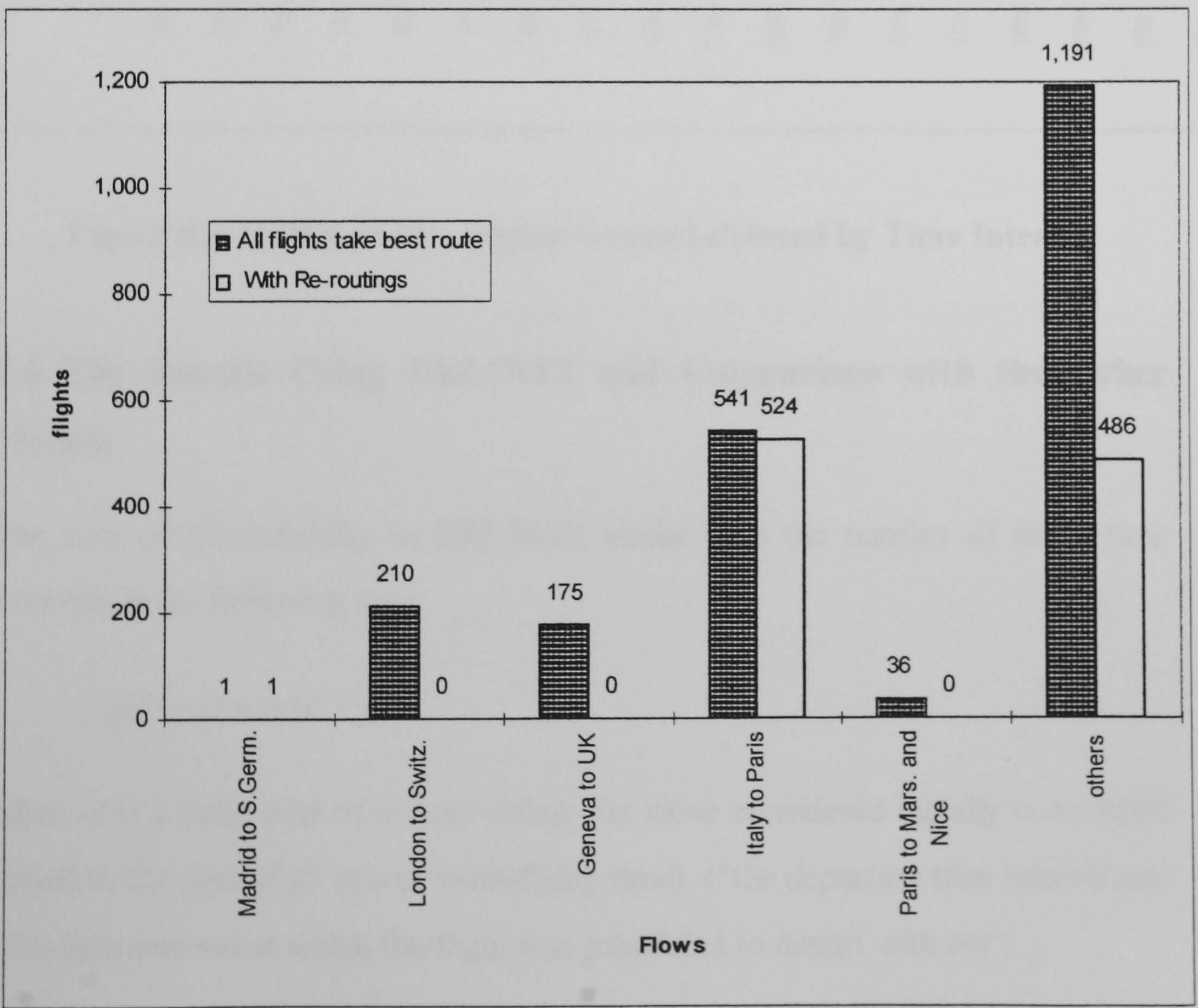


Figure 8.5-1: DELINT1 - Flights Ground-delayed by Flow Group

Figure 8.5-2 shows, once again, that flow re-routings have the potential to smooth congestion peaks significantly, with congestion here represented in terms of flights ground-delayed.

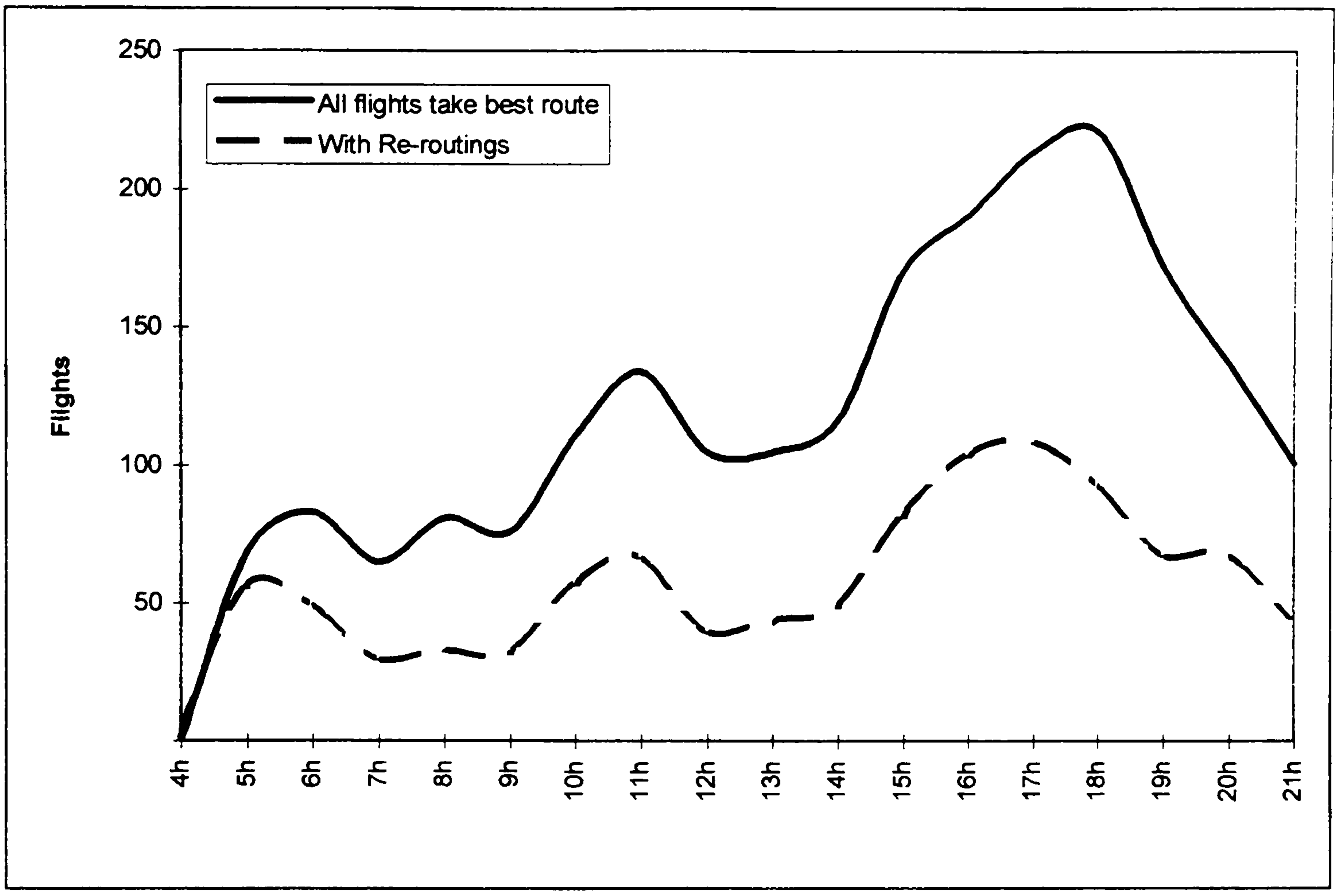


Figure 8.5-2: DELINT1 - Flights Ground-delayed by Time Interval

8.6 The Results Using DELINT2 and Comparison with the Other Models

The cost of ground-delay in DELINT2 varies with the number of delay time intervals in the following way:

$$g(t' - t) = a.(t' - t)^2$$

where a is a basic cost of ground-delay; the value considered initially is $a = 2500$ (equal to the cost of 25 min of extra-flying time), t' the departure time interval and t the time interval at which the flight was scheduled to depart with $t<t'$.

Time is divided into 19 hourly time intervals with an additional 20th interval to allow delayed flights to depart. The maximum number of time intervals flights can be delayed is 4, that is 4 hours. The size of the problem and the summary of results are shown respectively in Table 8.6-1 and Table 8.6-2. Despite being a larger model than DELINT1 this model appears to be less hard to solve to optimality: the solution presented is optimum and was obtained in very little time. The gap between DELINT2 optimum value and the linear relaxation optimum value is also very small: 0.17%.

Table 8.6-1: DELINT2 - Problem Size

Capacity constraints	779
Assignment constraints	138
Flights have to be routed onto flow route	6536
Relation flights scheduled/departing	3401
Total constraints	10854
Assignment variables	303
Departure variables	30616
Total variables	30919

DELINT1 (see Table 8.5-2) total delay is shorter than DELINT2 total delay, which can be explained by a different way of costing delay: in DELINT2 the cost depends, not on the total delay but on the length of delay affecting each flight whereas in DELINT1 it depends solely on the number of flights ground-delayed.

Table 8.6-2: DELINT2 - Summary of Results

(1) Cost if all flights take best route	9685000
(2) Optimum value	3522140
variation between (1) and (2)	-63.63%
(3) Linear relaxation-optimum value	3515978
variation between (3) and (2)	0.17%
Flows re-routed	38
Flights re-routed	351
(4) Flights ground-delayed if all take best route	1273

(5) Flights ground-delayed with re-routings	560
variation between (4) and (5)	-56.01%
(6) Total g. delay if all flights take best route (minutes)	116760
(7) Total g. delay with re-routings	46620
variation between (6) and (7)	-60.07%
CPU time (sec)	281
Number of B&B nodes	82

Table 8.6-3 shows the flights re-routed using the different models and identifies the number of flights which are re-routed in every model in the column labelled 'ALL'. There are 175 flights which are re-routed whatever the model used. In addition, there are flow groups, such as *Madrid to Frankfurt and Stuttgart*, which have, at least, one flow re-routed whatever the model used (see Appendix F). These re-routings move flows from more congested sectors to less congested ones. For instance, the flows *Italy to UK* are repeatedly re-routed from the best route, a route that crosses a congested sector, UFXF, to a route crossing less congested sectors: UH and UE. Some flows are not re-routed whatever the model used, such as the *North Italy to Lisbon and Madrid* flows, because they cross sectors that clearly are not congested on this date. It should be noted that one of the non-congested sectors, UM, is very congested on other days of the week, when the traffic flows to and from the Balearics are substantially heavier (see Appendix D).

In a context where re-routing control measures are used systematically, even considering that the pattern of traffic will vary according to the day of the week, it is unsustainable, in terms of equity, to re-route always the same flights. Re-routing flights from congested sectors while benefiting all the traffic crossing those sectors has only costs for the aircraft operators of the flights re-routed. Ways of compensating for this inequity are to change the cost of re-routing a flow with the number of times it has been re-routed or to exclude *a priori* those flows which have been re-routed previously.

Table 8.6-3: Comparison of Flights Re-routed

Flow Group	DEL2	DEL1	BALD1	BALD2	BALD3	ALL
UK to Balearics, Barcelona and Alicante	*7*	*6*	*0*	*0*	*12*	*0*
Germany (exc. . West) and Swit. to Balearics and Barcelona	*2*	*2*	*2*	*2*	*2*	*2*
W. Germany to Balearics and Barcelona	*7*	*5*	*5*	*5*	*5*	*5*
Barcelona and Balearics to W. Germany	*2*	*2*	*0*	*0*	*0*	*0*
Barcelona and Alicante to Brussels and Amsterdam	*0*	*9*	*8*	*8*	*10*	*0*
Barcelona, Balearics and Alicante to Germany and Switzerland	*3*	*0*	*3*	*3*	*0*	*0*
Barcelona, Balearics and Alicante to UK	*19*	*6*	*12*	*12*	*1*	*1*
Madrid to Frankfurt and Stuttgart	*2*	*2*	*8*	*8*	*6*	*0*
Madrid to Southeast Germany and Switzerland	*0*	*0*	*0*	*0*	*0*	*0*
Madrid to W. Germany	*0*	*0*	*0*	*0*	*0*	*0*
Athens and Rome to Lisbon and Madrid	*0*	*0*	*0*	*0*	*0*	*0*
North Italy to Lisbon and Madrid	*0*	*0*	*0*	*0*	*0*	*0*
Lisbon and Madrid to Athens and Rome	*0*	*0*	*0*	*0*	*0*	*0*
Lisbon and Madrid to North Italy	*0*	*0*	*0*	*0*	*0*	*0*
UK (exc. London), Brussels and Amsterdam to Swit.	*0*	*0*	*15*	*15*	*15*	*0*
London to Switzerland	*21*	*21*	*21*	*21*	*21*	*21*
Swit to Brussels and Amsterdam	*6*	*6*	*0*	*0*	*0*	*0*
Geneva to UK	*18*	*18*	*18*	*18*	*18*	*18*
Zurich to UK	*21*	*0*	*21*	*21*	*21*	*0*
UK to Italy	*3*	*1*	*4*	*4*	*6*	*0*
Italy to UK	*2*	*4*	*4*	*4*	*4*	*2*
Paris to Italy	*67*	*67*	*57*	*57*	*54*	*54*
Italy to Paris	*0*	*0*	*7*	*7*	*0*	*0*
Paris to Toulouse	*0*	*0*	*0*	*0*	*0*	*0*
Paris to Marseilles and Nice	*82*	*82*	*82*	*82*	*44*	*44*
Toulouse to Paris	*30*	*30*	*30*	*30*	*0*	*0*
Brussels, Amsterdam and W Germany to Madrid and Malaga	*4*	*6*	*4*	*0*	*4*	*0*
Germany (exc. West) to Madrid and Malaga	*16*	*16*	*16*	*16*	*11*	*11*
UK to Madrid and Malaga	*29*	*29*	*29*	*29*	*17*	*17*
South Germany to Canary Islands	*0*	*0*	*0*	*0*	*0*	*0*
Germany (exc. South) to Canary Islands	*10*	*0*	*0*	*0*	*0*	*0*
UK to Canary Islands	*0*	*0*	*0*	*0*	*0*	*0*
Total Flights Re-routed	351	312	346	342	251	175

To assess whether the saving in cost and delay provided by DELINT2 cannot be to a large extent obtained re-routing fewer flights, this instance of

DELINT2 is compared with a situation, named SFR, where only six flows, gLOND-ZUR, GENE-gLOND, PARI-MILAN, PARI-ROME, PARI-MARS and gLOND-MADR, totalling 136 flights are re-routed. These flows are re-routed in all the models (see Appendix F). Figure 8.6-1 and Figure 8.6-2 indicate that re-routing a few flows already alleviates substantially congestion, and that it becomes much more difficult to improve congestion as it decreases: to reduce the number of flights ground-delayed by 528, from 1273 to 745, it takes the re-routing of 136 flights, whereas to reduce the number of flights ground-delayed by 185, from 745 to 560, it takes the re-routing of 215 flights. This analysis also suggests that DELINT2 can be used as a 'benchmark' against which different re-routing possibilities can be evaluated. Various re-routing control measures which require re-routing fewer flows than the optimum solution or involve re-routing different flows can be experimented and compared with the DELINT2 optimum solution.

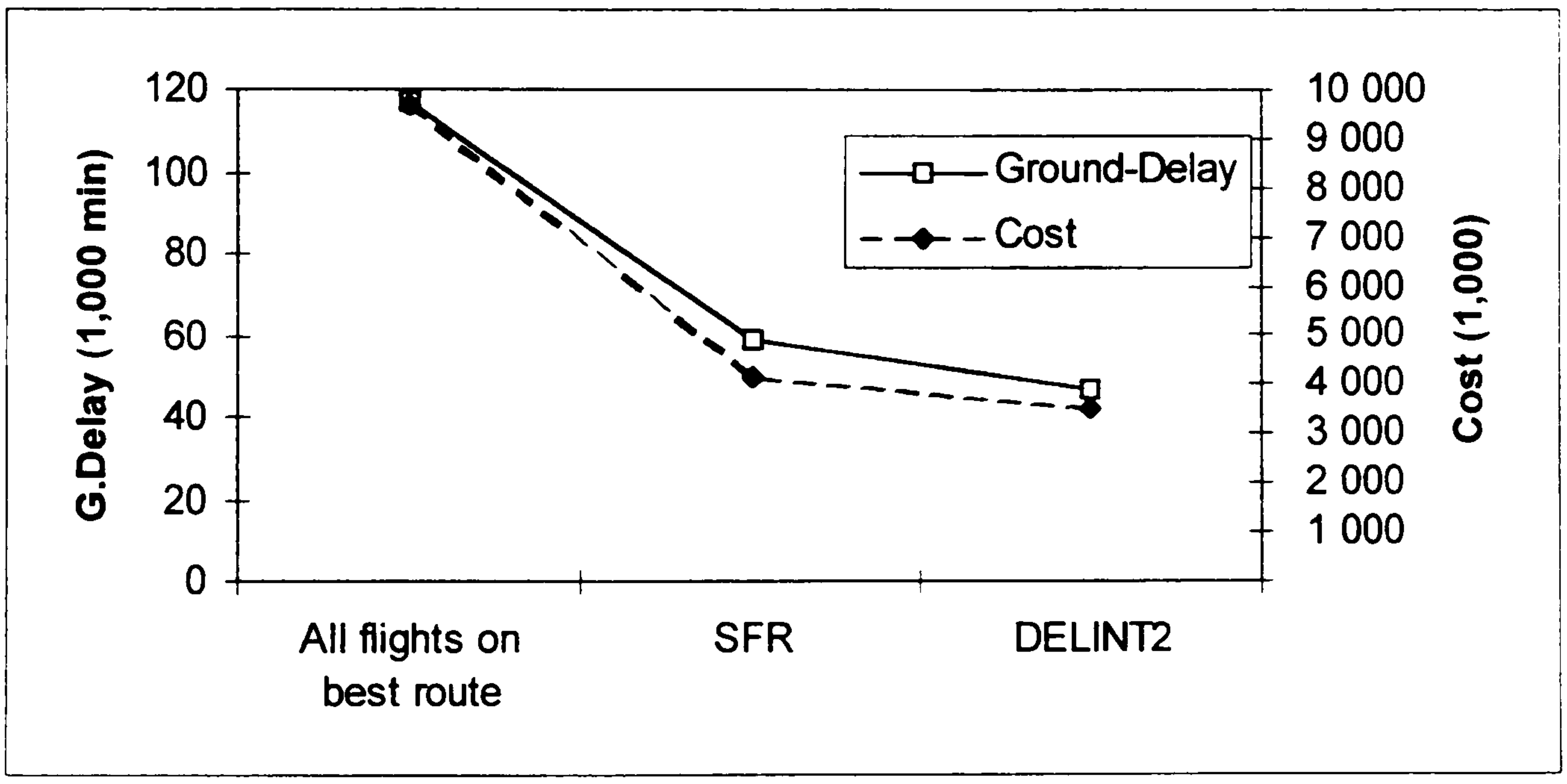


Figure 8.6-1: SFR Vs DELINT2

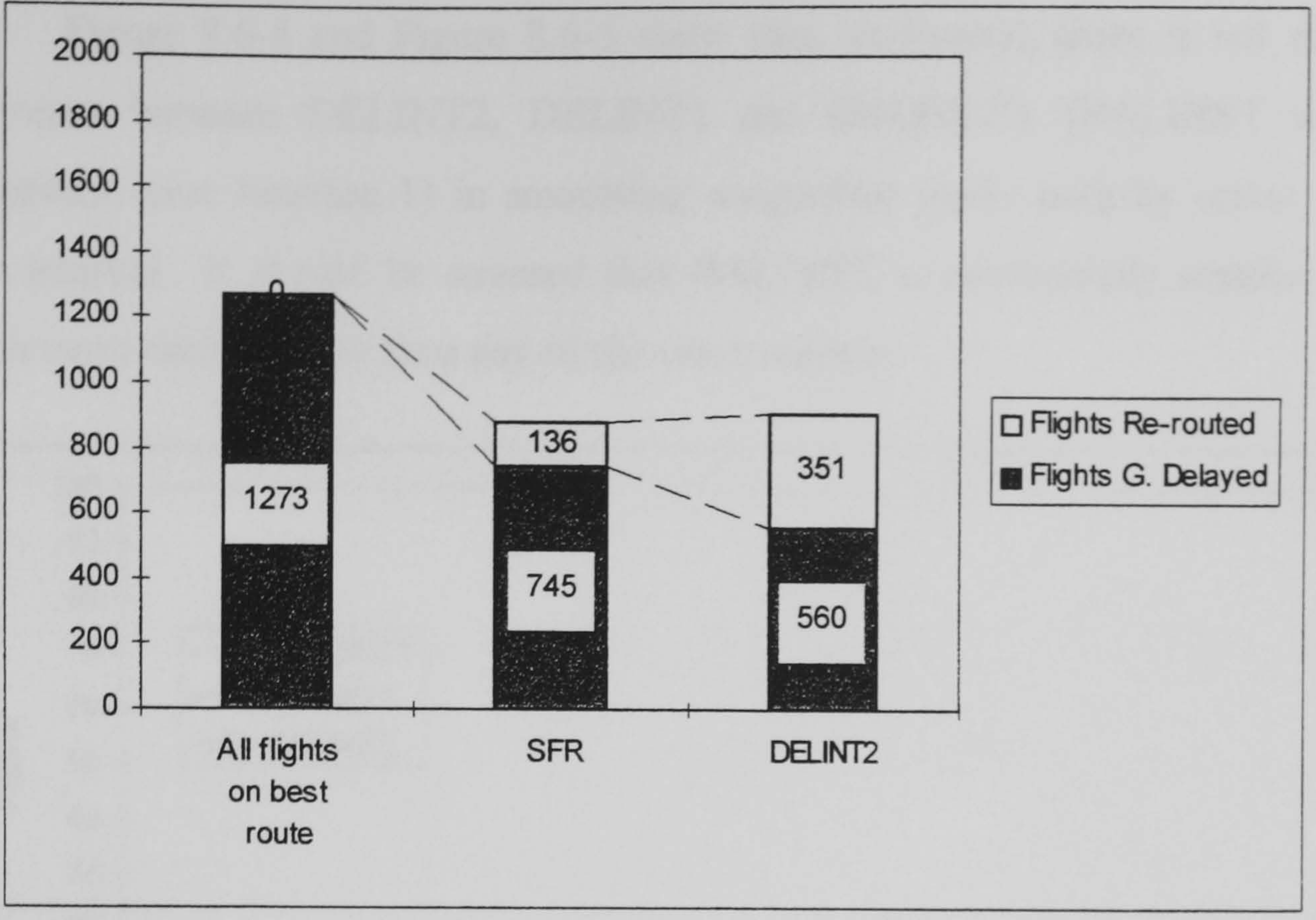


Figure 8.6-2: SFR Vs DELINT2 - Flights Ground-delayed and Re-routed

DELINT2 takes into account the length of ground-delays affecting flights, a factor that is not considered by the other models. Figure 8.6-3 shows that DELINT2, compared with a situation where all the flights take the best route, reduces substantially the length of ground-delays. As noted, the ground-delays as calculated by DELINT2 are longer than they would be in a real environment.

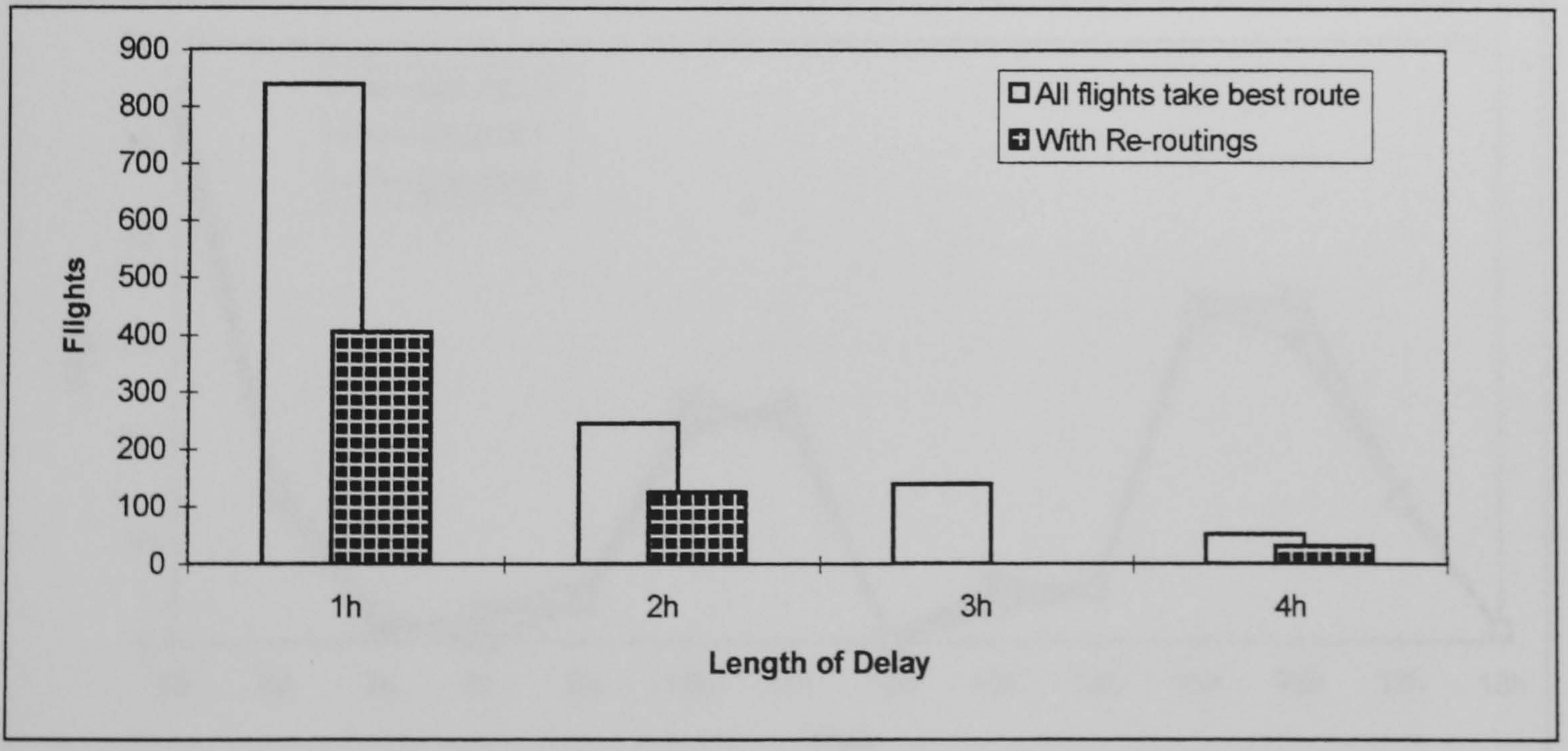


Figure 8.6-3: Flights Ground-delayed by Length of Delay

Figure 8.6-4 and Figure 8.6-5 show that, in general, there is not much difference between DELINT2, DELINT1 and BALDIST1 (BALDIST using congestion cost function 1) in smoothing congestion peaks both by sector and time interval. It should be stressed that BALDIST is substantially smaller and much more time efficient than any of the other models.

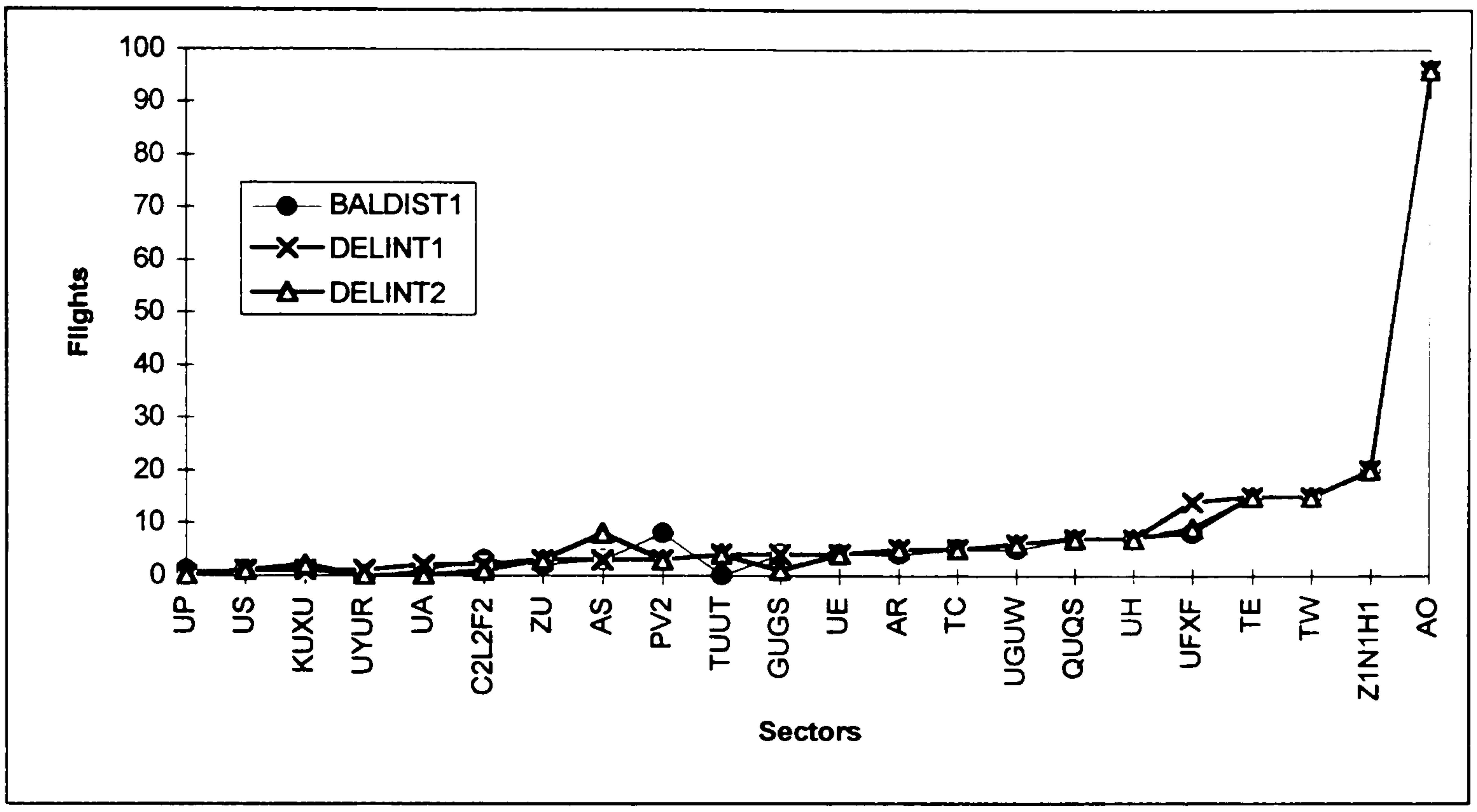


Figure 8.6-4: Flights Above Capacity by Sector

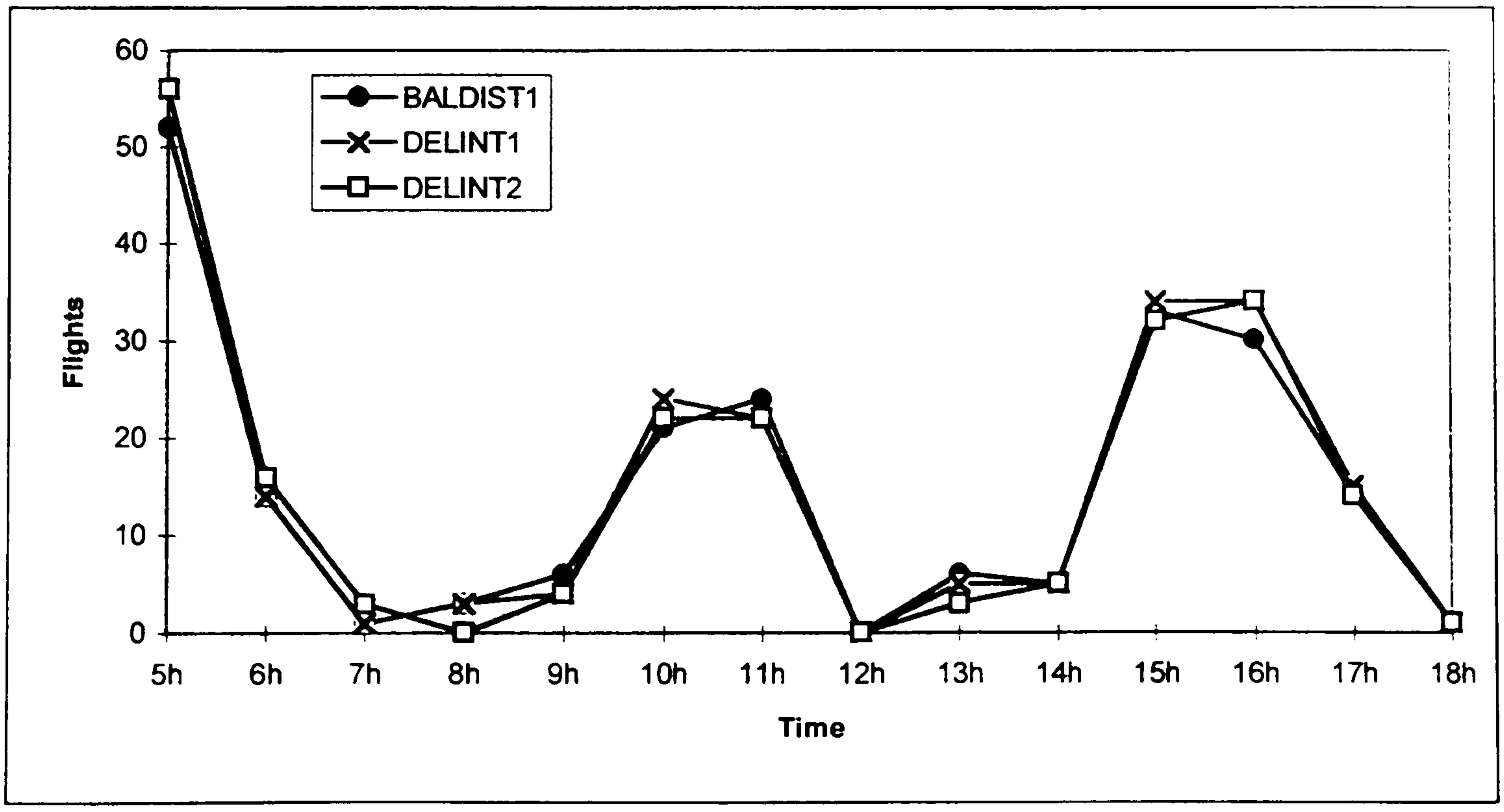


Figure 8.6-5: Flights Above Capacity by Time Interval

To assess the quality of BALDIST results in terms of ground-delay, DELINT2 was run using the routing scheme obtained using BALDIST1. DELINT2 and DELINT2 using BALDIST1 routing scheme provide significantly less ground-delay than DELINT1 and distribute the ground-delay more evenly between the flows, as shown in Table 8.6-4 and Figure 8.6-6.

Table 8.6-4: Ground-delay Using BALDIST, DELINT1 and DELINT2 (minutes)

	BALDIST1 Routing Scheme	DELINT1	DELINT2
North Italy to Lisbon and Madrid	60	0	60
W. Germany to Balearics and Barcelona	60	0	0
Germany (exc. West) and Swit. to Balearics and Barcelona	60	0	0
Barcelona and Alicante to Brussels and Amsterdam	120	0	0
Barcelona , Balearics and Alicante to UK	60	0	0
London to Switzerland	0	0	60
Switzerland to Brussels and Amsterdam	180	0	60
Geneva to UK	60	0	60
UK to Balearics, Barcelona and Alicante	360	0	120
UK (exc. London), Brussels and Amsterdam to Switzerland	180	0	120
Zurich to UK	0	0	120
Brussels, Amsterdam and West Germany to Madrid and Malaga	120	0	120
Germany (exc. South) to Canary Islands	300	0	240
UK to Canary Islands	180	0	240
Paris to Italy	180	0	0
Paris to Marseilles and Nice	0	0	300
Paris to Toulouse	240	0	360
Italy to UK	120	0	420
Toulouse to Paris	300	0	600
Madrid to Frankfurt and Stuttgart	0	60	60
Italy to Paris	10080	31440	10380
Others	34740	29160	33300
Total	47400	60660	46620

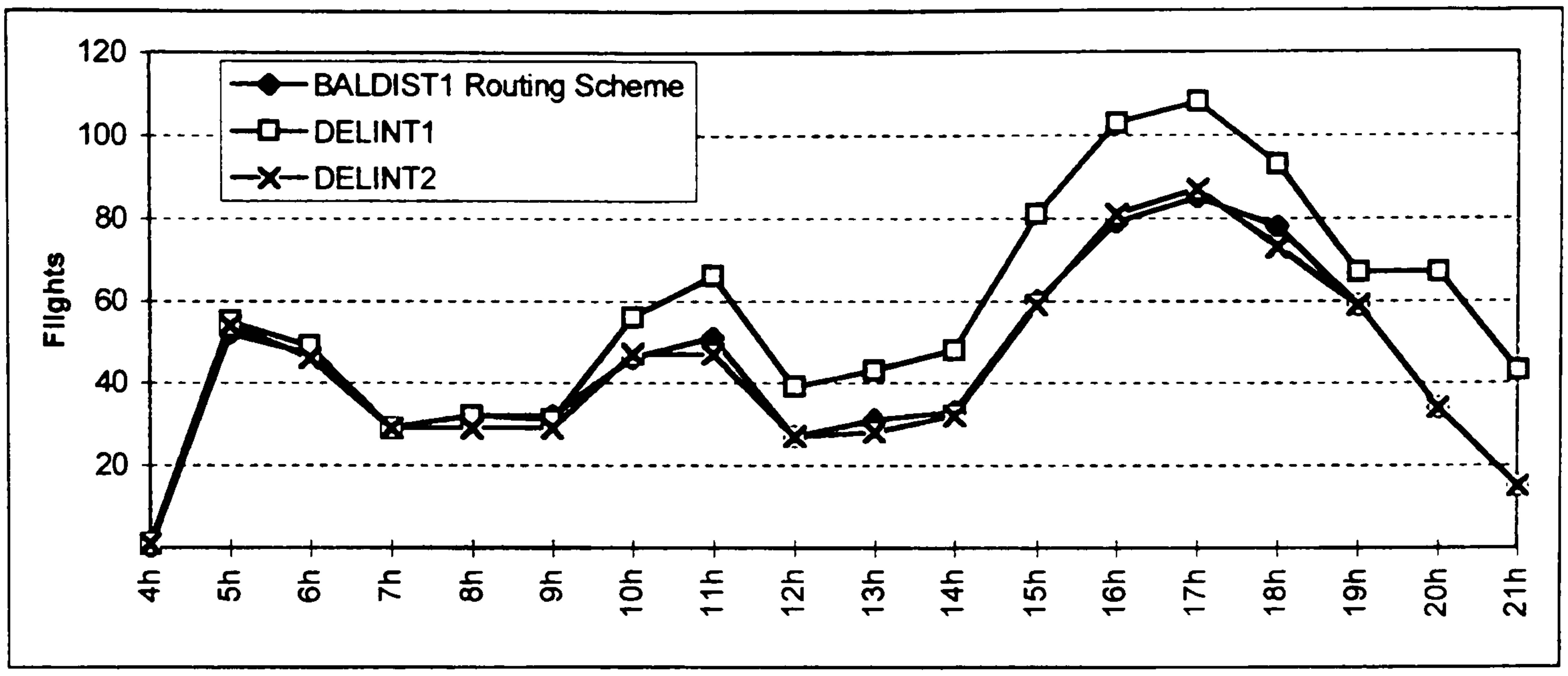


Figure 8.6-6: Flights Ground-delayed by Time Interval

To study the behaviour of DELINT2 with different trade-offs between re-routing and ground-delay, DELINT2 was run using different basic costs of ground-delay (*a*) and the results are compared. The seven ground-delay cost functions considered are shown in Table 8.6-5.

Table 8.6-5: DELINT2 - Different Ground-delay Costs

Function 1	$g(t' - t) = 750.(t' - t)^2$
Function 2	$g(t' - t) = 1250.(t' - t)^2$
Function 3	$g(t' - t) = 2500.(t' - t)^2$
Function 4	$g(t' - t) = 6000.(t' - t)^2$
Function 5	$g(t' - t) = 9000.(t' - t)^2$
Function 6	$g(t' - t) = 12000.(t' - t)^2$
Function 7	$g(t' - t) = 16000.(t' - t)^2$

The summary of results in Table 8.6-6 shows that DELINT2 can be harder to solve to optimality than the initial results indicated. For five out of the seven functions considered, DELINT2 was not solved to optimality, and the best solution found after 10,000 iterations was collected. However, the values of the solutions obtained are all very close to the optimum values, as shown by their distance from the linear relaxation optimum values. Except for the flow gLOND-MADR, all these functions repeatedly re-route the same core of flows identified in Table 8.6-3, a total of 158 flights.

The number of flights re-routed and delayed appears to stabilise, respectively at 368 and 556, as the basic cost of ground-delay grows (see Figure 8.6-7 and Table 8.6-6). It can also be observed that, after a certain point, it is very difficult to reduce the number of flights ground-delayed, for instance to reduce the number of flights ground-delayed by 7 from 567, with function 1, on to 560, with function 3, the number of flights re-routed increased by 44, from 307 to 351.

Table 8.6-6: DELINT2 Using Different G. Delay Costs - Summary of Results

	Function 1	Function 2	Function 3	Function 4	Function 5	Function 6	Function 7
(1) Optimum value			3522140	8408430			
(2) Best value - 10000 iterations	1074960	1775310			12605890	16784430	22368430
(3) Linear relaxation-optimum value	1072868	1771815	3515978	8396203	12579199	16760918	22333985
variation between (1) or (2) and (3)	0.19%	0.20%	0.18%	0.15%	0.21%	0.14%	0.15%
Flows re-routed	39	36	38	41	41	40	40
Flights re-routed	307	327	351	370	387	368	368
Total delay (minutes)	47040	46740	46620	46560	46620	46560	46560

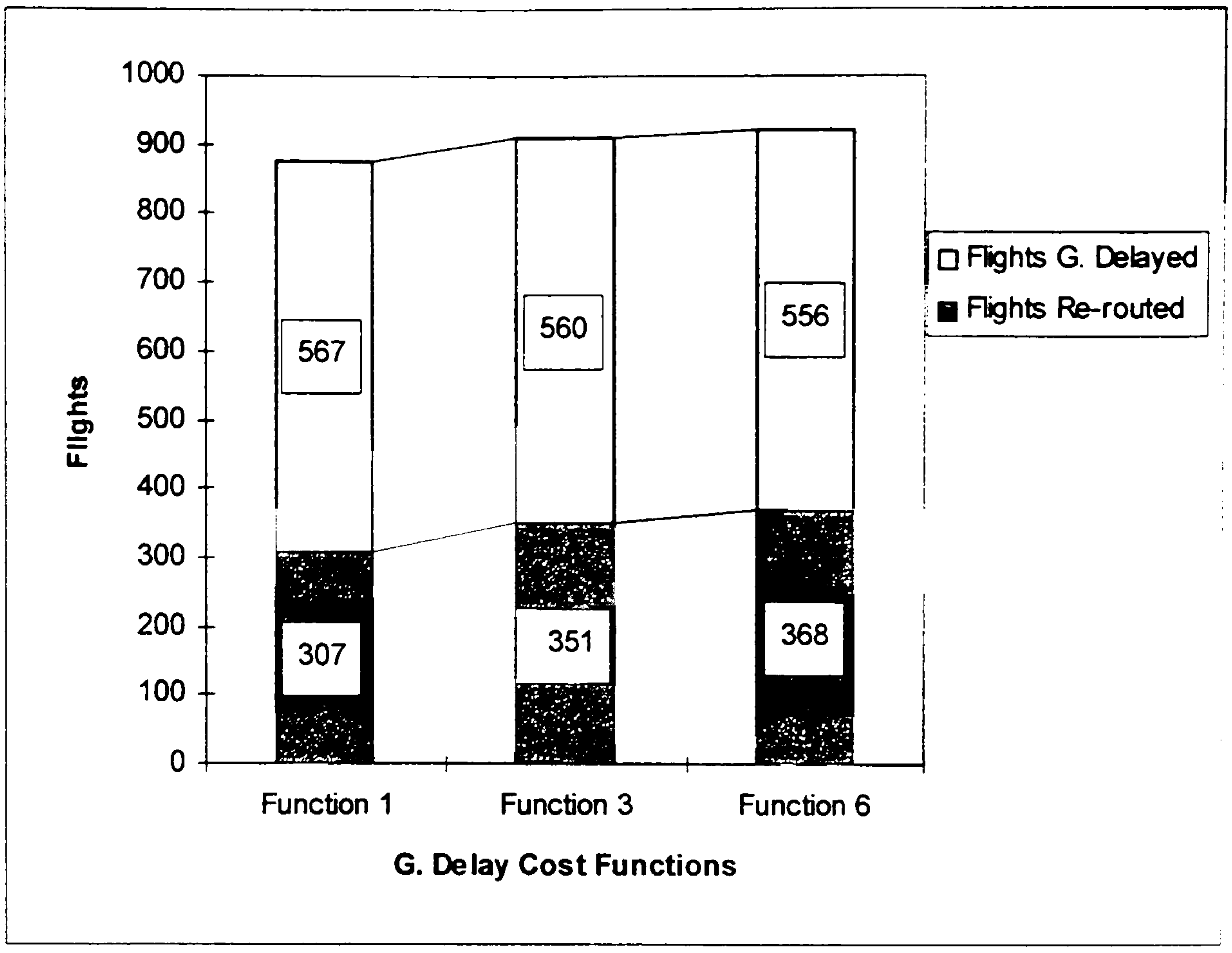


Figure 8.6-7: DELINT2 with Growing G. Delay Cost

Table 8.6-7 and Table 8.6-8 indicate that there is a very slight improvement in distribution of congestion both by sector and time, as delay cost increases. Only sectors or time intervals for which there were flights above capacity are shown.

Table 8.6-7: Flights Above Capacity by Sector

	Function 1	Function 3	Function 7
AO	96	96	96
AR	5	5	5
AS	4	8	8
C2L2F2	2	1	0
GUGS	4	1	1
KUXU	1	2	2
PV2	3	3	3
QUQS	8	7	7
TC	5	5	5
TE	15	15	15
TUUT	3	4	4
TW	15	15	15
UA	1	0	0
UE	4	4	4
UFXF	12	9	9
UGUW	6	6	6

UH	10	7	7
US	1	1	1
UYUR	2	0	0
Z1N1H1	20	20	20
ZU	2	3	3
Total	219	212	211

Table 8.6-8: Flights Above Capacity by Time Interval

	Function 1	Function 3	Function 7
5h	57	56	56
6h	16	16	16
7h	1	3	3
8h	2	0	0
9h	4	4	4
10h	22	22	22
11h	24	22	22
12h	0	0	0
13h	4	3	3
14h	5	5	5
15h	36	32	31
16h	33	34	34
17h	14	14	14
18h	1	1	1
Total	219	212	211

8.7 Summary of Results

The analysis of results leads to conclusions on two interrelated levels: on the usefulness of re-routing control measures and on the usefulness of the optimisation models. Re-routing control measures appear to be useful if there are imbalances in the distribution of congestion, and if the range of flows considered for re-routing is adequate to re-distribute congestion. Analysing the results of this test, it is clear that after a certain point, given the flows considered for re-routing and the reductions in congestion already made, re-routing control measures have very little effect in reducing congestion. It is also apparent that there are some sectors whose very severe congestion peaks can be attenuated but not eliminated by applying re-routing control measures. This suggests the need to increase sector capacity during the peak hours to address the more serious and persistent congestion problems. The effect of increasing capacity during the peak hours could be tested and its cost compared with the savings in congestion costs.

The test indicates that the optimisation models can be of use in re-routing flows and can provide savings in ground-delays. To get an estimate of the effect of the models two situations are compared: a situation where all flights take the best route, and the situation resulting from the application of the optimisation models. In the cases studied, re-routings reduced total ground-delay by more than 50% and produced cost-savings (cost of congestion + cost of re-routings) of more than 40%. However, these results should be seen in context: they compare with an extreme situation where all flights take the best route irrespective of the congestion situation. In a real environment, both airlines and flow managers will take action to limit the extent of ground-delays, for instance, some airlines will re-route flights to by-pass congested elements of the airspace. Further evaluation of the models is needed in a dynamic environment to assess more fully their impact on congestion. An important question is whether these re-routings reduce the need for re-routing individual flights or for slot allocation regulations at the tactical level.

There are 175 flights that are re-routed in every model. There are also flow groups which have, at least, one flow re-routed whatever the model used. In a context where these models are used daily, even allowing for the fact that the traffic will vary according to the day of the week, these results raise concerns over equity between airspace users. Possibilities of addressing this inequity are to include the number of times a flow has been re-routed in the cost of re-routing a flow or to exclude *a priori* those flows which have been re-routed previously.

BALDIST is undoubtedly the smallest (917 constraints and 15,104 variables of which only 303 are decision variables) and fastest model; it provided the optimum solutions in approximately 30 sec. DELINT1 (10,584 variables and 11,377 constraints) is the hardest model to solve of the three, since it was not possible to obtain the optimum solution. However, it provided a feasible solution whose value was less than 0.8% away from the optimum value. DELINT2 despite being substantially larger (30,919 variables and 10,854 constraints) than DELINT1 appears to be easier to solve: in two out of the 7 trials carried out, the optimum solution was reached in less than 10 minutes. In the remaining five, feasible solutions less than 0.3% away from the optimum were obtained in 10 minutes. Considering the impact on congestion, the execution time and the size, BALDIST appears to be the most efficient model of the three. The comparisons in section 8.6 show that BALDIST results in an alleviation of congestion, both in terms of capacity-demand imbalances and ground-delay, which is almost the same as DELINT2. DELINT2 has the advantages of taking into account the length of ground-delay affecting flights and providing more detailed information on the impact of the re-routing control measures. DELINT1 is out-performed by both the other models in terms of impact on congestion and execution time.

The optimisation models here presented can also be used as 'benchmarks' against which various re-routing possibilities are evaluated. Frequently, it will not be feasible to re-route all the flows in the optimum solution, in which case, it becomes important to calculate the impact of re-routing fewer flows and to identify sub-sets of flows which provide good approximate solutions. A case is illustrated in section 8.6, where re-routing part of the flows in DELINT2 optimum solution, provides a substantial reduction in congestion.

8.8 Feasibility Of The Models

To assess the feasibility of the models several criteria are considered: acceptance by the stakeholders, appropriateness of the support provided and flexibility, data requirements, size and execution time.

- **Acceptance by Stakeholders**: as discussed, acceptance of optimisation models by the stakeholders can be difficult. They can have problems accepting mathematically complicated models with an aggregate cost function which does not take their individual decision criteria sufficiently into account. In ATFM, equity between airspace users is also an important factor in their acceptance of the models. The optimisation models have to take into account aspects such as how many times a flow or a flight has been re-routed previously (see section 8.6). The user feedback on the demonstrator suggested they found the output of the models useful. However, more extensive testing and user (and other stakeholders) involvement is needed to guarantee stakeholders acceptance of the models. Airlines, ATC and flow managers need to be involved in defining the constraints and decision criteria to be used.

- **Support Provided and Flexibility:** it is important to recall that these models are intended for pre-tactical ATFM, a planning stage with a time horizon of a few days where traffic is analysed in aggregate terms, by flows instead of individual flights. Therefore, what flow managers need to know, when considering re-routing control measures, is which flows to re-route, onto which routes and the effect these re-routings will have on congestion. BALDIST provides routing schemes and their impact on capacity-demand imbalances. DELINT1 and DELINT2 in addition provide an estimate of delay by flow and time interval, with DELINT2 providing also the length of delay affecting flights. However, the information on delay provided by DELINT1 and DELINT2 is not precise since time is considered in discrete hourly intervals and flights are very aggregated. To have more precise information on ground-delay, time would have to be represented in shorter intervals (10/15 min) and traffic demand forecasts would also have to be more accurate.

Some of the parameters of the models are easily changed: traffic demand, capacities, constraints on which flows to re-route, costs of delay and of re-routings, number of time intervals considered. Other features, such as the definition of sectors, routes and flows are not easily changed. In an environment where patterns of traffic change daily, ATC sectors are split or merged daily in different but pre-defined configurations, the ability to change these parameters is needed. A system with some degree of 'intelligence' is needed to change flows, sectors and redefine routes accordingly.

- **Data Requirements:** the centralised systems in place at EUROCONTROL provide updated traffic and airspace data, however prior to running the optimisation models several data processing operations have to take place: flows have to be defined, the alternative routes for each flow determined and represented in terms of the sectors they cross and the traffic data grouped into flows and departure time intervals. As noted, these operations require, either an experienced human user to define the relevant flows beforehand or a partly 'intelligent' computer system able to define flows.

- **Size and Execution Time:** The execution time of the models is not as critical at pre-tactical as at tactical ATFM, however, to be repeatedly and daily used by flow managers, the models have to provide solutions in relatively short timespans, say of 30 minutes maximum. BALDIST is a small model and in the above test it provided optimum solutions in 30 sec. DELINT2 provided optimum solutions or solutions whose value was less than 0.3% away from the optimum value in 10 minutes or less. However, DELINT2 can lead to very large integer problems, for instance, a problem with 300 flows could easily reach 150,000 variables. DELINT1 provided solutions whose value was not more than 0.8% away from the optimum value in less than 10 minutes but it is harder to solve than any of the other models and it is significantly larger than BALDIST. Further evaluation of the feasibility of using these models in a re-routing DSS will also have to take into account the size of the data component and the time required to prepare the data to run the optimisation models.

Another key aspect in the feasibility of the models is how they are going to be embedded in a re-routing decision support system. In Chapter 6, different possibilities for a re-routing decision support tool, in terms of functionality and degree of automation, were presented. If a highly automated system is intended for re-routing air traffic flows, optimisation models on their own cannot serve as a basis for a decision support tool which is designed to suggest whole routing schemes to improve congested situations. A tool of this type would have to comprise, at least, three subsystems:

1. Definition of Scope

A system which defines the boundaries and scope of the problem, addressing issues such as which areas of the airspace should be looked at and how to define and what the flows to be considered are. This system would need knowledge based on experience, traffic data, possibly in the form of case-based reasoning or heuristics to work.

2. Data Processing

A mainly procedural system which pre-processes the traffic data in terms of routes and time intervals, in order to be able to run it through the optimisation system, and can also process the output of the optimisation system in order to make it more understandable to the user.

3. Optimisation

A system which, given the boundaries defined in 1, and the data processed in 2 will provide the best routing scheme, suggesting which flows to re-route onto which routes and at what cost.

Systems 2 and 3, to a large extent, can be done by the computer with the human user having an influence on the decision criteria and/or reviewing the solutions proposed by the optimiser. Substantial ground-clearing work still has to be done, in order to automate system 1. What follows is a first effort to describe the issues faced in defining the scope of re-routing problems:

What sectors are to be considered? As a starting point, there are two approaches: to consider the whole European Airspace, or select only the sectors that might be affected, directly or indirectly, by bottlenecks. To work every time with the whole European airspace, given its size, does not appear to be efficient. Focusing on the bottleneck approach, the first step is to identify the bottleneck sectors and the second step is to identify the sectors which could substitute for each of the bottleneck sectors. These alternative sectors, are sectors that are crossed by routes by-passing the bottleneck sectors.

However, to define the routes, the flows of traffic, origin/destination pairs, have to have been identified. Several layers of flows can be identified: There are the flows that normally cross the bottleneck sectors, the flows that normally cross the alternative sectors and so on and so forth. This process could be repeated over and over again adding more flows and sectors until eventually all the sectors in the European airspace were considered in the problem. Thus, another aspect has to be defined, when should this process of adding more flows and sectors to the problem stop? To answer to this question two types of bottlenecks can be identified: 1) chronic bottlenecks, that tend to happen over and over again, for example, the same day every week during the Summer season; and 2) other bottlenecks. For chronic bottlenecks, experience and knowledge build up and it is possible to have key sectors and flows to re-route pre-defined. For other bottlenecks, the process of adding sectors and flows to the problem can stop when an acceptable solution, in terms of total delay and loads on sectors is obtained. If there are sectors in the problem whose pattern of traffic is exactly the same, with and without re-routings, then they can be eliminated from the problem, thus reducing its size.

What flows are relevant and how should they be defined? Statistics of past traffic can provide information on the importance of the different flows crossing the bottleneck sectors. An immediate problem is how best to group the flights into flows for re-routings so that all flights in the flow have approximately the same choice of routes. If flights were grouped according to their airports of origin and destination, that is by city-pairs, the choice of routes would be the same for the flights in the flow.

However, this would lead to a gigantic number of flows in the problem. In addition, many of these flows would also be irrelevant in terms of effect on the traffic.

At least, two other approaches can be considered to group flights into flows:

1. Reference Points: group flights according to pairs of geographic points. These points are chosen according to the likelihood of flights getting close to or overflying them on the way from a certain origin to a certain destination area. Alternative routes are defined with reference to these points.
2. Zones of Origin/Destination: group airports into zones of origin/destination, taking into account their geographic co-ordinates and size (number of passengers or movements). A main airport is identified and all the airports which are within a certain radius of that airport are included in the zone.

The first approach is more bottleneck oriented, since reference points are defined taking into account not only the origin/destination areas but also the bottleneck sectors. In this way, the number of flows in the problem can be kept low. However, the points have to be chosen very carefully, using statistics of past traffic as there is the possibility that some of the flights included in the flow might have routes that do not overfly nor come close to the reference points. The first approach appears to be more adequate for re-routing problems addressed locally, whereas the second approach appears to be suitable for more global re-routing problems, where whole regions or even the whole European airspace is considered. The first approach was used in the three-sector example described in Appendix C, the second approach was used in the test described in this chapter.

Whatever the approach, it is clear that the grouping of flights changes with the specific problem at hand. For instance, for a bottleneck situated in Continental Portugal, flows are mostly South/North bound and therefore there is a case for grouping Northern German flights with Scandinavian flights. However, if the bottleneck is situated in Switzerland the grouping of flights will be different.

There is a need for a tool that filters and processes information in order to define flows: a tool that automatically calculates distances between points and aerodromes and can process past traffic data in order to group and ungroup flights. This would be an information intensive tool that could retrieve past groupings of flights to be used in similar situations or to deal with chronic bottlenecks. An issue to be defined is who directs this search, the human or the computer. In other words: who decides what sectors and on the criteria to group flights.

In a context where human knowledge to address these problems is still in its early stages and in a decision-making environment grounded on negotiation and co-operation between different stakeholders, it is advisable to leave these decisions to the human, while the computer provides all the data search and processing necessary to answer the different queries. In time, when knowledge and experience on these measures have consolidated it might be then possible to delegate some of the above decisions to the computer.

The benefits of a tool of this complexity and level of automation, will have to be measured against the clearly substantial resources needed to develop it. It is also possible to consider, at least as an intermediate stage, a less automated system, where the flow manager has a more active role in the definition of scope and in adjusting results, and the processing of data and optimisation are performed by the computer. A simulation tool could help the flow manager to define the scope of the optimisation model or to assess, in a more detailed way, the feasibility of the solutions proposed by the optimisation model and their impact on congestion.

8.9 Conclusions

In this chapter, the test of the optimisation models for re-routing air traffic flows is described and the results are analysed. The models were tested on a set of data based on the actual traffic crossing the French upper airspace on 25 April 1996. The analysis of results, subject to the limitations of the models and of the test, provides conclusions on two interrelated levels: on the usefulness of re-routing control measures and on the usefulness of the optimisation models.

Re-routing control measures are more effective if there are imbalances in the distribution of congestion and if the range of flows considered for re-routing is adequate to re-distribute congestion. It is also apparent that there are some sectors whose very severe congestion peaks can be attenuated but not eliminated by applying re-routing control measures and which need to have their capacity increased.

The test indicates that the optimisation models developed can be of use in re-routing flows and can provide savings in ground-delays. To get an estimate of the effect of the models two situations were compared: A situation where all flights take the best route, and the situation resulting from the application of the optimisation models. In the cases studied, re-routings reduced total ground-delay by more than 50% and produced cost-savings of more than 40%. However, these results should be seen in context: they compare with an extreme situation where all flights take the best route irrespective of the congestion situation. In a real environment, both airlines and flow managers will take action dynamically to limit the extent of ground-delays. Further evaluation of the models is needed in a dynamic environment to assess more fully their impact on congestion.

The test also revealed that there is a core of flows that are re-routed whatever the model used. These repeated re-routings are prompted mostly by the severe congestion affecting one or more sectors crossed by the best route of the flows and raise concerns of equity in re-routing control measures. Possibilities of reducing inequity between flows are suggested. Considering that, frequently, it will not be feasible to re-route all the flows in the optimum solution but a sub-set or even a different set, the use of the optimisation models as 'benchmarks' against which different re-routing control measures can be evaluated is also illustrated.

The feasibility of the optimisation models is assessed using the following criteria: stakeholders acceptance, decision support provided and flexibility, data requirements, size and execution time. Feedback from the flow managers suggests they find the output of the models useful but more extensive testing and stakeholders involvement in the modelling process (namely in the definition of the decision criteria) is needed to guarantee stakeholders acceptance. The test showed that the three models could be used to support decisions on which flows to re-route but DELINT1 is out-performed by any of the other models in terms of impact on congestion and execution time. BALDIST is the most efficient model of the three providing optimum solutions while requiring significantly less resources than DELINT1 and DELINT2. In addition, the solutions obtained using BALDIST are not significantly different from the solutions obtained using DELINT2 both in terms of flights re-routed and ground-delayed. Its main disadvantage is the limitation in the information provided to support the re-routing decision. The three optimisation models require data processing operations some of which are already available at EUROCONTROL or easy to implement. Other data processing operations require some degree of expertise, provided either by a flow manager and/or a system with some degree of 'intelligence'.

This chapter also identifies the additional modules needed in a highly automated re-routing DSS to complement the optimisation models: An 'intelligent' component to define the scope of the optimisation problem and a component to process all the data and format it for the optimisation model. It was noted that considerable research and knowledge build-up is needed to automate the module which defines the scope of the optimisation model. Some of the issues involved in defining the scope of the optimisation problem were discussed:

- Identifying the airspace where the re-routing will apply: whether to select only the sectors that might be affected, directly or indirectly, by bottlenecks or the whole European airspace.

- Definition of flows: whether to group flights according to city-pairs, reference beacons which are crossed by the flights or zones of origin and destination (i.e. groups of airports).

It was concluded that a data-intensive sub-system able to sort traffic data and to work with various airspace configurations is needed to support the definition of scope. The use of a simulation tool to help the flow manager define the scope of the optimisation model is suggested. The simulation tool could also be used to evaluate the feasibility of the solutions provided by the optimisation model.

In the next chapter extensions to the optimisation models are suggested. These address some of the limitations of the models highlighted in this chapter.

Chapter 9

Extensions to the Models

9.1 Introduction

This chapter proposes changes to the models described in Chapter 7 and tested in Chapter 8, in order to deal with some of their limitations and to address different situations. Whenever data was already available, the resulting models were tested. The next section looks at how to impose changes on the flows to be re-routed. Sections 3 and 4 reformulate the models for a context where flow managers can re-route flows onto more than one route or re-route individual flights. Section 5 considers a situation where minimising under-used capacity is also an ATFM priority.

9.2 Changing the Flows to Be Re-Routed

There are at least two ways of changing the flows to be re-routed. The more direct and straightforward way is to define *a priori* which flows are or are not to be re-routed. If a flow should not be re-routed, the best route is assigned to the flow before running the model ($x_{i1}=1$ where the index $j=1$ denotes the best route for flow i). If a flow should be re-routed, the variable representing the assignment of the best route to the flow is made equal to 0 ($x_{i1}=0$).

The other way is to reflect the priority given to re-routing a flow in the cost of re-routing. For instance, the cost of re-routing a flow could increase with the number of times a flow had been re-routed in the past. On a certain week of the season the cost of alternative route j for flow i would be $c_{ij} = c_{j0} f(n)$ where c_{j0} is the extra-fuel cost of route j and n is the number of times the flow had already been re-routed during that season. If priorities were to be assigned according to the number of passengers the flights in the flow carry, the cost of re-routing a flow could be defined as a weighted sum of the various types of flight in the flow, for example $c_{ij} = c_{j0}\,(c_p f_{ip} + c_{p'} f_{ip'} + c_{p''} f_{ip''})$ where p, p' and p'' represent different sizes of aircraft in terms of number of passengers, c_p, $c_{p'}$ and $c_{p''}$ are the corresponding priorities and f_{ip}, $f_{ip'}$ and $f_{ip''}$ the number of flights in the flow which use aircraft of the types *p*, *p'* and *p''*.

9.3 Routing flows onto more than one route

In a hypothetical situation where flow managers could route traffic flows onto more than one route, the resulting models would become much smaller and easier to solve: the constraints 'one flow-one route', the assignment variables (x_{ij}) and the constraints linking the assignment variables to the departure variables are eliminated. For example, DELINT2 is reformulated in the following way:

$$\min\ w = \sum_{i=1}^{m} \sum_{j \in R_i} \sum_{t=1}^{p} \sum_{t'=t+1}^{t+\bar{q}} [c_j + g(t'-t)] d_{ijtt'} \qquad \textbf{(9.3.1)}$$

subject to:

$$\sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{\tau_{jk}} \sum_{t=1}^{t'-t_{jk}-r+1} d_{ijt,t'-t_{jk}-r+1} \leq u_{kt'} \qquad (k=1,\dots,l; t'=1,\dots,p) \qquad \textbf{(9.3.2)}$$

$$\sum_{j \in R_i} \sum_{t'=t}^{t+\bar{q}} d_{ijtt'} = f_{it} \qquad (i=1,\dots,m; t=1,\dots,p) \qquad \textbf{(9.3.3)}$$

$$d_{ijtt'} \geq 0 \text{ and integer} \qquad (i=1,\dots,m; j \in R_i; t=1,\dots,p; t'=t,\dots,t+\bar{q} \leq p+1) \qquad \textbf{(9.3.4)}$$

Applying this model, DELINTX2, to the test data, with the same cost functions used in DELINT2, the size of the problem is shown in Table 9.3-1. The model is significantly smaller than DELINT2 and the results shown in Table 9.3-2 indicate that DELINTX2 is easier to solve than DELINT2: the CPU execution time is substantially less and the optimum value is equal to the linear relaxation optimum value. This can be attributed to the network structure of the constraints matrix. It is also possible to observe that DELINTX2 delays slightly fewer flights than DELINT2 while re-routing many fewer flights (see Table 9.3-3). The added flexibility of re-routing flows onto more than a single route improves the efficacy of re-routing control measures. The results in Appendix G show that DELINTX2 distributes more re-routing control measures between the different flows than DELINT2.

Table 9.3-1: DELINTX2 - Problem Size

Capacity constraints	779
Relation flights scheduled/departing	3401
Total constraints	4180
Total constraints DELINT2	10854
Departure variables	30616
Total variables	30616
Total variables DELINT2	30919

Table 9.3-2: DELINTX2 - Summary of Results

	DELINTX2	DELINT2	%
Optimum Value	3485580	3522140	-1.04%
Linear relaxation-optimum value	3485580	3485580	0.00%
Flights re-routed	201	351	-42.74%
Ground-delay (minutes)	45960	46620	-1.42%
CPU time (sec)	96	281	-65.84%
Number of B&B nodes	0	82	-100.00%

Table 9.3-3: DELINTX2 - Flights Re-routed

Flow Group	DELINTX2	DELINT2
UK to Balearics, Barcelona and Alicante	3	7
Germany(exc. West) and Switzerland to Balearics and Barcelona	2	2
West Germany to Balearics and Barcelona	5	7
Barcelona and Balearics to West Germany	0	2
Barcelona and Alicante to Brussels and Amsterdam	3	0
Barcelona, Balearics and Alicante to Germany and Switzerland	0	3
Barcelona, Balearics and Alicante to UK	1	19
Madrid to South Germany	3	2

UK(exc. London),Brussels and Amsterdam to Switzerland	4	0
London to Switzerland	21	21
Switzerland to Brussels and Amsterdam	1	6
Geneva to UK	18	18
Zurich to UK	4	21
UK to Italy	8	3
Italy to UK	8	2
Paris to Italy	46	67
Italy to Paris	1	0
Paris to Toulouse	10	0
Paris to Marseilles and Nice	44	82
Toulouse to Paris(Charles de Gaulle and Orly)	4	30
Brussels, Amsterdam and West Germany to Madrid and Malaga	2	4
South Germany to Madrid and Malaga	8	16
UK to Madrid and Malaga	6	29
Germany (exc. South) to Canary Islands	1	10
Total Flights Re-routed	203	351

However, the efficacy of this approach depends on the flow managers having the authority to decide how many flights of a flow are routed on to a certain route hourly, which rarely happens at present.

9.4 Re-routing Individual Flights

The model described in the previous section can be adapted to re-route individual flights instead of flows. The following changes are made:

i index for flight

t_i departure time period for flight i (scheduled)

$$d_{ijt} = \begin{cases} 1 & \text{if flight } i \text{ departs at } t \text{ on route } j \\ 0 & \text{otherwise} \end{cases}$$

and the model becomes:

$$\min\ w = \sum_{i=1}^{m} \sum_{j \in R_i} \sum_{t=t_i}^{p+1} (c_j + g(t - t_i)) d_{ijt} \qquad \textbf{(9.4.1)}$$

subject to:

$$\sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{\tau_{jk}} d_{ij,t-t_{jk}-r+1} \le u_{kt} \qquad (k = 1,\dots,l; t = 1,\dots,p) \qquad \textbf{(9.4.2)}$$

$$\sum_{j \in R_i} \sum_{t=t_i}^{t_i+\bar{q}} d_{ijt} = 1 \qquad (i = 1,\ldots,m) \qquad \textbf{(9.4.3)}$$

$$d_{ijt} \in \{0,1\} \qquad (i = 1,\ldots,m; j \in R_i; t = t_i,\ldots,t_i + \bar{q} \le p + 1) \qquad \textbf{(9.4.4)}$$

This model is more accurate in terms of costs and time, since each flight, with its own cost function and travelling time, is considered individually. Flights can also have different costs of re-routing or of ground-delay according to how many times they have been re-routed during the season or the number of passengers they are carrying. The constraints matrix, similar to DELINTX2 is also simpler (0-1 coefficients), indicating that the model is easier to solve than DELINT2. In addition, data preparation is easier, because flights are not grouped into flows. However, the model will be considerably larger than any of the previous models mentioned. For instance, considering a number of flights close to the daily traffic crossing the French airspace, 5,000, each flight having a choice of two routes, and 20 time intervals, the number of variables could total 200,000.

The model BALDIST could also be adapted to re-route individual flights instead of flows, without becoming a large model. The following changes are made:

i index for flight

$$f_{it} = \begin{cases} 1 & \text{if flight } i \text{ is scheduled to depart at } t \\ 0 & \text{otherwise} \end{cases}$$

c_{ij} additional cost of route j for flight i

$$x_{ij} = \begin{cases} 1 & \text{if flight } i \text{ is assigned to route } j \\ 0 & \text{otherwise} \end{cases}$$

The resulting model is:

$$\min w = \sum_{i=1}^{m} \sum_{j \in R_i} c_{ij} x_{ij} + \sum_{z=1}^{\bar{Z}} \sum_{t=1}^{p} \sum_{k=1}^{l} g_{zk} o_{ztk} \qquad \textbf{(9.4.5)}$$

subject to:

$$\sum_{i=1}^{m} \sum_{j\in(R_i\cap L_k)} \sum_{r=0}^{\tau_{jk}} f_{i,t-t_{jk}-r+1}x_{ij} - \sum_{z=1}^{\bar{Z}} o_{ztk} \le u_{kt} \quad (k=1,\dots,l; t=1,\dots,p) \qquad \textbf{(9.4.6)}$$

$$\sum_{j\in R_i} x_{ij} = 1 \quad (i=1,\dots,m) \qquad \textbf{(9.4.7)}$$

$$x_{ij} \in \{0,1\} \quad (i=1,\dots,m; j\in \bigcup_i R_i) \qquad \textbf{(9.4.8)}$$

$$o_{ztk} \in \{0,1\} \qquad (z=1,\dots,\bar{Z}; t=1,\dots,p; k=1,\dots,l) \qquad \textbf{(9.4.9)}$$

Considering again a model with 5,000 flights, each flight having a choice of two routes, the number of decision variables would, in this case, total 10,000. These models can only be applied effectively to situations where flow managers have the authority to route individual flights and there is complete and precise data on individual flights. At present, complete and precise data only becomes available at tactical level, a few hours before the flights.

9.5 Reducing Under-used Capacity

ATC planning is also concerned with under-used capacity not only because it is a waste of resources but also because it affects negatively the performance of air traffic controllers. A common way of reducing under-used capacity is to merge sectors during less busy periods, but even so there are still many swings in traffic loads from dead periods to very busy periods. This concern can be taken into account in the models. Considering BALDIST, the following integer variables and parameters can be added:

b_{tk} = number of flights below capacity in sector k at t
h_k = unit cost of under - used capacity in sector k

and the model becomes:

$$\min w = \sum_{i=1}^{m}\sum_{j\in R_i}\sum_{t=1}^{p} c_j f_{it} x_{ij} + \sum_{z=1}^{\bar{Z}}\sum_{t=1}^{p}\sum_{k=1}^{l} g_{zk} o_{ztk} + \sum_{t=1}^{p}\sum_{k=1}^{l} h_k b_{tk} \qquad \textbf{(9.5.1)}$$

subject to:

$$\sum_{i=1}^{m}\ \sum_{j\in(R_i\cap L_k)}\ \sum_{r=0}^{\tau_{jk}} f_{i,t-t_{jk}-r+1} x_{ij} + b_{tk} - \sum_{z=1}^{\bar{Z}} o_{ztk} = u_{kt} \quad (k = 1,\dots,l; t = 1,\dots,p)$$

$$\textbf{(9.5.2)}$$

$$\sum_{j\in R_i} x_{ij} = 1 \quad (i = 1,\dots,m) \qquad \textbf{(9.5.3)}$$

$$x_{ij} \in \{0,1\} \quad (i = 1,\dots,m; j \in R_i) \qquad \textbf{(9.5.4)}$$

$$o_{ztk} \in \{0,1\} \quad (z = 1,\dots,\bar{Z}; t = 1,\dots,p; k = 1,\dots,l) \qquad \textbf{(9.5.5)}$$

$$b_{tk} \text{ integer} \quad (t = 1,\dots p; k = 1,\dots,l) \qquad \textbf{(9.5.6)}$$

The results of testing this model on the traffic sample used in Chapter 8, with $h_k = 8000 \quad \forall k$, are shown in Table 9.5-1 and Table 9.5-2 together with the results provided by BALDIST1, for comparison.

Table 9.5-1: BALDISTX - Summary of Results

	BALDISTX	BALDIST1	% Variation
Optimum value	82031460	4086660	
Flights above capacity	302	210	43.81%
Under-used capacity	9664	10095	-4.27%
Total capacity minus total demand	9362	9885	-5.29%
Flights re-routed	412	346	19.08%

The number of flows and flights re-routed increases significantly, by 19.08%, and flows that were not re-routed by any of the other models, such as the

Athens and Rome to Lisbon and Madrid flows, are now re-routed (see Table 9.5-2 and Appendix G). However, the resulting reduction of 431 in under-used capacity, despite being larger in absolute terms, is not so significant in relative terms, 4.27%. Considering both flights above and below capacity the balance is positive, that is there is a global improvement in capacity-demand imbalances of 5.29%.

Table 9.5-2- BALDISTX Flights Re-routed

Flow Group	BALDISTX	BALDIST1
UK to Balearics, Barcelona and Alicante	26	0
Germany(exc. West) and Switzerland to Balearics and Barcelona	2	2
West Germany to Balearics and Barcelona	0	5
Barcelona and Balearics to West Germany	5	0
Barcelona and Alicante to Brussels and Amsterdam	8	8
Barcelona, Balearics and Alicante to Germany and Switzerland	5	3
Barcelona, Balearics and Alicante to UK	1	12
Madrid to South Germany	8	8
Athens and Rome to Lisbon and Madrid	11	0
North Italy to Lisbon and Madrid	14	0
Lisbon and Madrid to Athens and Rome	9	0
Lisbon and Madrid to North Italy	13	0
UK(exc. London),Brussels and Amsterdam to Switzerland	27	15
London to Switzerland	21	21
Switzerland to Brussels and Amsterdam	19	0
Geneva to UK	18	18
Zurich to UK	0	21
UK to Italy	4	4
Italy to UK	6	4
Paris to Italy	64	57
Italy to Paris	30	7
Paris to Toulouse	44	0
Paris to Marseilles and Nice	38	82
Toulouse to Paris(Charles de Gaulle and Orly)	0	30
Brussels, Amsterdam and West Germany to Madrid and Malaga	0	4
South Germany to Madrid and Malaga	10	16
UK to Madrid and Malaga	2	29
UK to Canary Islands	27	0
Total Flights Re-routed	412	346

Looking at the variations in a more detailed way, Figure 9.5-1 and Figure 9.5-2 show that the reduction in under-used capacity is clear but not very significant. This may have to do with the linear way in which under-used capacity is valued in the objective function. The use of binary variables for each flight under capacity would enable the use of non linear costs. However, considering that under-used capacity is much larger than the number of flights above capacity, the definition of binary variables for each flight under capacity would enlarge the models to an unmanageable size. Another possibility would be to define a piecewise linear function for the cost of under-used capacity. For example:

$$h_k = \begin{cases} 400b_{tk} & if \quad 0 \le b_{tk} \le 10 \\ 1000b_{tk} - 6000 & if \quad 10 \le b_{tk} \le 20 \\ 8000b_{tk} - 146000 & if \quad b_{tk} \ge 20 \end{cases}$$

$$\forall t, k$$

The resulting optimisation problem can still be solved using integer programming (see Winston, 1991).

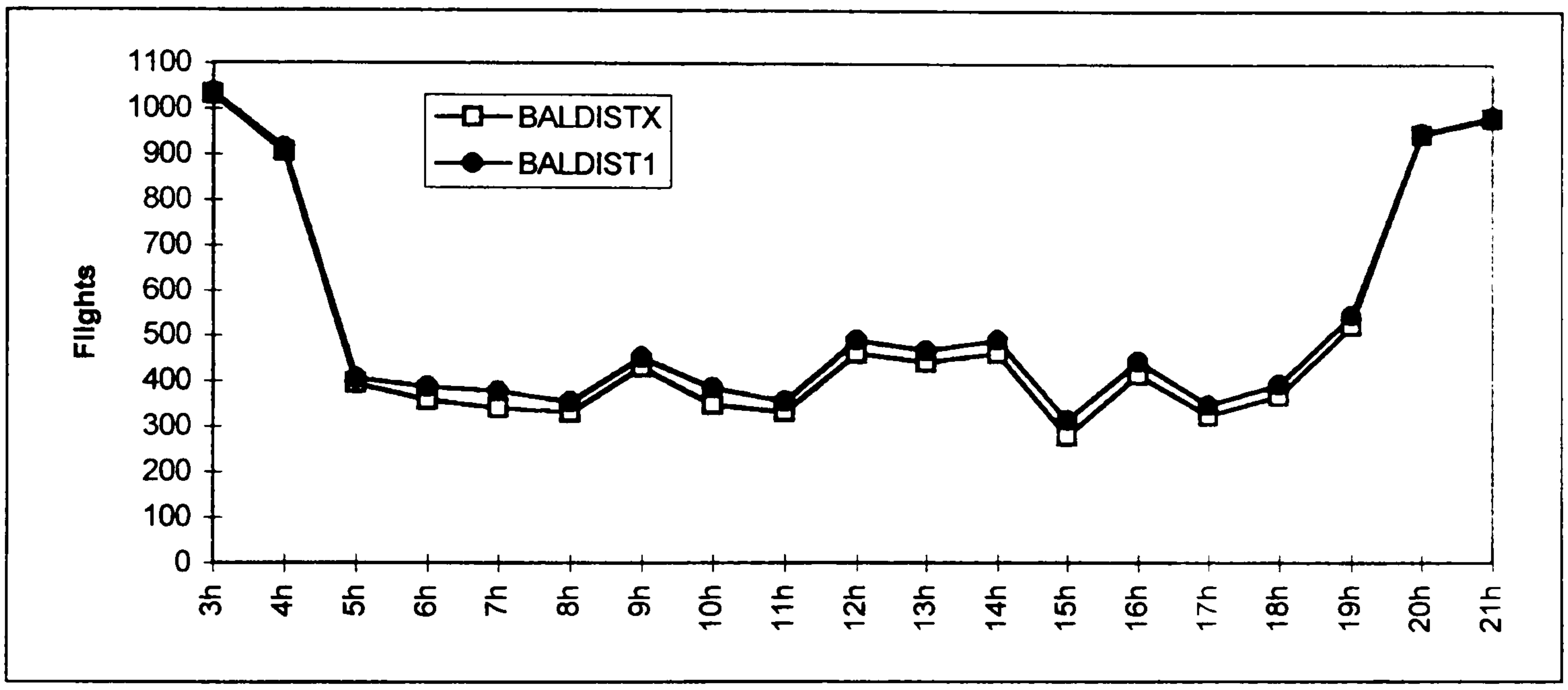


Figure 9.5-1: Under-used Capacity by Time Interval

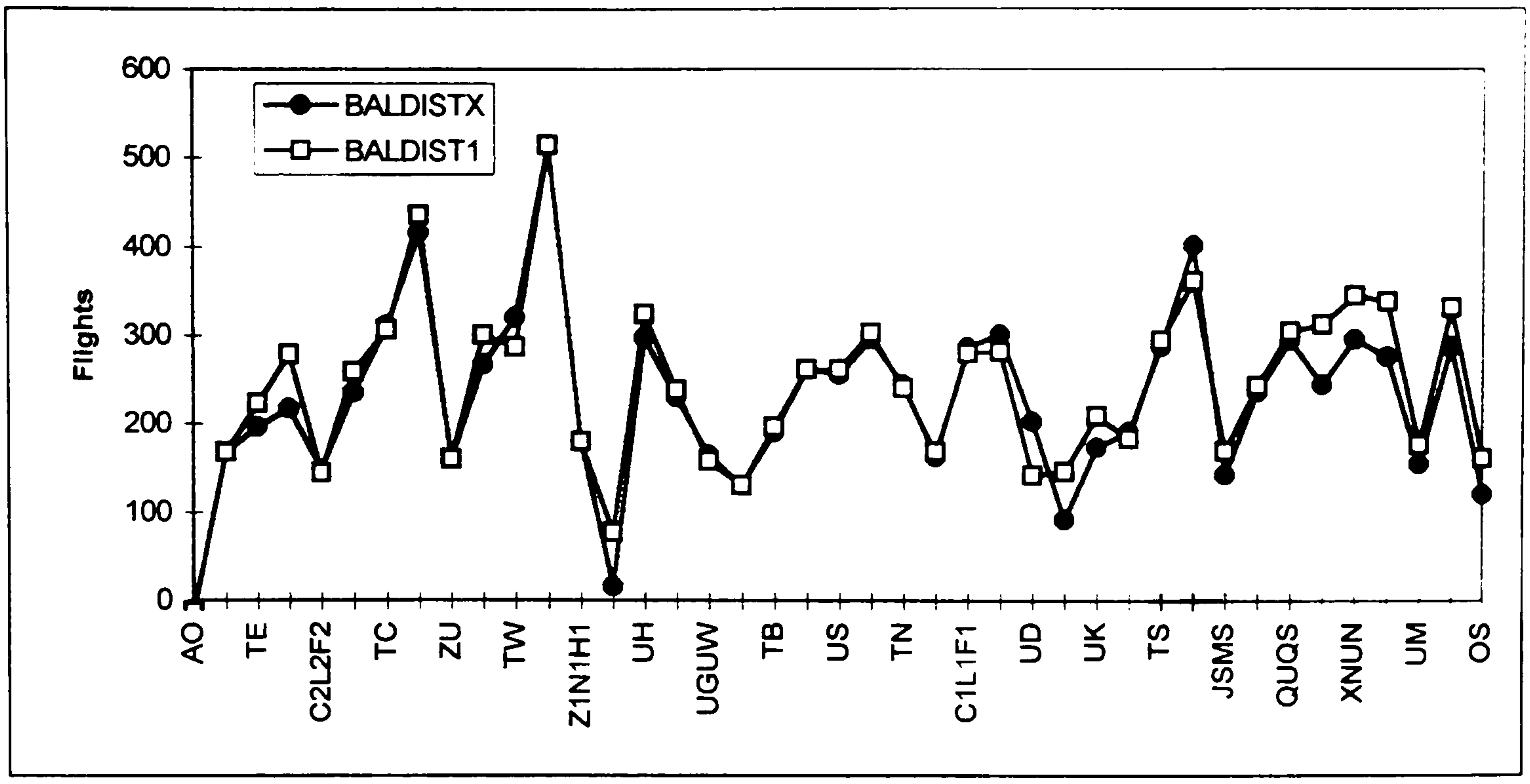


Figure 9.5-2: Under-used Capacity by Sector

Figure 9.5-3 shows that for the whole the French Upper airspace, total capacity exceeds demand during the whole day and the amount of under-used capacity is substantial. This suggests that before trying to reduce under-used capacity by means of re-routing control measures, measures aimed at re-distributing capacity between sectors should be considered. It should also be noted that re-routing control measures to reduce under-used capacity would not be easily accepted by aircraft operators, since they would have to pay the cost of re-routing the flights.

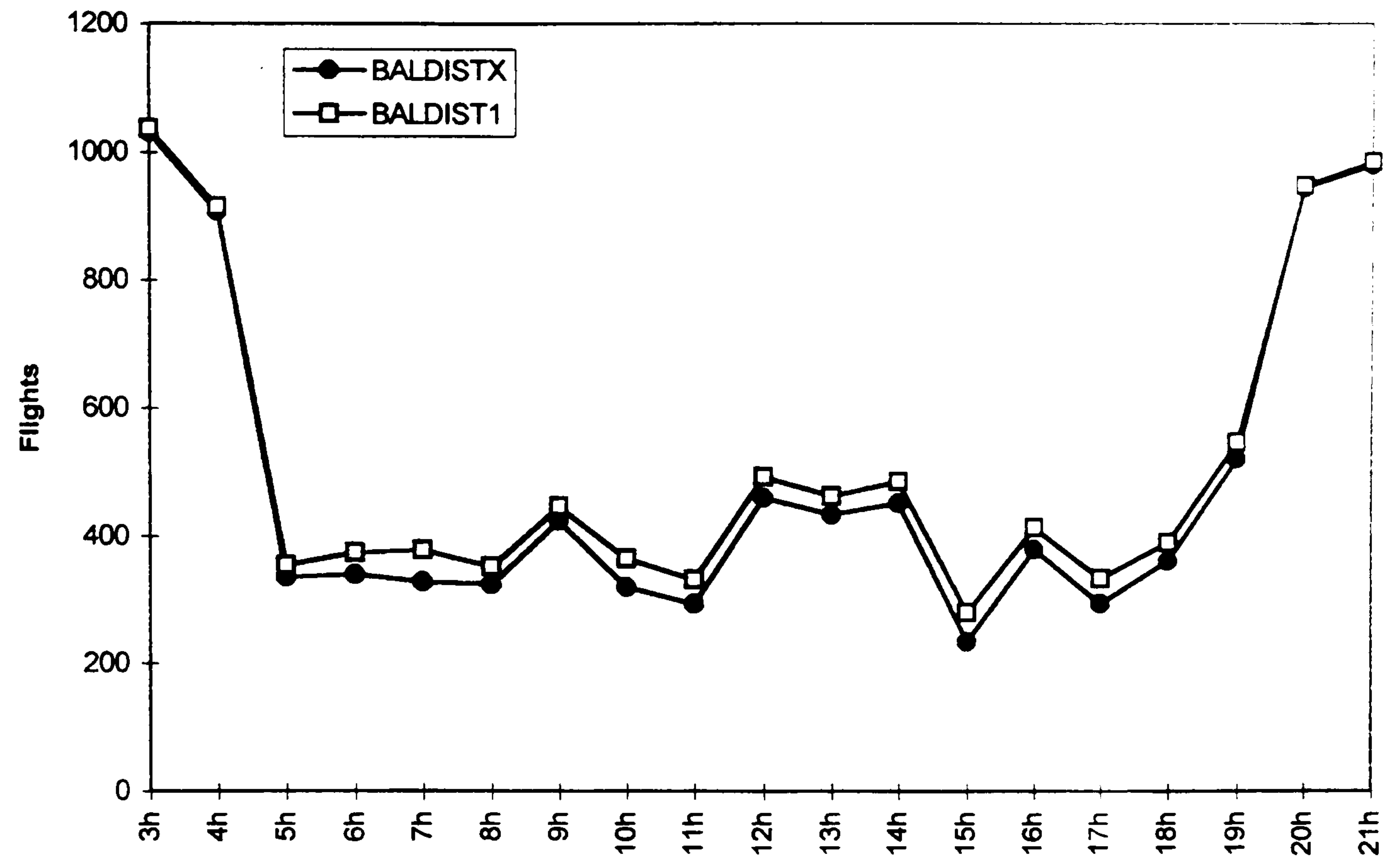


Figure 9.5-3: Total Capacity minus Demand

More detailed results for DELINTX2 and BALDISTX are in Appendix G. The next section summarises the results and conclusions of this chapter.

9.6 Conclusions

This chapter explores some extensions to the models described in Chapter 7 and tested in Chapter 8. The extensions considered are:

- Changing the flows to be re-routed: two possibilities are presented, one where flows are assigned to routes *a priori*, before running the models, and another, where the priority given to the re-routing of a flow is reflected in the cost of re-routing.
- Re-routing the flows onto more than one route: this possibility simplifies and shortens the models substantially. A model derived from DELINT2 is presented and tested on the traffic sample used to test the other models. The results show that the model is much easier to solve and that it provides slightly less congestion while re-routing many

fewer flights. However, the efficacy of this approach depends on the flow managers having the authority to decide how many flights of a flow are routed on to a certain route hourly, which rarely happens at present.

- re-routing individual flights: a model based on DELINT2 is presented. It is a simpler and more accurate model than DELINT2. However, given the very large number of flights to be considered, it would result in models that are much larger than any of the other models considered. A model adapted from BALDIST is then described which would lead to substantially smaller a more manageable models. It is noted that these models can only be applied to situations where flow managers have the authority to route individual flights and there is complete and precise data on individual flights. This rarely happens at present.
- Reducing under-used capacity: minimising dead periods or under-used capacity is also an ATC concern. A model based on BALDIST that includes under-used capacity in the objective function is presented and tested on the traffic sample available. The results do not show a significant reduction in under-used capacity while re-routing substantially more flights. The cost of under-used capacity considered, may be at the root of this result and a piecewise linear cost function is suggested. However, the data available shows that overall the French Upper airspace total capacity exceeds demand significantly during the whole day leading to the conclusion that before using re-routing control measures, measures aimed at re-distributing capacity between sectors should be considered. In addition, it should be noted that the objective of reducing under-used capacity would not be easily accepted by aircraft operators since they would bear the cost of the resulting re-routings.

Drawing on this and all the previous chapters, the next chapter, the conclusions, summarises the most important points of the research, assesses its contribution and limitations, and proposes directions for future research.

Chapter 10

Conclusions

The topic of this research was prompted by two gaps identified in the OR and systems literature on air traffic flow management: a lack of research into the European ATFM context and into re-routing decision support in Europe.

The main contributions of this research are: 1) a description of the European ATFM field and its decision support needs and problem setting for the re-routing of flights in Europe; 2) a framework for the development of re-routing decision support systems; and 3) investigation into the usefulness of optimisation approaches to the re-routing of flights in Europe. This includes the development and testing of new optimisation models for re-routing of air traffic flows.

The first section of this chapter reviews and reflects on the conclusions in the different areas of contribution. The second section highlights the limitations of this research and the third proposes directions for future research.

10.1 Review of Conclusions

The conclusions of this research are aimed at two groups: the research community and the user community. Therefore, this section is further divided into two: one section, directed at the research community, summarises the conclusions on the European ATFM field and decision support models for re-routing control measures. Another section, aimed mainly at the user community, contains the conclusions on the development of re-routing DSS and the use of optimisation models.

10.1.1 Conclusions for the Research Community

10.1.1.1 The European ATFM Field

European ATFM is a planning service aimed at protecting air traffic control from overloads and optimising the flow of air traffic. In Europe, the EUROCONTROL CFMU, with the assistance of flow management positions at the area control centres, is the sole provider of ATFM in the European Civil Aviation Conference Area. European centralised ATFM is still in its early stages: CFMU was created in 1989 and the transfer of ATFM functions from national flow management units to the CFMU was completed in 1996. Therefore, the knowledge and experience gathered by flow managers on centralised ATFM is, to some extent, exploratory. The stakeholders represented in European ATFM decision-making are: airlines, flow managers, air traffic controllers and national administrations. The decision-making process in European ATFM relies on the co-operation of these stakeholders.

Three different levels of planning were identified in European ATFM: strategic, pre-tactical and tactical. These three levels of planning differ in their specific objectives, stakeholders, timescale, and level of detail:

- Strategic planning starts with the end of the Summer season, and is aimed at obtaining a more balanced distribution of traffic in the next Summer season. The planning is based on very aggregated data and is steered by senior staff from the CFMU. Negotiation between airlines, national administrations and the CFMU plays an important role in decision-making. Strategic planning results in two main plans: the Traffic Orientation Scheme and the Contingency Routing Scheme. These specify mandatory routings for major European flows.
- Pre-tactical planning takes place a few days before the flights and it aims to prevent overloads. The planning for a certain day is done by flow managers at the CFMU. It is based on traffic data from the same day of the previous week and on input from the air traffic control centres and airline representatives. It results in the issue of an ATFM

notification message on the day prior to the flights. The message contains a list of the planned slot allocation regulations and a list of restricted air routes (e.g. air routes crossing military airspace) which will be opened.

- Tactical planning takes place on the day of operations and, in addition to preventing overloads, tries to limit the extent of delays. The data available for tactical planning are the actual flight plans filed by airlines. The planning at this level is done in a very volatile environment and its efficacy relies on the rapid response of the decision-makers: airlines' operations departments and the CFMU. When congestion is anticipated flow managers may try to negotiate increases in capacity with the air traffic control centres concerned. If this negotiation does not work flow managers may resort to slot allocation regulations and/or the re-routing of flights. The CFMU, for the allocation of slots, uses a system of supervisory control: flow managers monitor the traffic situation by means of TACT, the CFMU core computer system TACT provides information on planned flights, on traffic demand versus capacity and on delays. Whenever flow managers detect a potential overload, they activate a slot allocation regulation in TACT. TACT allocates slot delays automatically and sends the slot messages to the airlines without intervention from the flow managers.

Research into European ATFM revealed a major and urgent need for decision support tools at the different levels of planning. One of the ATFM control measures in pressing need of DSS is the re-routing of flights. This research investigated that need.

10.1.1.2 Decision Support Models for Re-routing Control Measures

Like ATFM, re-routing control measures can be taken at different levels, within the same timescales and with the same level of detail: strategic, pre-tactical and tactical levels. At the strategic level, major flows in Europe are routed in order to balance traffic distribution. At the pre-tactical level, flows are re-routed to prevent overloads. At the tactical level, individual flights with long slot allocation delays are re-routed.

The views of the main stakeholders in re-routing control measures, flow managers and aircraft operators, were gathered and the constraints imposed by other stakeholders, national administrations and air traffic controllers, were also considered. Flow managers can be seen as the users of re-routing DSS while aircraft operators are the customer of the CFMU. The latter pay for the development of DSS and are the eventual beneficiaries (positive or negative) of the use of the re-routing DSS. The observation and interviews of aircraft operators and flow managers obtained information on the use of re-routing measures, on decision criteria and constraints affecting re-routing control measures and on re-routing decision support needs.

The airlines interviewed are open to re-routing control measures as long as they were perceived as fair and worthwhile in reducing slot allocation delays. Many re-routings of individual flights are first suggested by aircraft operators. At the time of the fieldwork in 1995 and 1996, centralised ATFM was at its launch stage. Experience of centralised ATFM, including re-routing control measures, was scarce. Flow managers had different levels of experience of the use of re-routing control measures at national level. Some flow managers had moved directly from air traffic control to the CFMU and had no experience of flow management, others had worked for one of the national flow management units. Therefore, their views on the use of re-routing control measures and their decision support needs varied.

The fieldwork also indicated that the main decision criterion used by flow managers in the re-routing of flights was time: slot delay versus extra-flying time. In the re-routing of flows, only flows with acceptable alternative routes, routes which did not require a long detour were considered for re-routing control measures. Decisions were aimed at preventing or alleviating overloads. The criteria used by aircraft operators on re-routing decisions differ substantially among the different operators. Scheduled airlines have a higher perceived cost of delay than charter airlines. The airlines interviewed did not object to the use of time criteria in re-routing decisions, but were concerned about equity between airlines in the use of re-routing control measures.

At the tactical level, aircraft operators are often the ones who first propose the re-routing of their flights to the flow managers. Most aircraft operators have flight planning systems which, given a certain set of routes and weather forecasts, provide the best route for an aircraft. Aircraft operators with a well-equipped operations service know the alternative routes. The information they need from the CFMU is the delay situation on the different routes. Aircraft operators with fewer facilities expect to obtain information on both alternative routes and the delay situation from the CFMU. The four aircraft operators interviewed stated that the CFMU should have a re-routing function to support tactical re-routings.

The authority of re-routing control measures is less clearly defined than the authority of slot allocation control measures. The choice of the flight route is largely regarded as a commercial decision that is up to the airline. In recent years, the growth of congestion and congestion-related delays has made re-routing control measures more acceptable to airlines. At present, re-routing control measures are mandatory at the strategic level and in contingency situations, and are advisory at pre-tactical and tactical levels. However, a more extensive use of re-routing control measures at the pre-tactical level has been discussed for some time between the CFMU and the airlines. The decision support models developed in this research assume that the CFMU would have authority to issue mandatory re-routing control measures at the pre-tactical level.

Optimisation models and heuristics were suggested to support re-routing control measures at the pre-tactical and tactical levels within the context of a re-routing demonstrator which illustrated various decision support functions (see 0). These included coupling shortest route algorithms with heuristics to select flights which could be re-routed.

Specific optimisation models were developed to support the more complex function in the re-routing demonstrator which determined the set of flows to be re-routed. Models relevant to the re-routing of air traffic flows were identified. The use of network flow models or integer models was debated. Integer models were selected due to the discrete features of the re-routing problem and the added flexibility in their formulations. An iterative process ensued in order to capture the relevant features of the problem. Trade-offs between size, level of detail and execution time of the model guided this process. As a result, three integer models, BALDIST, DELINT1 and DELINT2, which differ in the way congestion is represented were developed and tested using traffic data provided by the CFMU. The differences between the three models are outlined in Section 0. Conclusions on their potential impact on congestion and their feasibility are in Section 0 and directions for further improvement are in Section 0.

10.1.2 Conclusions for the User Community

10.1.2.1 Development of Re-routing DSS

The case for the development of DSS for the re-routing of flights is based on their potential for responding quickly and consistently to complex problems. They can also provide training and support to less experienced staff. The design of re-routing DSS has to take into account the views of the different participants and the very different levels of experience of the users, the flow managers. During the fieldwork at the CFMU it was found that there were different, often conflicting, views on the user functions and degree of automation of a re-routing DSS. A further aspect which had to be considered was the still limited experience of flow managers in the use of centralised re-routing control measures. These considerations led to the development of a re-routing demonstrator which provided a tangible representation of different decision support possibilities and an assessment of their pre-feasibility.

The re-routing demonstrator provided a representation of functions to support pre-tactical and tactical re-routing of flights. The demonstrator functions ranged from simple to more complex and automated functions. Optimisation models and heuristics to support the demonstrator functions for re-routing flights were developed. A set of test data based on the actual traffic crossing three contiguous ATC upper sectors of Southern France for 4 hours on a busy day was used to illustrate the demonstrator functions. For the re-routing of flows, the need for specific models was highlighted (see 0). Feedback from users and other participants on the demonstrator indicated that all the functions represented in the demonstrator would be useful and suggested the directions that future development of re-routing DSS might take.

The demonstrator served as a basis for debating the level of automation and complexity of a re-routing DSS. It was concluded that the functions to support pre-tactical re-routings are more complex than the functions to support tactical re-routings and that they require knowledge that is still in short supply. In addition, given that tactical re-routing decisions have to be made rapidly in a volatile environment, it is suggested that a form of supervisory control is adopted for tactical re-routings. For pre-tactical re-routings a form of manual control with the DSS providing advice and the flow manager making the decisions at all levels of decision-making is proposed. Finally, it is argued that the development of re-routing DSS has to take into account future developments in the European air traffic management environment such as the changes to the European air route network and associated air space structure (which are being decided in the context of EATCHIP) and the progress in the standard flight planning systems used by airlines.

10.1.2.2 Use of Optimisation Models for Re-routing Air Traffic Flows in Europe

To define the models, the issue of whether the CFMU can take the decision on the re-routing of flows was debated. Considering the current situation and likely developments in European ATFM it was assumed that the CFMU will be given the authority to take decisions on the re-routing of flows but not on the re-routing of individual flights. Considering that the routes assigned to each flow have to be acceptable to the airlines in terms of extra-flying time and additional cost, the decision problem was broken down into two stages: in the first stage a set of acceptable routes (in terms of extra-flying time or additional cost) is identified for each flow. In the second stage, given a set of capacity constrained ATC elements, a route is assigned to each flow so that the total cost of re-routings and congestion is minimised.

Three optimisation models were developed: BALDIST, DELINT1 and DELINT2. The models differ in the way congestion is represented. Two possibilities were considered: (1) use penalties whenever traffic demand exceeds capacity, and (2) use ground-delays to keep the demand within the capacity. BALDIST is based on possibility (1), DELINT1 and DELINT2 are based on possibility (2) with each having a different level of detail. Possibility (1) results in smaller and simpler models, and shorter execution times than possibility (2). However, because possibility (1) does not take into account the cumulative effect of capacity/demand imbalances over time it may underestimate congestion.

Models with ground-delays have two types of decision variables: (1) variables assigning one route to each flow; and (2) variables assigning ground-delays (or departure time intervals) to flights. The first type of variables depends on the number of flows and the choice of routes available. Definition of the ground-delay variables, given the large number of flights involved, was not straightforward. DELINT1 and DELINT2 result from two different ways of defining ground-delay variables. In DELINT1 ground-delays are modelled in terms of 'number of flights of flow i delayed at t' whereas in DELINT2 ground-delays are modelled in terms of 'number of flights of flights of flow i scheduled to depart at t departing at a later time interval (t1)'.

These models were applied to a set of traffic data based on the actual traffic crossing the French upper airspace on 25 April 1996. The results of this test provided conclusions on two interrelated levels: on the usefulness of re-routing control measures and on the usefulness of the optimisation models. Re-routing control measures appear to be more effective if there are imbalances in the distribution of congestion or if the range of flows considered for re-routing is significant. It also became apparent that there are some sectors whose congestion peaks are so serious that they can only be attenuated but not eliminated by applying re-routing control measures.

On the usefulness of the optimisation models developed, it is concluded that they are of use in re-routing flows and could provide savings in congestion related delays. Comparing a situation where all flights would take the best route with the flow re-routing solution provided by the model, the test indicates that re-routings could reduce ground-delay by more than 50%. However, it should be noted that the results are compared with an extreme situation where all flights take the best route irrespective of the congestion situation. In a real environment, airlines and flow managers take action to prevent ground-delays to build-up, such as re-routing of particular flights.

The feasibility of the optimisation models was assessed using the following criteria: stakeholder acceptance, decision support provided, flexibility, data requirements, size and execution time.

- *Stakeholder Acceptance:* as discussed, acceptance of optimisation models by the stakeholders can be difficult. They can have problems accepting mathematically complicated models with an aggregate cost function which does not take their individual decision criteria sufficiently into account. The users' feedback on the demonstrator suggests they find the output of the models useful but more testing and user (and other stakeholders) involvement is needed to enhance the likelihood that they accept the models.
- *Decision Support and Flexibility*: the models were designed to meet the queries likely to be made in pre-tactical ATFM: the flows to be re-routed. The models can also allow for changes to features such as traffic demand, capacity of sectors, constraints on which flows to re-route, costs of delay, costs of re-routings and number of time intervals. Other features, such as the definition of sectors, routes and flows to be included in the re-routing control measures are not easily changed. As discussed, expertise in flow management is needed to make these changes.
- *Data Requirements:* prior to running the optimisation models a number of data processing operations have to take place, some of these

operations require expertise provided either by a flow manager and/or a system with some degree of 'intelligence'.

- *Size and Execution Time:* the execution time of the models is not critical because they are aimed at pre-tactical ATFM. The three models provided either optimal solutions or solutions whose value was less than 0.8% away from the optimum value in less than 8 minutes. Comparing the models, the test suggests that BALDIST, the simplest model, is the most efficient of the three in terms of size, execution time and quality of the solutions. DELINT1 in spite of being smaller than DELINT2 proved harder to solve to optimality and its use is not recommended. DELINT2 offers the best results in alleviating congestion, and provides more information than the other models, but it is a large model thus requiring much more space than DELINT1 and BALDIST and more time than BALDIST to be solved. The importance and relevance of these differences in performance will depend on the optimisers and computer resources available and on how close to the optimum value the solutions need to be.

Extensions to the optimisation models were developed to address some of their limitations and widen the range of situations where they are applicable. The following extensions were explored:

- Changing the flows to be re-routed: two possibilities were introduced, one where flows are assigned to routes *a priori*, and another where the priority given to the re-routing of a flow is reflected in the cost of re-routing.
- Re-routing flows onto more than one route: this was illustrated with a model based on DELINT2. The model is substantially smaller than DELINT2. In addition, the example used indicates that it is easier to solve and provides slightly less congestion while re-routing many fewer flights. The feasibility of this approach depends on whether flow managers have authority to implement these re-routing control measures, in practice. This happens rarely at present.

- Re-routing individual flights: a model based on DELINT2 was presented. It is a simpler and more accurate model than DELINT2 but it is considerably larger. A substantially smaller and more manageable model adapted from BALDIST was also presented. These models require two conditions which are rarely observed at present, to be effectively used: first, accurate and complete flight information has to be available two days prior to the flights. Second, flow managers have to have the authority to re-route individual flights.
- Reducing under-used capacity: a model based on BALDIST that includes minimisation of under-used capacity in the objective function was presented and tested. The results indicate that this is not a very effective approach: under-used capacity was only slightly reduced while substantially more flights were re-routed.

If a highly automated DSS is intended for the re-routing of flows two additional modules are needed to complement the optimisation models: an 'intelligent' component to define the scope of the optimisation problem and a component to process all the data and format it for the optimisation model. It was noted that considerable further research is needed to automate the module which defines the scope of the optimisation model. Some of the issues involved in defining the scope of the optimisation problem were pointed out:

- Identifying the airspace where the re-routing will apply - whether to select only the sectors that might be affected, directly or indirectly, by bottlenecks or the whole European airspace. If the former is chosen, decisions have to be made as to where the line on the sectors indirectly affected by bottlenecks should be drawn.
- Definition of flows - whether to group flights according to city-pairs, reference beacons which are crossed by the flights, or zones of origin and destination (i.e. groups of airports).

10.2 Limitations of this Research

The limitations of this research may be defined at three levels: the research approach, the fieldwork and the modelling approach. The limitations of the research approach have to do with the use of an 'action research' approach. As discussed (Chapter 3), action research engenders subjective interpretations of events and makes generalisation difficult. It can also place considerable responsibility on the researcher when his or her work is at odds with other stakeholders in the organisation. The latter was not apparent in this research but, by working closely with the client, the researcher may have accepted assumptions and constraints which could be more effectively challenged from a more distanced research standpoint.

The fieldwork for this research happened at the launching stage of the CFMU, at a time of fast change. As a result, part of the research into the context may become outdated rapidly. Mitigating this limitation is the fact that after the fieldwork an effort has been made to maintain contact with the CFMU and with the latest developments in European ATFM. The fieldwork could also have involved interviews with a wider range of airlines to have a more comprehensive set of standpoints on re-routing control measures. For instance, this could have uncovered distinctions not only between charter and scheduled airlines but also between airlines according to their size. However, time and geographical constraints made holding more interviews problematic.

The limitations of the optimisation models in terms of stakeholders acceptance, decision support, flexibility, data requirements, size and execution time were explained in section 0. In addition, the following limitations can be identified:

- The optimisation models provided here are meant for a scenario where flow re-routings are routinely prepared at the pre-tactical level (see Chapter 7). In support of this scenario, re-routing flows at the pre-tactical level has become more common in recent years.

- The models were tested on the French upper airspace. It was implicitly assumed that there was no congestion in the remainder of the ECAC airspace. The test was limited to one, albeit typical, day of traffic.
- In preparing the data for testing the models, decisions were made in defining the scope of the optimisation problem, for example in grouping flights into flows and selecting the routes. These decisions affected the results obtained.
- The models were tested using a simplified and static representation of 'the real-world'.
- The cost functions used in the models were based on the literature, on published operational costs of aircraft and on the interviews with four airlines. The input from airlines consisted of examples of trade-offs between ground-delays and re-routings, and information on overall costs. To ensure equity between flights, it was assumed that all flights had identical ground-delay and re-routing cost functions.
- The models, in their present form, re-route flows not taking into account how many times they have been re-routed before and penalising the flows which comprise more flights (however, the cost function used in the model can reflect how many times a flow or flight has been re-routed).

Ultimately, this research is limited by its scope: it did not test the feasibility of providing the data in a suitable form, in the time required for a re-routing DSS to be effective and it did not go as far as developing a full re-routing DSS in use at the CFMU, although there is evidence that results from this research are being taken up (see Chapter 3).

10.3 Directions for Future Research

The directions for future research may be grouped into two areas: DSS for European ATFM and models and algorithms for the re-routing of flows:

10.3.1 Decision Support for ATFM

ATFM lacks tools to support decisions at its different levels of planning. This research has provided decision support models for the re-routing of flows and flights but it constitutes a small part of what is needed. The following expand on the decision support needs and potential areas of application of OR for the different levels of European ATFM. The decision support needs are explained mostly in terms of computer tools and OR techniques needed to build those tools. It should be stressed that most of these decision support needs require the use of approaches which combine different techniques such as simulation, optimisation and artificial intelligence. A single technique, such as simulation or optimisation on its own is not sufficient to provide comprehensive decision support.

- Strategic ATFM: for the negotiations and preparation of the Traffic Orientation Scheme or the Standard Routing Scheme (see Chapter 4) a forecasting tool is needed to produce sufficiently accurate traffic demand forecasts; a fast-time simulation tool to be used by the flow manager is needed to assess the impact of different schemes on the congestion problems and the overall traffic situation; an optimisation tool is needed to suggest which flows to allocate to which routes to obtain a more balanced distribution of traffic.
- Pre-tactical ATFM: for decisions on re-routing of flows, re-routing functions as illustrated in the demonstrator are needed (see Chapter 6). These can be supported by optimisation models as presented here (see Chapters 7 and 8). These models require an extensive data processing component and expertise in defining the scope of the problem. For the production of regulation plans, a staged development of decision support tools is proposed. In a first stage a simulation tool based on TACT, with a traffic demand forecast module (producing more detailed forecasts than at strategic level) is developed to assist flow managers on a daily basis. This tool would enable the simulation of different regulation plans and routing of flows. The above mentioned simulation tool could also be used to experiment with different re-routing control

measures. In a second stage, when more knowledge of centralised ATFM has been gathered, a case-based reasoning tool, able to recognise 'similar' problems and to guide decision-making by looking at past situations, is added.

- Tactical ATFM: for the allocation of slot delays, there is scope to examine the technical and social feasibility of using heuristics based on priority rules or optimisation methods which take into account the connections between flights. For the re-routing of individual flights, heuristics and optimisation models were proposed by this research (see Chapter 6). These need to be coupled with detailed rules on the use of the airspace.

Another level of ATFM could be considered: planning when the aircraft have already departed. At present, ATFM is assumed to finish once aircraft depart. However, congestion problems occur when aircraft are already in the air and the case has been argued for ATFM to intervene in those situations. Control measures at this level of planning include, speed control and en-route re-routings. Computer tools will be needed to support decisions at this level of planning which is closer to the actual flights and takes place in a more volatile and dynamic environment than tactical ATFM. The use of an approach combining optimisation and simulation techniques for 'after departure' ATFM should be examined.

10.3.2 Models and Algorithms to Support Flow Re-routings

This research has shown that re-routing decision support systems cannot rely solely on optimisation models. Some form of 'intelligence' is needed to guide searches and define the scope of the optimisation problems. Future developments of optimisation models for re-routing of flows have to take this into account. This section proposes directions for future research which include the combined use of optimisation with other approaches or the alternative use of other approaches. The following directions for future research are proposed:

- The models presented here need to be tested on an even larger airspace, including several European countries or even the whole ECAC airspace.

- The models need to be tested in an environment closer to the real-world, possibly using computer simulation. A question that needs to be investigated is how much do these pre-tactical re-routings reduce the need for tactical control measures such as slot delays and flight re-routings.

- The definition of scope of the optimisation problem needs to be further investigated to answer the questions 'what sectors are to be considered in the problem' and 'what flows are relevant and how should they be defined'. Sensitivity analysis, addressing the impact of decisions made in the definition of the scope of the optimisation problem on the optimisation results should be carried out.

- The cost functions used in the optimisation models should be fine-tuned in consultation with aircraft operators and ATC costing centres. The inclusion of priority indices in the cost function of optimisation models to improve equity between airspace users should be investigated. For all flows with acceptable alternative routes, priority indexes could be defined according to how many times a flow has been re-routed and the number of flights in the flow. If a flow is composed of flights from different flows then a weighted index taking into account the number of flights from each flow and the frequency of re-routings could be built. The impact of different cost functions on equity should be examined.

- The optimisation models should be compared with constraint programming languages on the grounds that constraint programming languages appear to offer more flexibility in terms of changing and adding constraints and parameters to the models.

- The alternative or combined use of meta-heuristics such as tabu search, simulated annealing and genetic algorithms in the re-routing of flows should be considered as a way of improving the efficiency in the search for a re-routing solution.

- This research applied the definition of equity in use at the CFMU, equity between flights. Other definitions of equity should be investigated, such as equity between aircraft operators or between passengers. The question of how acceptable these functions are to the various stakeholders in ATFM should be addressed.
- As noted in section 0, the use of simulation models to support flow managers in testing various re-routing control measures should be investigated.
- The use of heuristics based on priority rules (see Chapter 5) in the re-routing of flows should be investigated. Priority rules could be defined in terms of the number of passengers in a flight or of how many times a flow has been re-routed. The effect of using these priorities on equity should be examined.

Congestion in the European airspace is severe and is expected to grow in the foreseeable future. Air traffic flow management plays and will play a key role in managing the available capacity and alleviating congestion. The need for decision support tools for flow management is urgent and vast. This research contributes to addressing that need and it may stimulate further research in a field of great practical importance.

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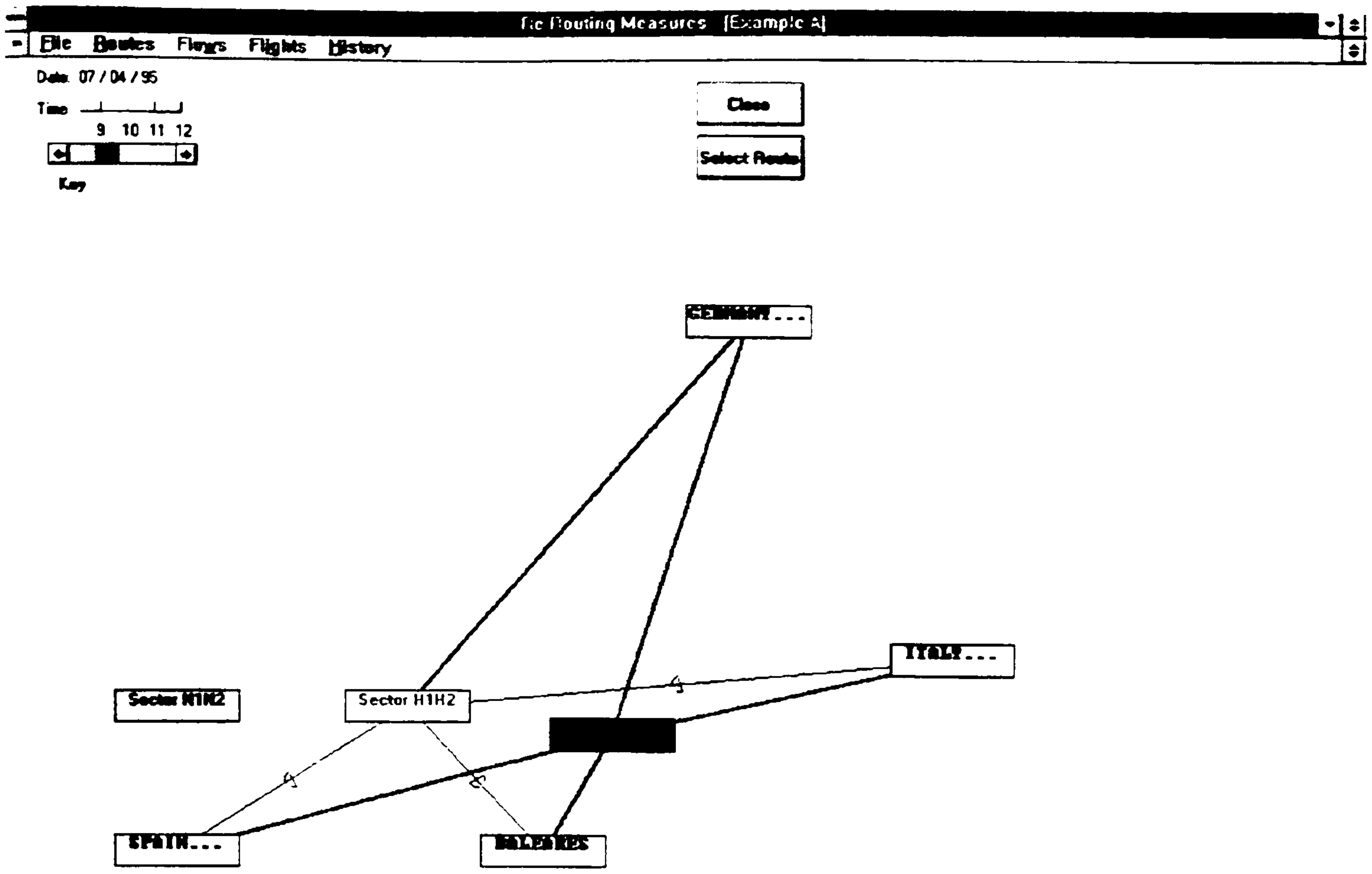
Appendix A - Re-routing Demonstrator Windows

This appendix contains the main windows of the Re-routing Demonstrator presented in Chapter 6. The windows were developed in Visual Basic. The example used in the demonstrator involves 3 air traffic control sectors of Southern France: UM, H1H2 and N1N2, of which UM (Marseilles) is the most congested. The flights are extracted from the traffic crossing at least one of these three sectors on 7/4/95 between 08:00 and 12:00h. The flows considered are:

- Germany and beyond - Balearics and Barcelona
- Balearics and Barcelona - Germany and beyond
- Spain and beyond (excluding Balearics and Barcelona) - Germany and beyond
- Germany and beyond - Spain and beyond
- Spain and beyond - Italy and beyond

More details on this example are in Appendix C.

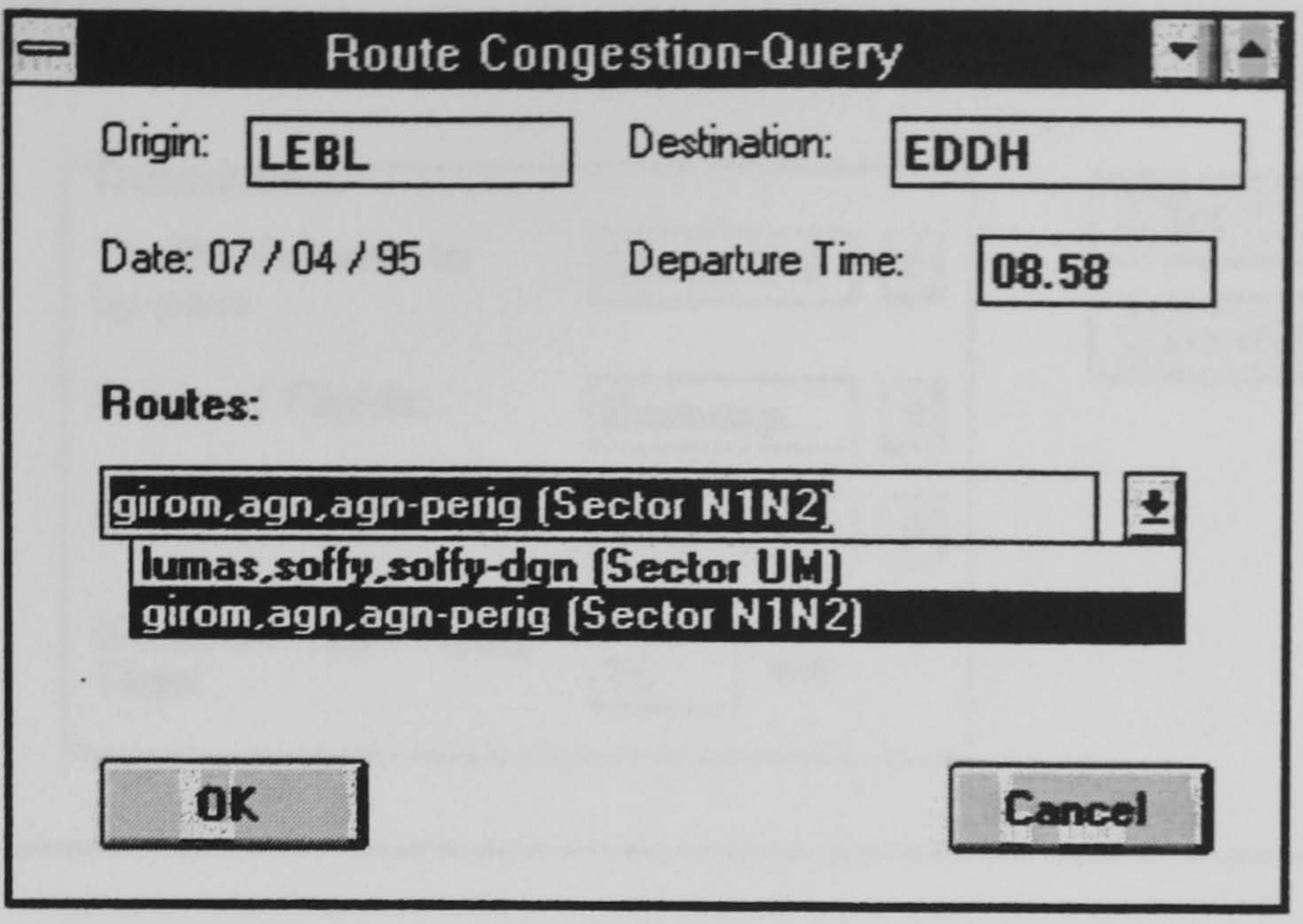
Figure A-1 shows the main window of the demonstrator. A graph connecting the different origin-destinations and the routes connecting them (the routes are defined in terms of the sectors they cross), is displayed. The colour of the sectors and the routes crossing them (not shown here) represents the level of delay: if the maximum delay in a sector is above 30 min the colour is red, if the delay is below 30 minutes the colour is yellow, and if there are no delays the colour is green. There is a time gauge enabling the flow manager to have a visual image of delays for each hour.



Date: 07 / 04 / 95

Figure A-1: Main Window

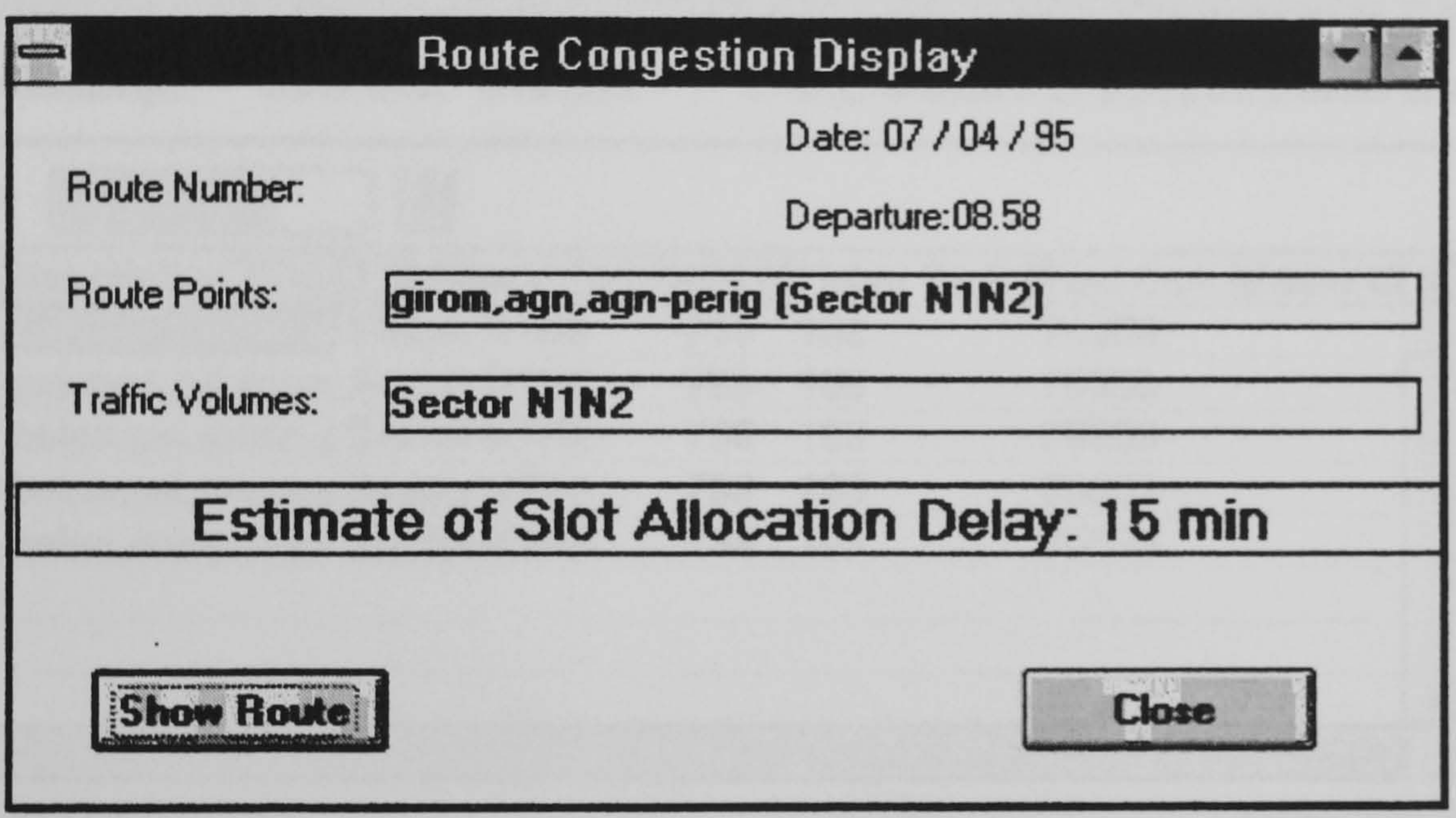
Figure A-2 shows the initial window for the function <Route Congestion>. An example of when this window would be needed is: Iberia rings the CFMU because flight IBE3950, from LEBL (Barcelona) to EDDH (Hamburg), scheduled to depart at 08:58, has a slot delay of 30 minutes. They want to know what the delays are like on a route going round UM, e.g. girom, agn, agn-perig (sector N1N2). Figure A-3 provides a reply to this query. The colour of the estimate of delay once again represents the length of the delay.



Origin: LEBL
Destination: EDDH
Date: 07 / 04 / 95
Departure Time: 08.58

Routes:
girom,agn,agn-perig (Sector N1N2)
lumas,soffy,soffy-dgn (Sector UM)
girom,agn,agn-perig (Sector N1N2)

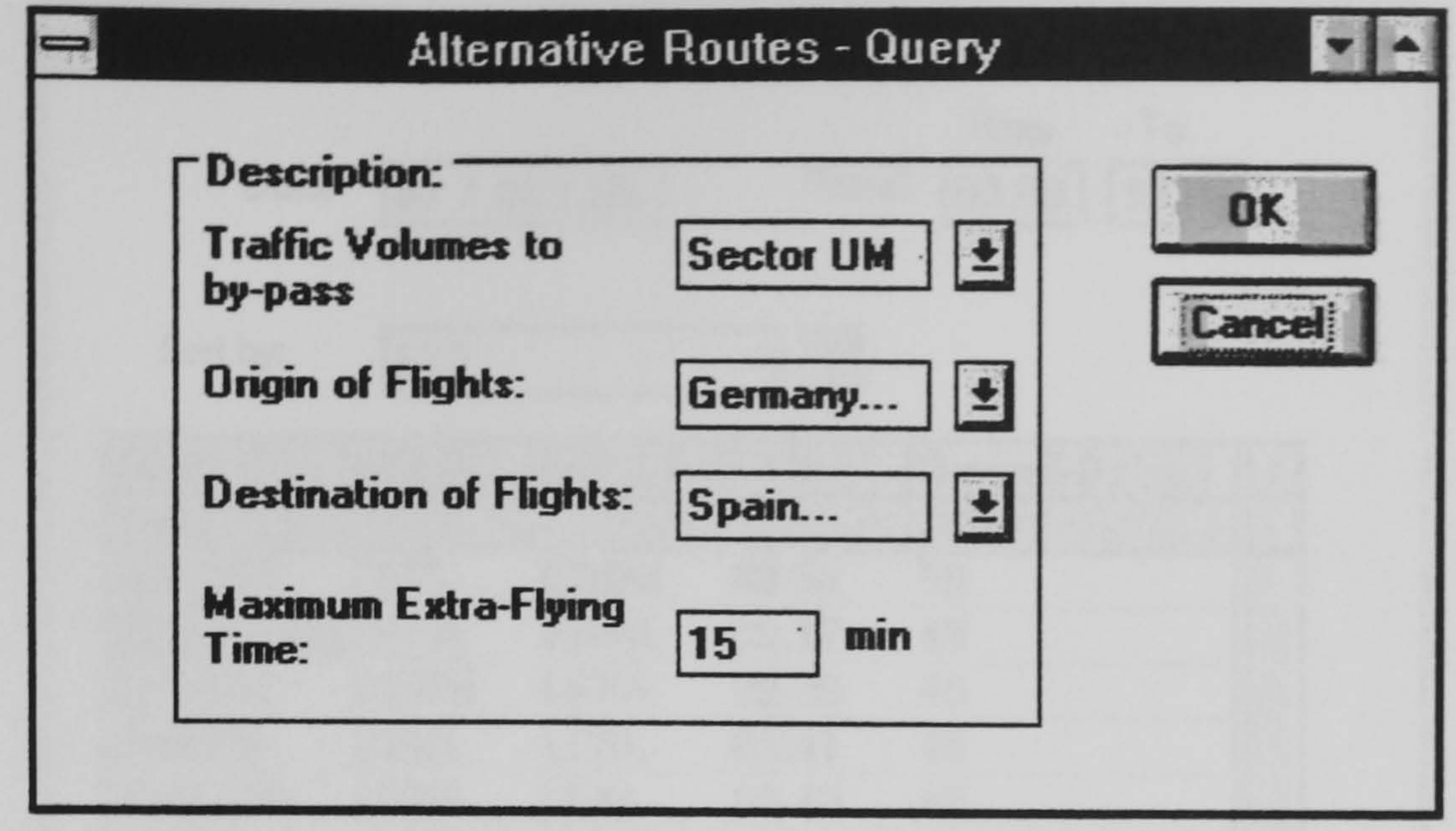
Figure A-2



Date: 07 / 04 / 95
Route Number:
Departure:08.58
Route Points: girom,agn,agn-perig (Sector N1N2)
Traffic Volumes: Sector N1N2
Estimate of Slot Allocation Delay: 15 min

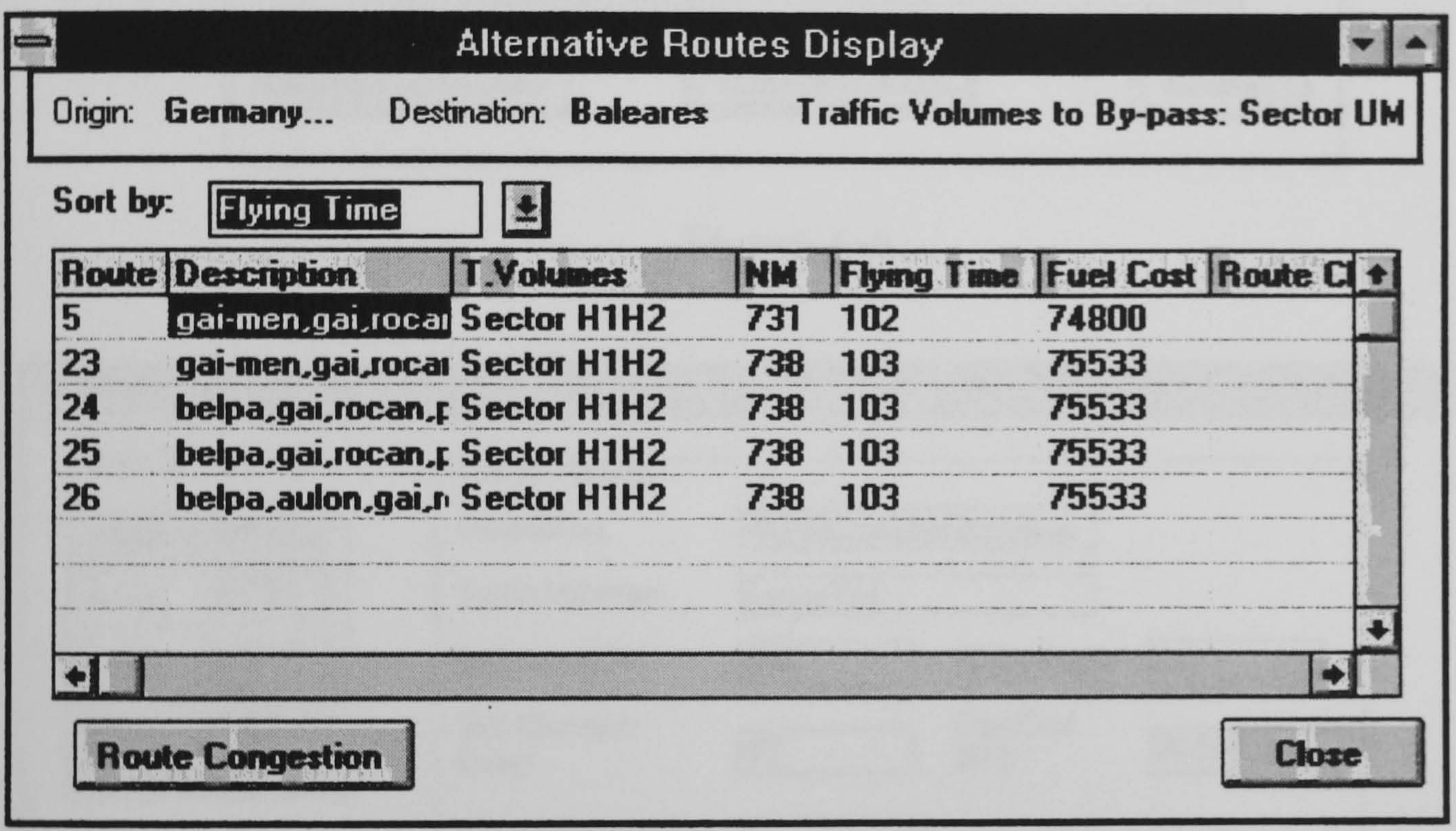
Figure A-3

Figure A-4 shows the initial window for the function <Alternative Routes>. An example of when this window would be used is: Sector UM has serious delays, flow managers need to identify alternative routes by-passing UM for flows crossing it. Figure A-5 shows the result of a query referring to the flow Germany and beyond - Balearics and Barcelona.



Description:
Traffic Volumes to by-pass: Sector UM
Origin of Flights: Germany...
Destination of Flights: Spain...
Maximum Extra-Flying Time: 15 min

Figure A-4



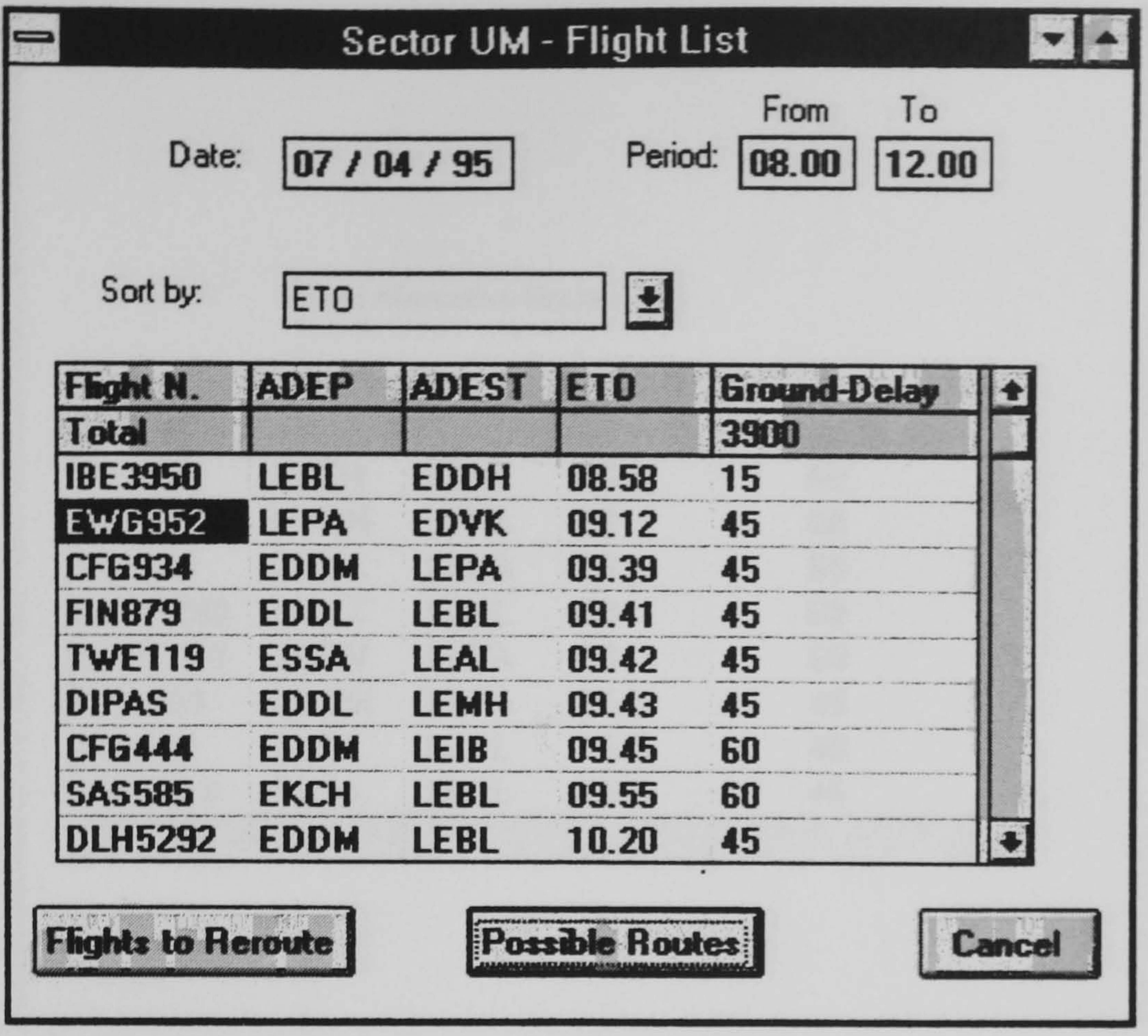
Origin: Germany... Destination: Baleares Traffic Volumes to By-pass: Sector UM

Sort by: Flying Time

Route	Description	T.Volumes	NM	Flying Time	Fuel Cost	Route C
5	gai-men,gai,roca	Sector H1H2	731	102	74800	
23	gai-men,gai,roca	Sector H1H2	738	103	75533	
24	belpa,gai,rocan,	Sector H1H2	738	103	75533	
25	belpa,gai,rocan,	Sector H1H2	738	103	75533	
26	belpa,aulon,gai,	Sector H1H2	738	103	75533	

Figure A-5

Figure A-6 is a possible starting point for the function <Routes For Flights>. It would be used in a situation such as, when the airline of flight EWG952, with a slot delay of 45 minutes, calls the CFMU to ask for a re-routing. Figure A-7 shows a choice of alternative routes ordered by a criterion which combines slot delay and flying time. The window in Figure A-6 can also be used for the function <Which Flights to Re-route>: Sector UM is seriously congested, the flow manager needs to know which flights crossing UM could be re-routed and onto which routes. Figure A-8 provides a list of flights which could be re-routed (see Chapter 6 for details on the criteria used).



Sector UM - Flight List

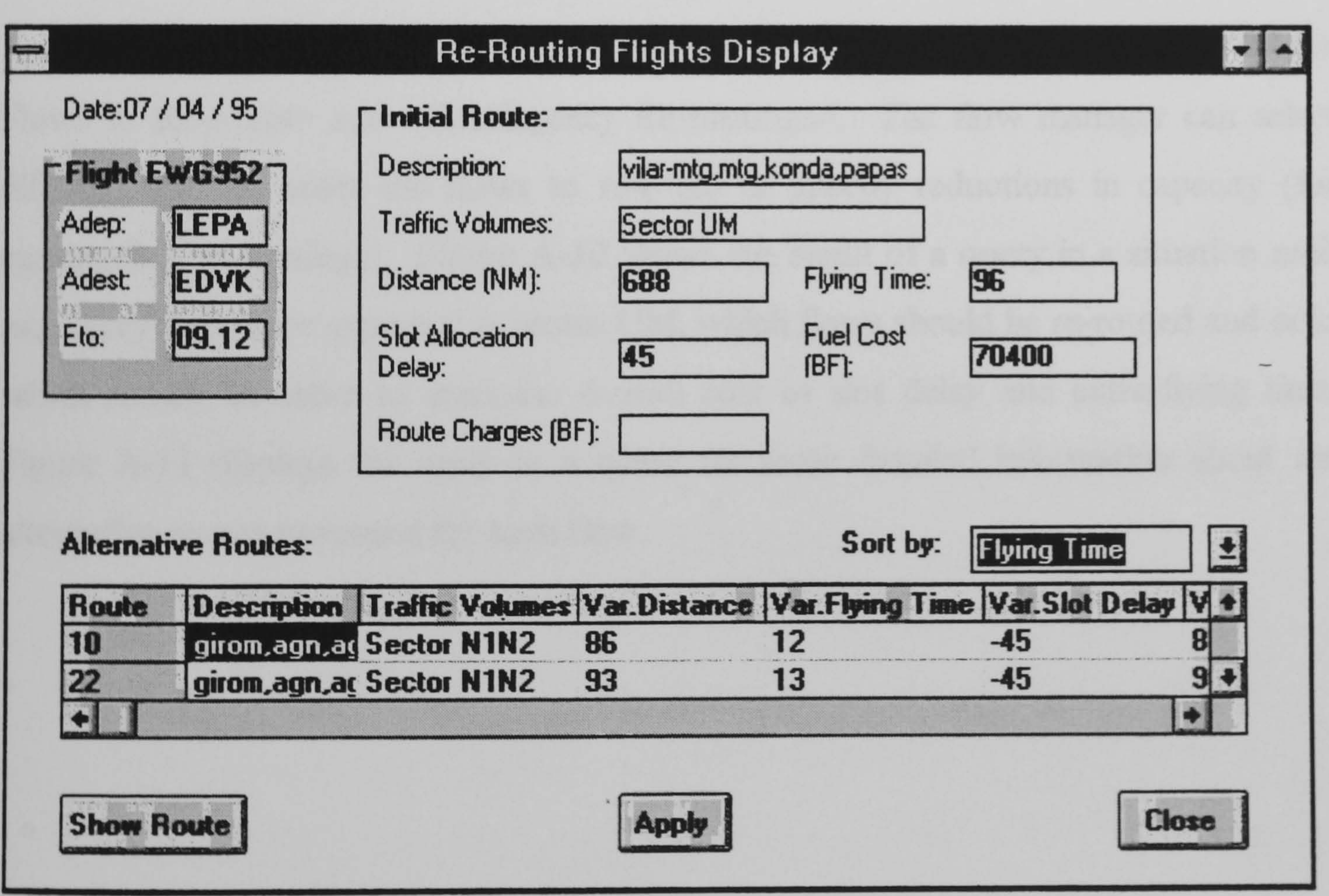
Date: 07 / 04 / 95

Period: From 08.00 To 12.00

Sort by: ETO

Flight N.	ADEP	ADEST	ETO	Ground-Delay
Total				3900
IBE3950	LEBL	EDDH	08.58	15
EWG952	LEPA	EDVK	09.12	45
CFG934	EDDM	LEPA	09.39	45
FIN879	EDDL	LEBL	09.41	45
TWE119	ESSA	LEAL	09.42	45
DIPAS	EDDL	LEMH	09.43	45
CFG444	EDDM	LEIB	09.45	60
SAS585	EKCH	LEBL	09.55	60
DLH5292	EDDM	LEBL	10.20	45

Figure A-6



Re-Routing Flights Display

Date:07 / 04 / 95

Flight EWG952

Adep: LEPA

Adest: EDVK

Eto: 09.12

Initial Route:

Description: vilar-mtg,mtg,konda,papas

Traffic Volumes: Sector UM

Distance (NM): 688

Flying Time: 96

Slot Allocation Delay: 45

Fuel Cost (BF): 70400

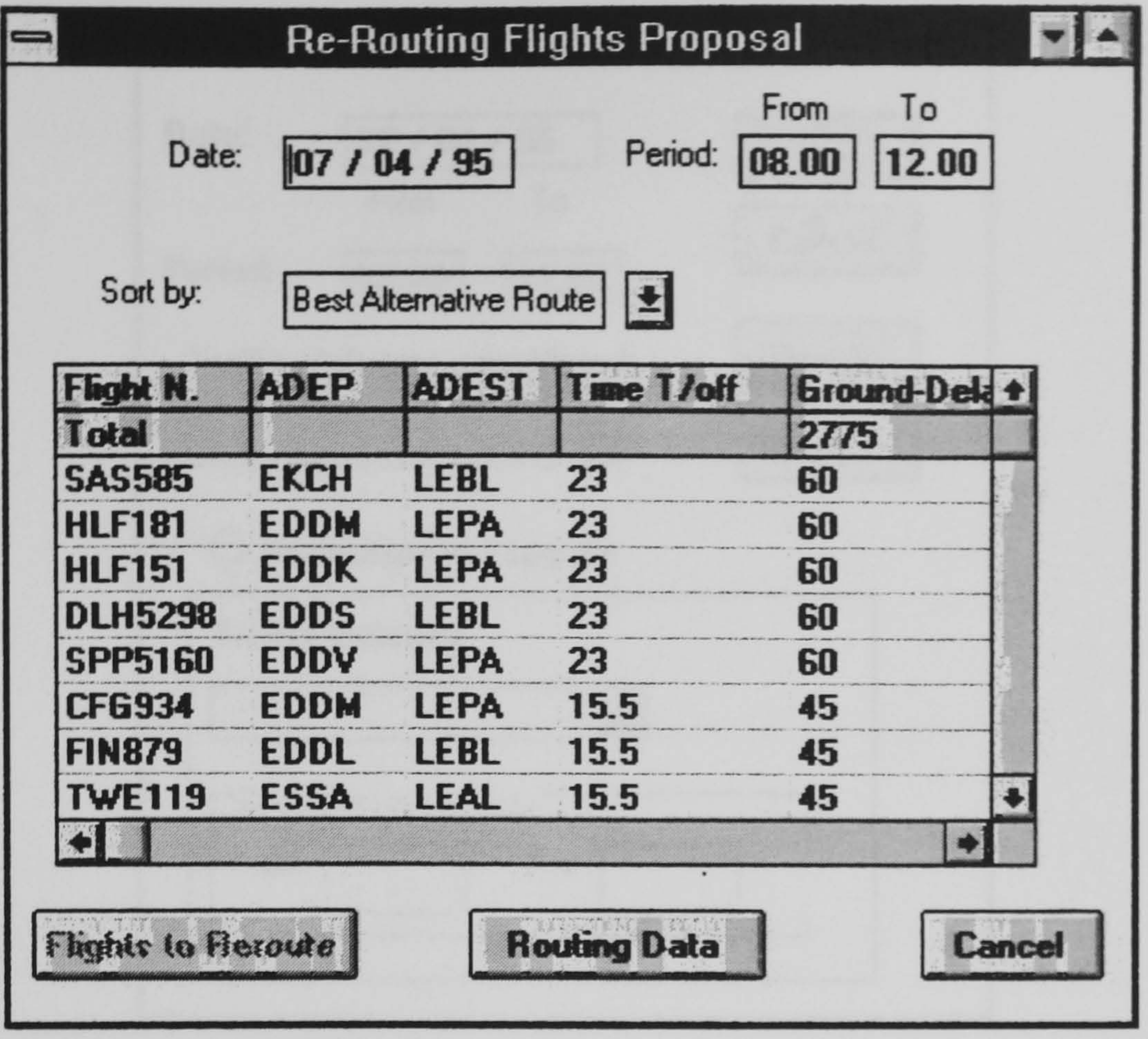
Route Charges (BF):

Alternative Routes:

Sort by: Flying Time

Route	Description	Traffic Volumes	Var.Distance	Var.Flying Time	Var.Slot Delay	V
10	girom,agn,ag	Sector N1N2	86	12	-45	8
22	girom,agn,ag	Sector N1N2	93	13	-45	9

Figure A-7



Date: 07 / 04 / 95

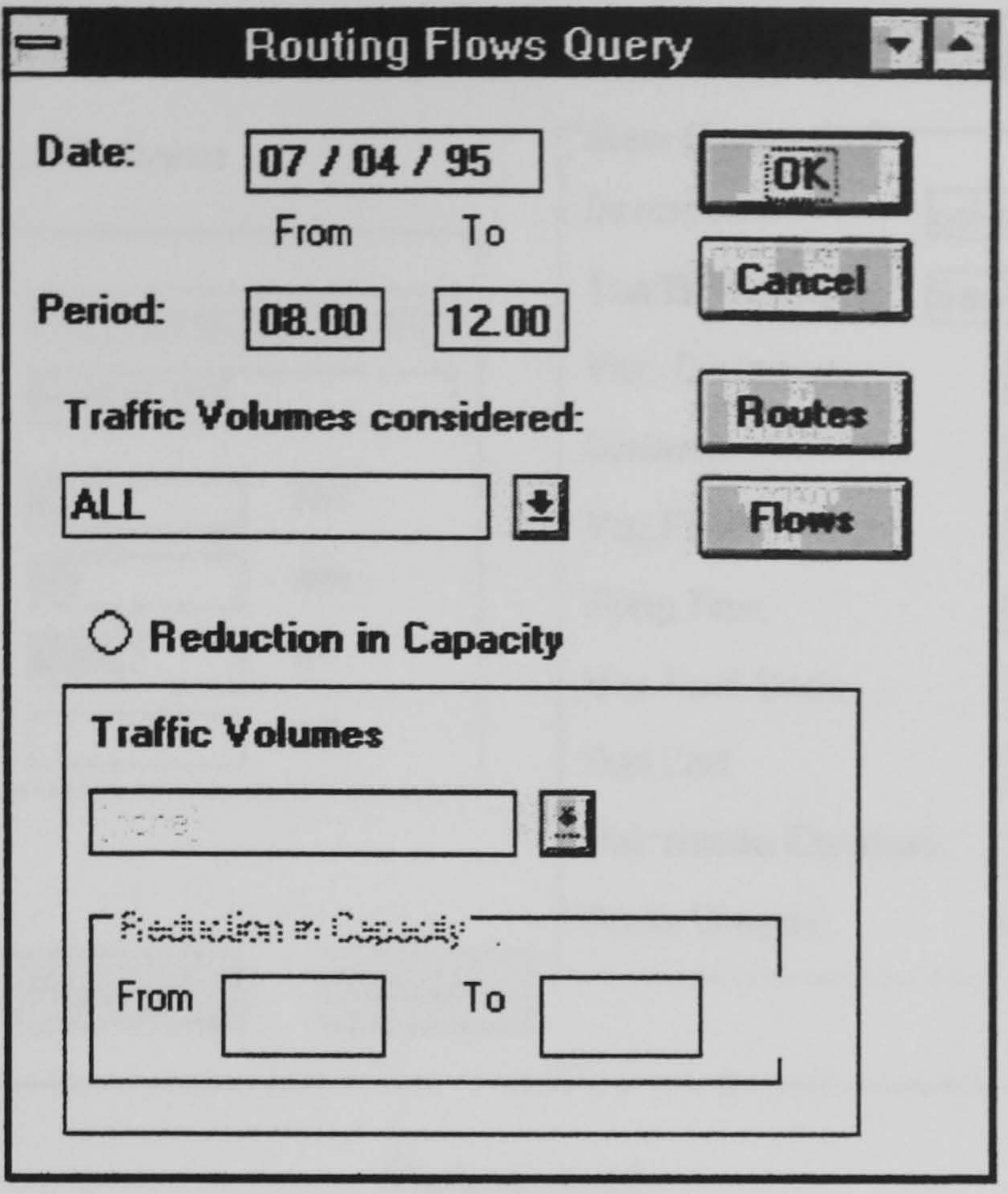
Period: From 08.00 To 12.00

Sort by: Best Alternative Route

Flight N.	ADEP	ADEST	Time T/off	Ground-Del
Total				2775
SAS585	EKCH	LEBL	23	60
HLF181	EDDM	LEPA	23	60
HLF151	EDDK	LEPA	23	60
DLH5298	EDDS	LEBL	23	60
SPP5160	EDDV	LEPA	23	60
CFG934	EDDM	LEPA	15.5	45
FIN879	EDDL	LEBL	15.5	45
TWE119	ESSA	LEAL	15.5	45

Figure A-8

Figure A-9 is the initial window for the functions <Routes For Flows>, <Which Flows to Re-route> and <Contingency Re-routings>. The flow manager can select different sectors, enter the flows to re-route or specify reductions in capacity (for contingency re-routings). Figure A-10 shows the result of a query in a situation such as: heavy delays are expected in sector UM, which flows should be re-routed and onto which routes, in order to minimise overall cost of slot delay and extra-flying time. Figure A-11 displays the reply to a query for more detailed information about the alternative routes proposed for each flow.



Date: 07 / 04 / 95

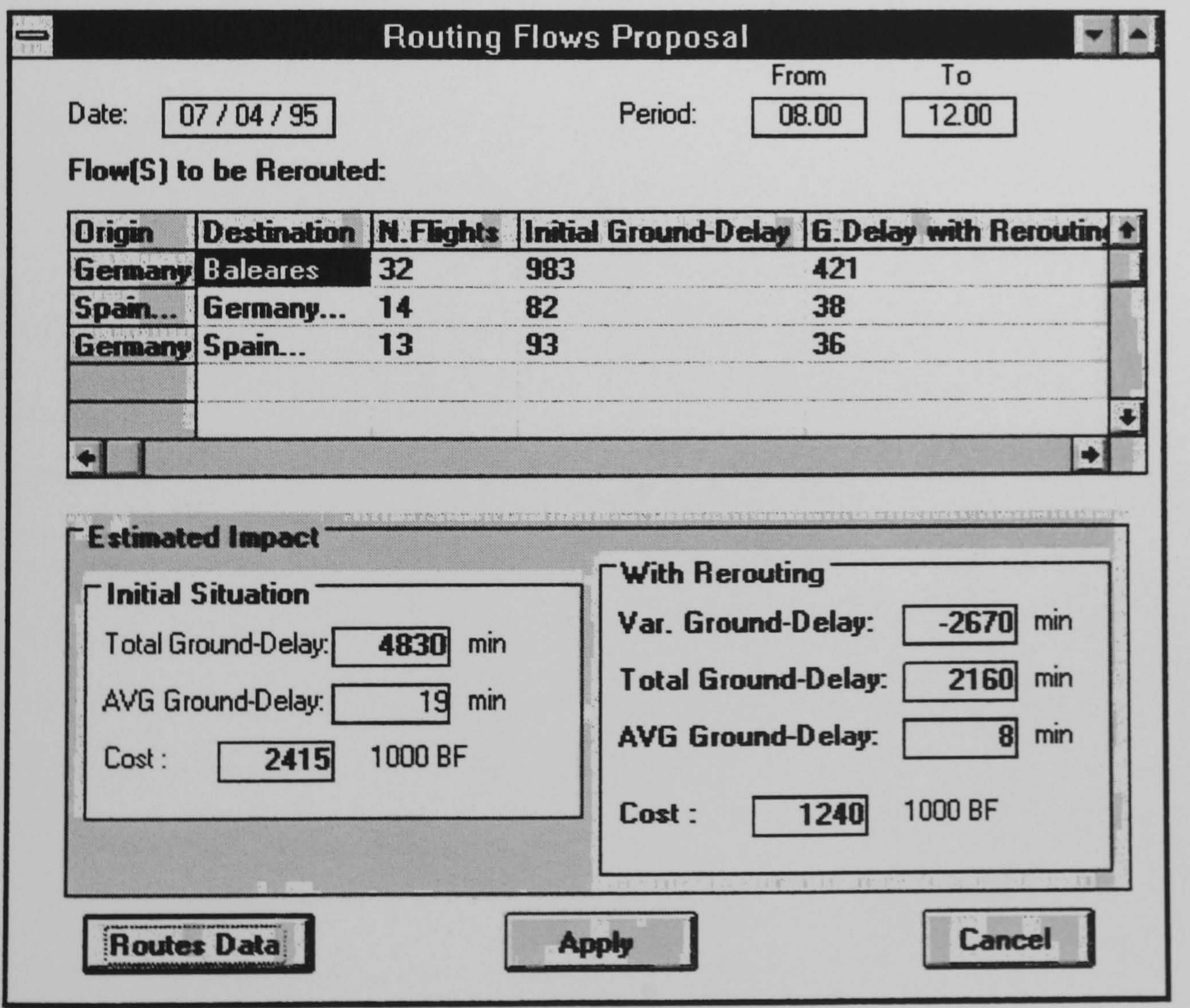
Period: From 08.00 To 12.00

Traffic Volumes considered: ALL

○ Reduction in Capacity

Traffic Volumes: (none)

Figure A-9



Date: 07 / 04 / 95

Period: From 08.00 To 12.00

Flow(S) to be Rerouted:

Origin	Destination	N.Flights	Initial Ground-Delay	G.Delay with Reroutin
Germany	Baleares	32	983	421
Spain...	Germany...	14	82	38
Germany	Spain...	13	93	36

Estimated Impact

Initial Situation

Total Ground-Delay: 4830 min

AVG Ground-Delay: 19 min

Cost : 2415 1000 BF

With Rerouting

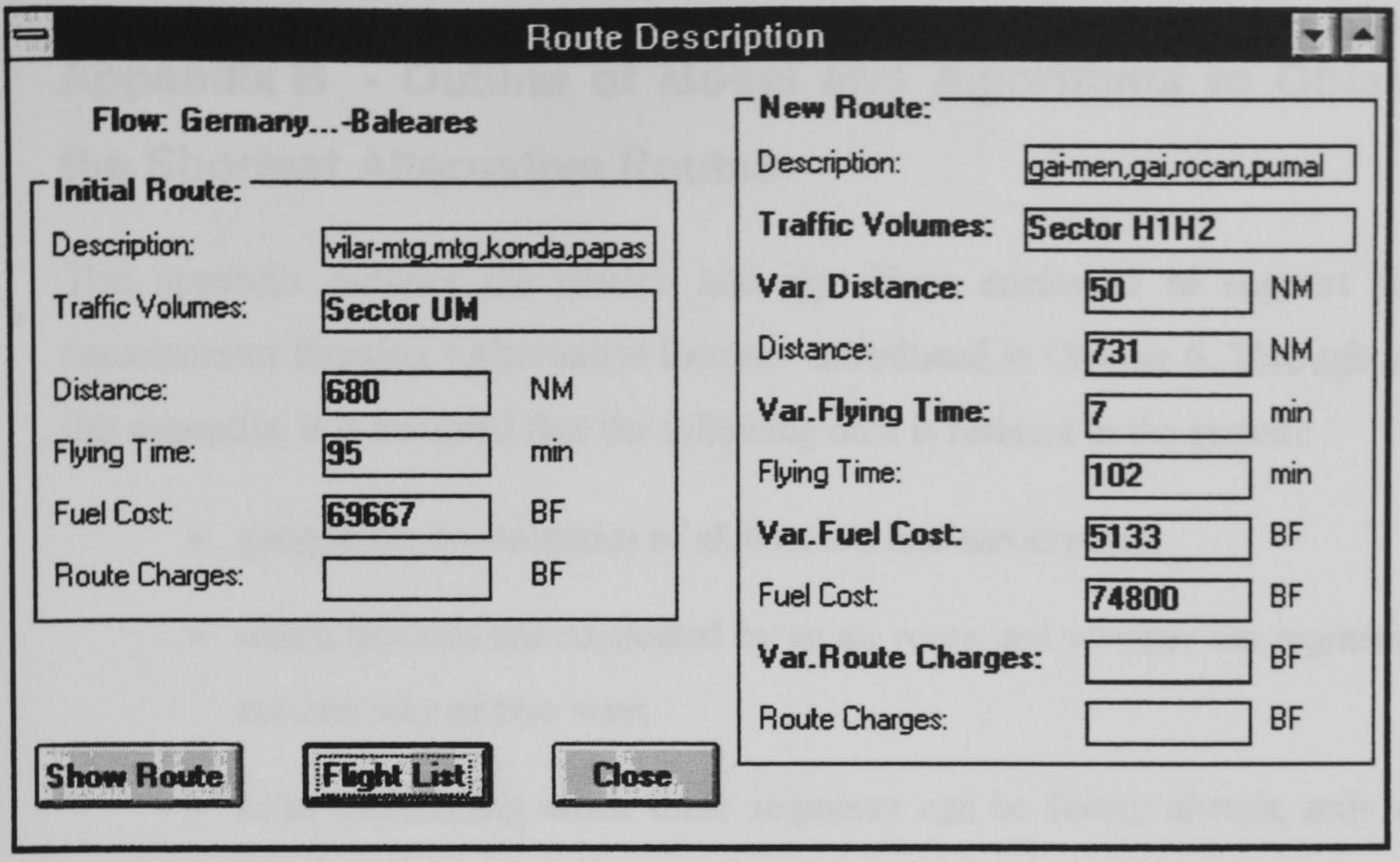
Var. Ground-Delay: -2670 min

Total Ground-Delay: 2160 min

AVG Ground-Delay: 8 min

Cost : 1240 1000 BF

Figure A-10



Flow: Germany...-Baleares

Initial Route:

Description:	vilar-mtg,mtg,konda,papas	
Traffic Volumes:	Sector UM	
Distance:	680	NM
Flying Time:	95	min
Fuel Cost:	69667	BF
Route Charges:		BF

New Route:

Description:	gai-men,gai,rocan,pumal	
Traffic Volumes:	Sector H1H2	
Var. Distance:	50	NM
Distance:	731	NM
Var.Flying Time:	7	min
Flying Time:	102	min
Var.Fuel Cost:	5133	BF
Fuel Cost:	74800	BF
Var.Route Charges:		BF
Route Charges:		BF

Figure A-11

Appendix B - Outline of Model and Algorithms to Obtain the Shortest Alternative Routes

This appendix outlines the models and algorithms envisaged to support the demonstrator function <Alternative Routes> introduced in Chapter 6. Throughout this appendix, it is assumed that the following data is resident in the system:

- geographic co-ordinates of all beacons and aerodromes;
- which beacons are connected by an air route and whether the segments are one way or two way;
- rules establishing when these segments can be flown: always, only at the weekend, or only at certain times of the day;
- unit fuel cost, speed and route charges.

The function, <Alternative Routes>, provides alternative routes between two points, selected in terms of flying time or nautical miles. The input is an origin and a destination, which can be points or aerodromes, and optionally traffic volumes to by-pass and/or a maximum flying time. The output is a list of routes sorted by flying time with additional information on the fuel cost, route charges and nautical miles of each route.

Model

The airspace can be seen as a directed network, where beacons are nodes, and segments are arcs. If a segment is two way there will be two arcs on the network. Moreover, if different ranges of flight levels are considered (and consequently different speeds) there can be as many arcs as ranges of flight levels connecting two nodes. The origin and destination can be represented by what is called the source and the sink of the network. Below, there is an example of how a network model would look. The numbers represent flying time.

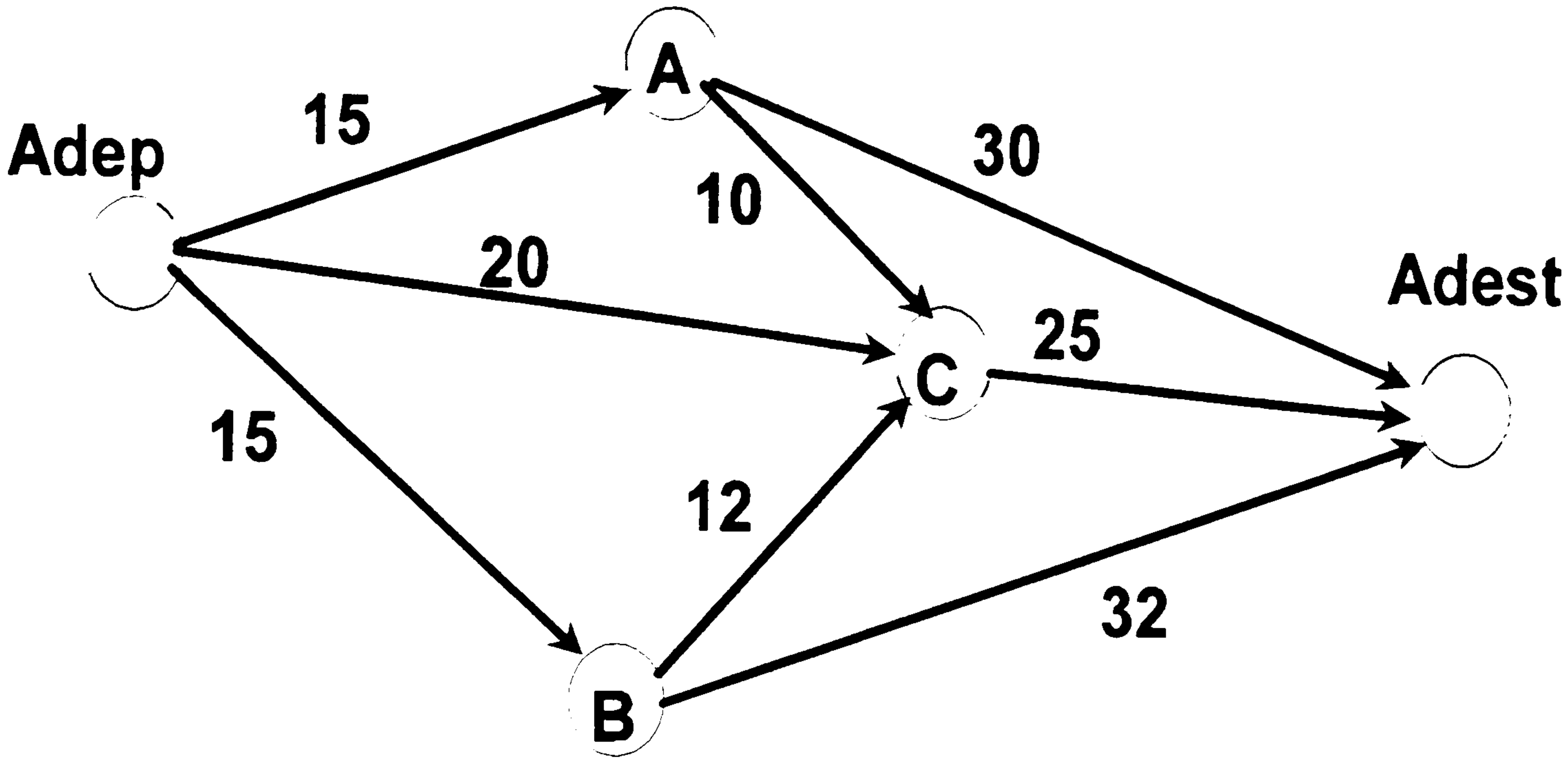


Figure B-1: Example of Distance Problem

Within this framework, the problem of obtaining alternative routes can be seen as the problem of obtaining k-shortest routes between two points, and the function to be minimised is flying time.

Size

Assuming that on average there is a ratio of two-to-one between arcs and nodes, the size of the network would be n nodes and 2n arcs. However, in a problem where one wants to obtain the routes between two points, there has to be a way of excluding from the network all the sectors which imply too long a detour. One rule of thumb could be to exclude all the sectors which do not fulfil at least one of the following criteria:

- being contiguous to the origin or destination sectors;
- being geographically situated, within certain boundaries.

In the re-routing demonstrator, when the option 'airspace elements to by-pass' is specified, the arcs and nodes corresponding to those elements, including the arcs that lead or start solely at those airspace elements, are excluded from the network.

Algorithms

The algorithms to calculate the shortest route between two points are fairly standard. One of the most used algorithms is the Dijkstra labelling algorithm (Syslo, 1983) for problems with non-negative *weights*. At each step of the algorithm, the closest node to the source is permanently labelled with the corresponding distance. The algorithm stops when the sink (destination) is labelled. Following the arcs whose labels match backwards, the shortest route is identified. This algorithm can be easily adjusted to solve the case where the shortest distances between the source and every other point in the network have to be calculated.

However, for the alternative routes function, more than one route may be needed. For this case several algorithms have been proposed (Perko, 1986) which are based on the concept of *deviation*. A *deviation* from a route, is the tail node of an arc not belonging to the route but whose head node does. The basic idea is to build routes from other routes by means of deviations.

Outline of algorithm:

1. run **Dijkstra algorithm** to determine the shortest routes from the origin to all other points. If the shortest route from the origin to the destination does not exceed max. flying time (or cost) go on, otherwise stop [there is no-route whose flying time is less than the max. flying time];
2. calculate first order **deviations** from the shortest route (R) in the following way: for each node P on the route (except for the origin) a set of new routes is formed as follows: let (M,P) be an arc not in R. Let D be the route (s,(M,P),r). Where s is the shortest route from the origin to M, and r is the sub-route of R from P to the destination. s is called the spur and r the root of route D. M is called the deviation and P the branch nodes of D. It is clear that length(D)≥length(R).

To ensure that D is loopless its spur cannot include any points already in R from P to the destination.

Using the nodes in the spurs of the first order deviations, as branch nodes, second order deviations can be obtained, and so on and so forth. The algorithm stops when k routes have been found or when all deviations have been (implicitly or explicitly) enumerated.

To filter, and limit the routes thus obtained, there is an upper bound. To start with, this upper bound is the maximum flying time(or cost). When K admissible (loopless and shorter than the upper bound) routes have been found, the upper bound is made equal to the length of the Kth route.

The deviation routes are put on a queue, ordered by increasing lengths.

Complexity and Efficiency

The worst case complexity of an algorithm of this type can be $O(Kn^3)$ (Perko, 1986), where K is the number of alternative routes and n is the number of nodes in the network. This means that the growth of the execution time of the algorithm is bounded by a function of the type Kn^3 which is a polynomial function. Therefore, in terms of execution time this type of algorithm can be considered efficient.

Another issue where efficiency is concerned is storage requirements. In Perko (1986) suggestions are made in order to use little storage space. For instance, all the routes built by means of deviations, ultimately come from the shortest route and can be tracked just by keeping ordered lists of the spur, deviation node and corresponding arc, and a reference to the parent path entry.

Appendix C - Test Results of M-CFMU

The example studied refers to three sectors of Southern France: UM (Marseilles ACC), H1H2 and N1N2 (Bordeaux ACC). These sectors were chosen for the following reasons: (1) UM is a congested sector and H1H2 and N1N2 provide alternative routes for UM (especially for South and Northbound flows); and (2) the availability of data and experience on re-routing of flows.

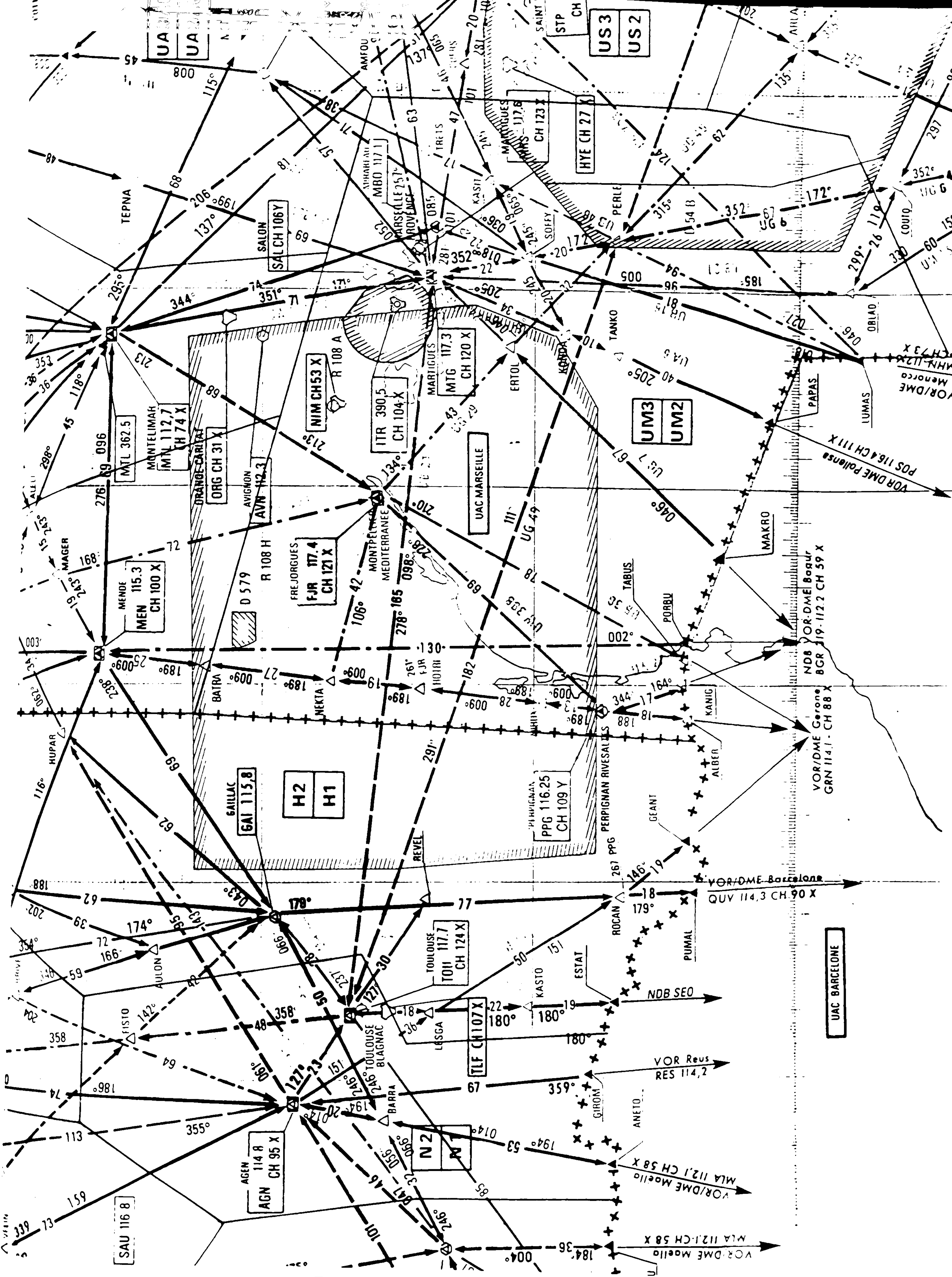


Figure C-1: Sectors in Example

The traffic data, 261 flight plans, was extracted from SPORT (a computer system intended for the French airspace which uses past traffic data to prepare pre-tactical ATFM plans) and refers to the flights that entered these sectors on 07/04/95 between 8.00 and 12.00.

The flows are defined in terms of origin and destination areas outside these sectors. Taking into account the pattern of traffic crossing these sectors, six flows were considered:

1. Germany and Beyond - Baleares[1];
2. Baleares - Germany and beyond;
3. Italy... - Spain and beyond;
4. Spain and beyond - Italy...;
5. Germany and beyond - Spain and beyond excluding Baleares;
6. Spain and beyond excluding Baleares - Germany and beyond.

To calculate distances, reference beacons or aerodromes were defined for each flow: Germany and Baleares (FFM and LEPA), Italy and Spain (OST and LEPA), Germany and Spain excluding Baleares (FFM and TBO). Flows of traffic between Paris TMA and airports in Marseilles and Bordeaux, in spite of their importance were not explicitly considered, given the difficulty in defining a unique reference point for the airports in Marseilles and Bordeax.

To calculate ground-delays, and to count traffic loads on sectors, time was divided into periods of 15 min each. A flight is supposed to arrive at the beginning of the period. For example, if a flight takes 40 min to cross a sector it is counted 3 times on three successive timeperiods. It is expected that on average, deviations from this assumption will counteract. The capacity considered for each of the three sectors, 32 flights per hour, was also defined in terms of 15 min intervals.

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[1] includes Barcelona.

Ground-delays occur whenever traffic demand at a certain sector exceeds its capacity.

The calculation of flying time is based on the cruising speed of an aircraft of the type Boeing 737: 430 nm/hour. The estimate for fuel cost resulting from extra-flying time is also based on the performance of a Boeing 737: 44000 BF/hour. The cost of ground-delays, adapted from (Terrab & Odoni, 1993) is estimated at 30000 BF/hour. All flights are assumed to have the same cost of ground-delay and fuel. The routes selected for each flow are shown in Table C-1 and the results are shown in Table C-2 and Table C-3.

Table C-1: Routes Selected for each Flow

Flow	Points	Sectors
Germany...-Baleares		
Route 1	vilar-mtg,mtg,konda,papas	UM
Route 5	gai-men,gai,rocan,pumal	H1H2
Baleares- Germany...		
Route 7	lumas,soffy,soffy-dgn	UM
Route 10	girom,agn,agn-perig	N1N2
Italy...- Spain...		
Route 11	mtg-stp,mtg,konda,papas	UM
Route 29	gai-men,gai,rocan,pumal	H1H2
Spain...-Italy...		
Route 13	lumas, lumas-stp	UM
Germany...-Spain...		
Route 17	gai-men,gai,gai-barb,tbo	H1H2+N1N2
Route 27	agn-guere,agn,barba,tbo	N1N2
Spain...-Germany...		
Route 15	tbo-hupar. hupar	N1N2+H1H2
Route 28	tbo,barba,agn,agn-perig	N1N2

Table C-2: M-CFMU Flows Re-routed

Flows/ Sectors	From Sector(s)	To Sector(s)
Germany...-Baleares	UM	H1H2
Spain...-Germany...	N1N2+H1H2	N1N2
Germany...-Spain...	H1H2+N1N2	N1N2

Table C-3: M-CFMU Impact of Re-routings

	Delay UM	**Delay H1H2**	**Delay N1N2**	**Total G. Delay**	**Avg. Delay**	**Total Cost (1000BF)**
No Re-routing	3900	480	450	4830	19	2415
With Re-routing	705	1170	285	2160	8	1240
Var.(%)	-82	144	-37	-55	-58	-49

(*) As there are only 3 sectors, it is possible to link delay directly to the sectors.

Appendix D - Initial Test of BALDIST, DELINT1 and DELINT2

The example studied refers to the same airspace and date of the one described in Appendix C. Three sectors of Southern France are considered: UM (Marseilles ACC), H1H2 and N1N2 (Bordeaux ACC). UM is a frequently congested sector and H1H2 and N1N2 provide alternative routes for UM (especially for South and Northbound flows). Re-routing measures affecting these sectors are common in practice. The flows are defined in terms of origin and destination areas outside these sectors. Taking into account the pattern of traffic crossing these sectors, six flows are considered:

1. Germany and beyond - Baleares (inc. Barcelona);
2. Baleares (inc. Barcelona)- Germany and beyond.
3. Italy and beyond - Spain and beyond.
4. Spain and beyond - Italy and beyond.
5. Germany and beyond - Spain and beyond excluding Baleares.
6. Spain and beyond excluding Baleares - Germany and beyond.

To calculate distances, reference beacons or aerodromes were defined for each flow: Germany and Baleares (FFM and LEPA), Italy and Spain (OST and LEPA), Germany and Spain excluding Baleares (FFM and TBO). Flows of traffic between Paris TMA and airports in Marseilles and Bordeaux, in spite of their importance were not isolated, given the difficulty in defining a unique reference point for the airports in Marseilles and Bordeaux. All flights not in any of the above flows were put in three artificial flows, one for each sector: Others UM, Others H1H2 and Others N1N2. In Table D-1 the admissible routes for each flow are described in terms of the sectors they cross and their additional fuel cost:

Table D-1: Description of Routes

Flow	Sectors	Additional Cost (c_j)
Germany...-Baleares		
Route 1	UM	0
Route 2	H1H2	11
Baleares- Germany...		
Route 3	UM	0
Route 4	N1N2	18
Italy...- Spain...		
Route 5	UM	0
Route 6	H1H2	37
Spain...-Italy...		
Route 7	UM	0
Germany...-Spain...		
Route 8	H1H2+N1N2	0
Route 9	N1N2	1
Spain...-Germany...		
Route 10	N1N2+H1H2	0
Route 11	N1N2	2

The calculation of flying time is based on the cruising speed of an aircraft of type Boeing 737: 430 nm/hour. The estimate for fuel cost resulting from extra-flying time is also based on the performance of an aircraft type Boeing 737. The traffic data, 736 flight plans, refers to the flights that entered these sectors on 07/04/95 between 8.00 and 20.00. This period of time was divided into 12 time intervals of one hour for BALDIST and DELINT1 and 48 time intervals of 15 min each for DELINT2. Table D-2 and Table D-3 show the flights of each flow scheduled to depart during each 15 min interval.

Table D-2: Flights Scheduled

Time (min)	Germany...-Baleares	Baleares-Germany..	Italy...-Spain...	Spain...-Italy	Spain...-Germany
0800-0815	1	1	0	0	1
0816-0830	2	5	0	0	0
0831-0845	1	1	1	2	3
0846-0900	1	5	0	1	0
0901-0915	1	4	1	0	0
0916-0930	1	1	0	0	1
0931-0945	5	0	0	0	1
0946-1000	1	3	1	0	1
1001-1015	0	0	0	0	0
1016-1030	2	2	0	1	0
1031-1045	3	0	0	2	2
1046-1100	4	2	2	0	0
1101-1115	5	1	0	0	3
1116-1130	2	1	1	0	2
1131-1145	1	0	1	0	3
1146-1200	3	1	0	1	2
1201-1215	5	0	0	1	0
1216-1230	1	1	1	2	1
1231-1245	1	3	0	1	3
1246-1300	7	1	2	0	1
1301-1315	4	3	0	1	0
1316-1330	2	3	1	0	1
1331-1345	1	6	1	0	2
1346-1400	2	1	2	0	1
1401-1415	2	4	1	0	1
1416-1430	1	2	1	0	2
1431-1445	0	2	1	0	2
1446-1500	0	1	2	1	0
1501-1515	1	5	0	1	0
1516-1530	0	0	0	0	1
1531-1545	2	3	1	0	1
1546-1600	2	2	1	0	0
1601-1615	4	0	0	2	0
1616-1630	0	2	0	0	2
1631-1645	2	2	0	2	0
1646-1700	3	0	0	1	0
1701-1715	3	0	0	2	0
1716-1730	3	1	2	0	0
1731-1745	2	1	0	1	0
1746-1800	2	0	1	0	0
1801-1815	1	1	1	0	0
1816-1830	2	2	0	0	1
1831-1845	4	1	0	0	2
1846-1900	0	0	0	0	1
1901-1915	1	4	0	0	0
1916-1930	1	2	0	0	1
1931-1945	0	1	0	2	1
1946-2000	0	1	0	0	2
TOTAL	92	82	25	24	45

Table D-3: Flights Scheduled (cont)

Time	Germany...-Spain	Others UM	Others H1H2	Others N1N2
0800-0815	1	3	6	4
0816-0830	2	3	4	1
0831-0845	0	2	4	5
0846-0900	3	4	3	2
0901-0915	1	3	1	1
0916-0930	0	4	1	5
0931-0945	0	8	2	3
0946-1000	1	0	0	2
1001-1015	1	4	2	4
1016-1030	1	3	4	3
1031-1045	1	1	2	1
1046-1100	2	3	1	3
1101-1115	1	4	1	4
1116-1130	2	5	5	5
1131-1145	0	4	4	3
1146-1200	2	1	4	5
1201-1215	1	9	1	3
1216-1230	1	3	2	3
1231-1245	3	1	5	2
1246-1300	2	4	4	2
1301-1315	1	3	1	3
1316-1330	2	4	2	5
1331-1345	0	0	1	0
1346-1400	0	5	3	2
1401-1415	1	0	3	2
1416-1430	1	1	3	7
1431-1445	2	4	3	3
1446-1500	0	9	4	6
1501-1515	1	1	3	4
1516-1530	0	3	0	2
1531-1545	2	0	6	5
1546-1600	0	1	1	1
1601-1615	0	3	3	4
1616-1630	0	4	4	3
1631-1645	0	2	5	2
1646-1700	0	0	2	2
1701-1715	1	4	4	3
1716-1730	1	1	6	2
1731-1745	0	2	4	4
1746-1800	0	3	1	4
1801-1815	1	4	2	1
1816-1830	0	4	2	2
1831-1845	2	3	4	4
1846-1900	0	2	4	3
1901-1915	2	1	4	1
1916-1930	0	3	4	2
1931-1945	0	3	3	5
1946-2000	1	3	2	0

Time	**Germany...-Spain**	**Others UM**	**Others H1H2**	**Others N1N2**
TOTAL	43	142	140	143

The capacity of each sector per hour is the same over the whole period, and is set below the actual value on that day, in order to increase congestion (see Table D-4)

Table D-4: Capacities of the Sectors

Sectors	Capacity per hour
UM	26
H1H2	23
N1N2	26

The example was solved using a standard integer programming package GAMS/LAMPS 1.66 on a SUN/SPARC workstation. Table D-4 shows the problem size for BALDIST and Table D-6 the results obtained.

Table D-5: BALDIST - Problem Size

Capacity constraints	36
Assignment constraints	5
Total number of constraints	41
Assignment variables (x_{ij})	10
Congestion variables (o_{ztk})	612
Total number of variables	622

Note: $\bar{Z} = 17$

Table D-6: BALDIST - Results

	Function 1	Function 2	Function 3
Value with No re-routings	32640.0	1397640.0	1910400876544.0
Optimal value (w^*)	2935.0	2235.0	42885.0

	Function 1	Function 2	Function 3
Linear Relaxation-Optimal value	2885.9	2235.0	41779.3

Note: the additional cost of a route is here measured in terms of fuel cost and for the cost of congestion three functions are considered:

Function 1: cost of congestion is measured using $g_{zk} = 10 \cdot z^2 \qquad (\forall k)$

Function 2: cost of congestion is measured using $g_{zk} = 5 \cdot 2^z \qquad (\forall k)$

Function 3: cost of congestion is measured using $g_{zk} = 2 \cdot 5^z \qquad (\forall k)$

For DELINT1, the cost incurred in the re-routings (c_j) is again measured in terms of fuel cost. The cost of ground-delays (g) is assumed to bear a linear relationship with the number of flights ground-delayed. The size of the problem for model DELINT1 is shown in Table D-7 and the results obtained are in Table D-8, Table D-9 and Table D-10.

Table D-7: DELINT1 - Problem Size

Capacity constraints	36
Assignment constraints	5
Flights have to be routed onto flow route	14
Relation flights delayed/departing	117
Total constraints	172
Assignment variables (x_{ij})	10
Ground-delay variables (y_{it})	108
Departure variables (d_{ijt})	182
Total variables	300

Note: DELINT1 in this initial test had the following constraints instead of (7.3.9)

$$\sum_{t=1}^{p+1} d_{ijt} \le |N_i| x_{ij} \qquad (i = 1, \dots m; j \in R_i)$$

Table D-8: DELINT1 - Results

Cost with no re-routings	60920.0
Optimum value (w^*)	6305.0
Linear Relaxation-optimum value	1914.0
Ground-delay before re-routings (min)	30360.0
Ground-delay in best solution (min)	2580.0
% improvement	91.5

Table D-9: DELINT1 Routes Selected

Flow	Sectors
Germany...-Baleares*	
Route 2	H1H2
Baleares- Germany...	
Route 3	UM
Italy...- Spain...	
Route 5	UM
Spain...-Italy...	
Route 7	UM
Germany...-Spain...*	
Route 9	N1N2
Spain...-Germany...*	
Route 11	N1N2

* flows re-routed.

Table D-10: Impact of Re-routings on Traffic Distribution

Sectors	UM		H1H2		N1N2	
	Flights	%	Flights	%	Flights	%
No re-routings	365	50	228	31	231	31

Table D-10: Impact of Re-routings on Traffic Distribution

(*)						
With re-routings	273	37	232	32	231	31

(*) total flights in the situation with 'no re-routings' exceeds 100% because some flights cross more than one sector.

For DELINT2, the additional cost of re-routings is the same as in BALDIST and DELINT1, the cost of ground-delays is given by a cost function, defined in terms of number of delay time periods: $g(t) = 15 \cdot t^2$. The capacity of each sector is redefined in terms of 15min intervals. The traffic in a sector at a certain time interval is the number of flights *present* in that sector during that time interval, for instance if a flights takes 40 min to cross a sector it is counted 3 times. As, in practice, capacity/demand comparisons are done hourly, the capacity per 15 min is above the capacity we would obtain just by dividing the hourly capacity by 4. Table D-11 shows the capacity of each sector.

As for BALDIST and DELINT1 the example was solved using GAMS/LAMPS 1.66 but due to its substantially larger size, it was solved in several steps: first, a route was assigned to each flow in order to find a feasible solution, then the value of that solution was used as an upper bound to find the optimum solution. The problem size and results for model DELINT2 are shown respectively in Table D-12, Table D-13 and Table D-14.

Table D-11: DELINT2 - Capacity of the ATC Sectors

Sectors	**Capacity per 15 min**
UM	9
H1H2	8
N1N2	9

Table D-12: DELINT2 - Problem Size

Capacity constraints	144
Assignment constraints	9
Flights have to be routed onto flow route	14
Relation flights departing/scheduled	432
Total Constraints	599
Assignment variables (x_{ij})	14
Departure variables ($d_{ijtt'}$)	17136
Total Variables	17150

Note: DELINT2 in this initial test had the following constraints instead of (7.3.18)

$$\sum_{t=1}^{t'}\sum_{t'=t}^{p+1} d_{ijtt'} \le |N_i| x_{ij} \qquad (i = 1,\ldots,m; j \in R_i)$$

Table D-13: DELINT2 - Results

Cost with no re-routings	833805.0
Optimum value (w^*)	190070.0
Linear Relaxation-optimum value	141031.5
Ground-delay with no re-routings (min)	70065.0

Table D-13: DELINT2 - Results

Ground-delay in optimum solution (min)	40485.0
% improvement	42.2

Table D-14: DELINT2 - Impact of Re-routings on Ground-delay

	No Re-routings		With Re-routings	
Flows	Total G.Delay	Avg G.Delay	Total G.Delay	Avg G.Delay
Germ-Bale	16845	183	4785	52
Bale-Germ	15015	183	6300	77
Spain-Italy	4110	171	1935	81
Italy-Spain	5655	226	2310	92
Germ-Spain	2040	47	2910	68
Spain-Germ	2160	48	1920	43
Others	24240	57	20325	48
Total	**70065**	**95**	**40485**	55

Appendix E - Input to the Models

This appendix complements Chapter 8, describing input to the models which was not included in Chapter 8 because it is too detailed.

Table E-1: Capacity of French Upper Airspace Sectors on 25.04.96

Sectors	**CAPACITY PER HOUR on 25.04.96**				
BREST					
OS	30 (3-22h)				
QUQS	30 (3-9h)	45 (9-11h)	30 (11-12h)	45 (12-14h)	30 (14-22h)
AS	21 (3-8h)	26 (8-22h)			
GUGS	24 (3-8h)	30 (8-22h)			
NUNS	28 (3-6h)	35 (6-9h)	46 (9-15h)	35 (15-22h)	
JSMS	32 (3-9h)	42 (9-15h)	32 (15-22h)		
KUXU	20 (3-6h)	25 (6-22h)			
PARIS					
UK	28 (3-22h)				
TH	24 (3-22h)				
TW	23 (3-22h)				
UP	28 (3-22h)				
UZ	45 (3-22h)				
TP	26 (3-18h)	25 (18-22h)			
TUUT	40 (3-22h)				
TB	25 (3-22h)				
TC	24 (3-22h)				
TE	25 (3-22h)				
TN	28 (3-22h)				
TS	40 (3-22h)				
AO	30 (3-22h)				
AR	28 (3-22h)				
UX	27 (3-22h)				
REIMS					
XNUN	35 (3-8h)	42 (8-16h)	35 (17-22h)		
UYUR	37 (3-5h)	45 (5-22h)			
UFXF	28 (3-22h)				
UE	30 (3-22h)				
UH	33 (3-22h)				
ZU	30 (3-22h)				
BORDEAUX					
PV1	15 (3-22h)				
PV2	25 (3-22h)				
N2H2	31 (3-22h)				
Z2	31 (3-22h)				
Z1N1H1	32 (3-22h)				
C1L1F1	33 (3-22h)				
C2L2F2	31 (3-22h)				
AIX					
UGUW	49 (3-8h)	60 (8-17h)	49 (17-21h)	30 (21-22h)	
UA	31 (3-7h)	52 (7-8h)	31 (8-11h)	52 (11-13h)	31 (13-22h)
UM	31 (3-11h)	51 (11-17h)	31 (17-22h)		

US	31 (3-22h)				
UD	23 (3-22h)				
K	31 (3-22h)				

Table E-2: List of Flows Considered for Re-routing Control Measures

UK to Balearics, Barcelona and Alicante NthUK-BALE, NthUK-BARC, NthUK-ALIC, SthUK-BALE, SthUK-BARC, SthUK-ALIC
Germany(exc.west) and Switzerland to Balearics and Barcelona STUTT-BALE, FRANK-BALE, ZUR-BALE, SthGE-BARC, NthGE-BARC, STUTT-BARC, ZUR-BARC, GENE-BARC
West Germany to Balearics and Barcelona WstGE-BALE, WstGE-BARC
Barcelona and Balearics to West Germany BARC-WstGE, BALE-WstGE
Barcelona and Alicante to Brussels and Amsterdam BARC-BRUX, BARC-AMS, ALIC-BRUX, ALIC-AMS
Barcelona, Balearics and Alicante to Germany and Switzerland BARC-SthGE, BARC-STUTT, BARC-NthGE, BARC-ZUR, BARC-GENE, BALE-SthGE, BALE-STUTT, BALE-ZUR, ALIC-SthGE, ALIC-GENE
Barcelona, Balearics and Alicante to UK BARC-LOND, BARC-NthUK, BALE-LOND, BALE-NthUK, BALE-MidUK, ALIC-LOND, ALIC-NthUK, ALIC-MidUK, ALIC-HumUK, ALIC-GLAS, ALIC-arLON
Madrid to Frankfurt and Stuttgart MADR-FRANK, MADR-STUTT
Madrid to Southeast Germany and Switzerland MADR-MUNI, MADR-GENE, MADR-ZUR
Madrid to West Germany MADR-WstGE
Athens and Rome to Lisbon and Madrid ATH-MADR, ATH-LISB, ROME-MADR, ROME-LISB
North Italy to Lisbon and Madrid MILAN-MADR, MILAN-LISB, GENO-MADR, VENI-MADR
Lisbon and Madrid to Athens and Rome LISB-ATH, MADR-ROME, LISB-ROME
Lisbon and Madrid to North Italy MADR-MILAN, MADR-BOLO, MADR-VENI, LISB-MILAN

Table E-2: List of Flows Considered for Re-routing Control Measures

UK(exc London), Brussels and Amsterdam to Switzerland NthUK-SWT, LUTON-ZUR, BRUX-SWT, AMS-SWT
London to Switzerland gLOND-GENE, gLOND-ZUR
Switzerland to Brussels and Amsterdam SWT-BRUX, SWT-AMS
Geneva to UK GENE-NthUK, GENE-gLOND
Zurich to UK ZUR-NthUK, ZUR-gLOND
UK to Italy NthUK-MILAN, NthUK-PISA, BOURN-TORI, BOURN-BOLO, LOND-MILAN, LOND-gPISA, LOND-ROME, LOND-NAPO, LOND-VERO
Italy to UK MILAN-LOND, MILA-NthUK, MILAN-STAN, VERO-GATW, ROME-LOND, NAPO-GATW, gPIS-SthUK, gPISA-STAN
Paris to Italy PARI-MILAN, PARI-ROME, PARI-BOLO, PARI-VERO, PARI-VENI, PARI-NAPO, PARI-gPISA
Italy to Paris MILAN-PARIS, ROME-PARIS, BOLO-PARIS, VERO-PARIS, VENI-PARIS, NAPO-PARIS, gPISA-PARIS
Paris to Toulouse PARI-BORDX
Paris to Marseilles and Nice PARI-MARS, PARI-NICE
Toulouse to Paris (Charles de Gaulle and Orly) TOU-PARIg, TOU-PARIo
Brussels, Amsterdam and West Germany to Madrid and Malaga BRUX-MADR, BRUX-MALAG, AMSwG-MADR, AMSwG-MALA
Germany (exc. West) to Madrid and Malaga FRANK-MADR, FRANK-MALA, MUNI-MADR, STTUT-MADR
UK to Madrid and Malaga

Table E-2: List of Flows Considered for Re-routing Control Measures

MiUK-MALA, gLOND-MADR, gLOND-MALA, NthUK-MADR, NthUK-MALA, SCOT-MALA
South Germany to Canary Islands MUNI-CANA, STTUT-CANA, SthGE-CANA
Germany (exc. South) to Canary Islands W1GER-CANA, FRANK-CANA, HAMB-CANA, W2GER-CANA
UK to Canary Islands MidUK-CANA, LOND-CANA, NthUK-CANA, WstUK-CANA, SCOT-CANA

Table E-3: Description of Routes

Route\Flow	Sectors Crossed	Additional Cost
NthUK1BALE	(KUXU,C2L2F2,N2H2)	0
NthUK2BALE	(JSMS,NUNS,C2L2F2,N2H2)	80
SthUK1BALE	(UK,KUXU,C2L2F2,N2H2)	0
SthUK2BALE	(UK,UX,KUXU,C2L2F2,N2H2)	110
SthUK3BALE	(UZ,ZU,UP,UGUW,UM)	70
SthUK4BALE	(UK,TP,TH,TW,C1L1F1,Z1N1H1)	750
NthUK1BARC	(KUXU,C2L2F2,N2H2,Z1N1H1)	0
NthUK2BARC	(UK,KUXU,C2L2F2,N2H2,Z1N1H1)	90
SthUK1BARC	(UK,KUXU,C2L2F2,N2H2,Z1N1H1)	0
SthUK2BARC	(UK,UX,C2L2F2,N2H2,Z1N1H1)	170
SthUK3BARC	(UK,UX,C1L1F1,Z1N1H1)	410
NthUK1ALIC	(KUXU,C2L2F2,N2H2)	0
NthUK2ALIC	(UK,KUXU,C2L2F2,N2H2)	80
SthUK1ALIC	(UK,KUXU,C2L2F2,N2H2)	0
SthUK2ALIC	(UK,UX,C2L2F2,N2H2)	160
SthUK3ALIC	(UK,UX,C1L1F1,Z1N1H1)	590
STUTT1BALE	(UA,UM)	0
STUTT2BALE	(UGUW,UM)	30
STUTT3BALE	(US,UM)	70
STUTT4BALE	(US,UD)	150
STUTT5BALE	(UGUW,N2H2)	150
FRANK1BALE	(UA,UM)	0
FRANK2BALE	(UGUW,UM)	30
FRANK3BALE	(US,UM)	70
FRANK4BALE	(US,UD)	150
FRANK5BALE	(UGUW,N2H2)	150
ZUR1BALE	(UA,UM)	0
ZUR2BALE	(UGUW,UM)	30
ZUR3BALE	(US,UM)	70
ZUR4BALE	(US,UD)	150
ZUR5BALE	(UGUW,N2H2)	150
WstGE1BALE	(UE,UH,UA,UM)	0
WstGE2BALE	(UE,UH,UGUW,UM)	40
WstGE3BALE	(UYUR,ZU,PV2,C2L2F2,N2H2)	40
SthGE1BARC	(UA,UM)	0
SthGE2BARC	(UGUW,UM)	60
NthGE1BARC	(UA,UM)	0
NthGE2BARC	(UGUW,UM)	60
STUTT1BARC	(UA,UM)	0
STUTT2BARC	(UGUW,UM)	60

ZUR1BARC	(UA,UM)	0
ZUR2BARC	(UGUW,UM)	80
GENE1BARC	(UA,UM)	0
GENE2BARC	(UGUW,UM)	80
WstGE1BARC	(UYUR,UZ,ZU,PV2,C2L2F2,N2H2,Z1N1H1)	0
WstGE2BARC	(UA,UM)	100
BARC1WstGE	(UM,UA,UH,UE)	0
BARC2WstGE	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	80
BALE1WstGE	(UM,UA,UH,UE)	0
BALE2WstGE	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	60
BARC1BRUX	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN,TB)	0
BARC2BRUX	(Z1N1H1,C1L1F1,UX,UZ,ZU,XNUN,TB)	510
BARC3BRUX	(UM,UA,UH,UE)	20
BARC1AMS	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN,TB)	0
BARC2AMS	(Z1N1H1,C1L1F1,UX,UZ,ZU,XNUN,TB)	510
BARC3AMS	(UM,UA,UH,UE)	20
ALIC1BRUX	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN,TB)	0
ALIC2BRUX	(Z1N1H1,C1L1F1,UX,UZ,ZU,XNUN,TB)	510
ALIC3BRUX	(UM,UA,UH,UE)	20
ALIC1AMS	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN,TB)	0
ALIC2AMS	(Z1N1H1,C1L1F1,UX,UZ,ZU,XNUN,TB)	510
ALIC3AMS	(UM,UA,UH,UE)	20
BARC1SthGE	(UM,UA)	0
BARC2SthGE	(N2H2,UGUW)	140
BARC1STUTT	(UM,UA)	0
BARC2STUTT	(N2H2,UGUW)	140
BARC1NthGE	(UM,UA)	0
BARC2NthGE	(N2H2,UGUW)	140
BARC1ZUR	(UM,UA)	0
BARC2ZUR	(N2H2,UGUW)	140
BARC1GENE	(UM,UA)	0
BARC2GENE	(N2H2,UGUW)	140

BALE1SthGE	(UM,UA)	0
BALE2SthGE	(N2H2,UGUW)	120
BALE1STUTT	(UM,UA)	0
BALE2STUTT	(N2H2,UGUW)	120
BALE1ZUR	(UM,UA)	0
BALE2ZUR	(N2H2,UGUW)	120
ALIC1SthGE	(UM,UA)	0
ALIC2SthGE	(N2H2,UGUW)	0
ALIC1GENE	(UM,UA)	0
ALIC2GENE	(N2H2,UGUW)	0
BARC1LOND	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
BARC2LOND	(N2H2,C2L2F2,NUNS,JSMS)	60
BARC1NthUK	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
BARC2NthUK	(N2H2,C2L2F2,NUNS,JSMS)	60
BALE1LOND	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
BALE2LOND	(N2H2,C2L2F2,NUNS,JSMS)	60
BALE1NthUK	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
BALE2NthUK	(N2H2,C2L2F2,NUNS,JSMS)	60
BALE1MidUK	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
BALE2MidUK	(N2H2,C2L2F2,NUNS,JSMS)	60
ALIC1LOND	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
ALIC2LOND	(N2H2,C2L2F2,NUNS,JSMS)	50
ALIC1NthUK	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
ALIC2NthUK	(N2H2,C2L2F2,NUNS,JSMS)	50
ALIC1MidUK	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
ALIC2MidUK	(N2H2,C2L2F2,NUNS,JSMS)	50
ALIC1HumUK	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
ALIC2HumUK	(N2H2,C2L2F2,NUNS,JSMS)	50
ALIC1GLAS	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
ALIC2GLAS	(N2H2,C2L2F2,NUNS,JSMS)	50
ALIC1arLON	(N2H2,C2L2F2,KUXU,UZ,ZU,XNUN)	0
ALIC2arLON	(N2H2,C2L2F2,NUNS,JSMS)	50
MADR1FRANK	(Z2,N2H2,UGUW)	0
MADR2FRANK	(Z2,C2L2F2,KUXU,UZ,ZU,UYUR)	60
MADR1STUTT	(Z2,N2H2,UGUW)	0
MADR2STUTT	(Z2,C2L2F2,KUXU,UZ,ZU,UYUR)	60

MADR1MUNI	(Z2,N2H2,UGUW)	0
MADR2MUNI	(Z1N1H1,UGUW)	340
MADR1GENE	(Z2,N2H2,UGUW)	0
MADR2GENE	(Z1N1H1,UGUW)	340
MADR1ZUR	(Z2,N2H2,UGUW)	0
MADR2ZUR	(Z1N1H1,UGUW)	340
MADR1WstGE	(Z2,C2L2F2,KUXU,UZ,ZU,UYUR)	0
MADR2WstGE	(Z1N1H1,C1L1F1,UX,UZ,UYUR)	500
ATH1MADR	(UD)	0
ATH2MADR	(K,US,UM)	2300
ATH1LISB	(UD)	0
ATH2LISB	(K,US,UM)	2000
ROME1MADR	(UD)	0
ROME2MADR	(K,US,UM)	120
ROME1LISB	(UD)	0
ROME2LISB	(K,US,UM)	90
MILAN1MADR	(US,UM)	0
MILAN2MADR	(US,UA,UGUW,N2H2,Z2)	1600
MILAN1LISB	(US,UM)	0
MILAN2LISB	(US,UA,UGUW,N2H2,Z2)	1600
GENO1MADR	(US,UM)	0
GENO2MADR	(US,UA,UGUW,N2H2,Z2)	1600
VENI1MADR	(US,UM)	0
VENI2MADR	(US,UA,UGUW,N2H2,Z2)	1600
LISB1ATH	(UD)	0
LISB2ATH	(UM,US,K)	2400
MADR1ROME	(UD)	0
MADR2ROME	(UM,US,K)	130
LISB1ROME	(UD)	0
LISB2ROME	(UM,US,K)	130
MADR1MILAN	(UM,US)	0
MADR2MILAN	(Z2,N2H2,UGUW,UA)	10
MADR1BOLO	(UM,US)	0
MADR2BOLO	(Z2,N2H2,UGUW,UA)	10
MADR1VENI	(UM,US)	0
MADR2VENI	(Z2,N2H2,UGUW,UA)	10

LISB1MILAN	(UM,US)	0
LISB2MILAN	(Z2,N2H2,UGUW,UA)	10
NthUK1SWT	(UE,UH)	0
NthUK2SWT	(UYUR,UZ,PV2,UP,TUUT)	150
LUTON1ZUR	(UE,UH)	0
LUTON2ZUR	(UYUR,UZ,PV2,UP,TUUT)	150
BRUX1SWT	(UE,UH)	0
BRUX2SWT	(UYUR,UZ,PV2,UP,TUUT)	1700
AMS1SWT	(UE,UH)	0
AMS2SWT	(UYUR,UZ,PV2,UP,TUUT)	1600
gLOND1GENE	(UZ,UP,TUUT)	0
gLOND2GENE	(UE,UH)	50
gLOND1ZUR	(UZ,AO,AR,UFXF,UH)	0
gLOND2ZUR	(UE,UH)	30
SWT1BRUX	(UH,UE)	0
SWT2BRUX	(UH,UFXF,UYUR,XNUN)	90
SWT1AMS	(UH,UE)	0
SWT2AMS	(UH,UFXF,UYUR,XNUN)	70
GENE1NthUK	(TUUT,AO,UYUR,XNUN)	0
GENE2NthUK	(UH,UE)	50
GENE1gLOND	(TUUT,AO,UYUR,XNUN)	0
GENE2gLOND	(UH,UE)	140
ZUR1NthUK	(UH,UFXF,UYUR,XNUN)	0
ZUR2NthUK	(UH,UE)	50
ZUR1gLOND	(UH,UFXF,UYUR,XNUN)	0
ZUR2gLOND	(UH,UE)	140
NthUK1MILA	(UZ,ZU,UP,TUUT)	0
NthUK2MILA	(UE,UH)	0
NthUK1PISA	(UZ,ZU,UP,TUUT)	0
NthUK2PISA	(UE,UH)	0
BOURN1TORI	(UZ,ZU,UP,TUUT)	0
BOURN2TORI	(UE,UH)	0
BOURN1BOLO	(UZ,ZU,UP,TUUT)	0
BOURN2BOLO	(UE.UH)	0
LOND1MILAN	(UZ.ZU,UP,TUUT)	0
LOND2MILAN	(UE,UH)	0

LOND1gPISA	(UZ,ZU,UP,TUUT)	0
LOND2gPISA	(UE,UH)	0
LOND1ROME	(UZ,ZU,UP,TUUT)	0
LOND2ROME	(UE,UH)	0
LOND1NAPO	(UZ,ZU,UP,TUUT)	0
LOND2NAPO	(UE,UH)	0
LOND1VERO	(UZ,ZU,UP,TUUT)	0
LOND2VERO	(UE,UH)	0
MILAN1LOND	(UFXF,UYUR,XNUN)	0
MILAN2LOND	(UH,UE)	60
MILA1NthUK	(UFXF,UYUR,XNUN)	0
MILA2NthUK	(UH,UE)	60
MILAN1STAN	(UFXF,UYUR,XNUN)	0
MILAN2STAN	(UH,UE)	60
VERO1GATW	(UFXF,UYUR,XNUN)	0
VERO2GATW	(UH,UE)	60
ROME1LOND	(UFXF,UYUR,XNUN)	0
ROME2LOND	(UH,UE)	60
NAPO1GATW	(UFXF,UYUR,XNUN)	0
NAPO2GATW	(UH,UE)	60
gPIS1SthUK	(UFXF,UYUR,XNUN)	0
gPIS2SthUK	(UH,UE)	60
gPISA1STAN	(UFXF,UYUR,XNUN)	0
gPISA2STAN	(UH,UE)	60
PARI1MILAN	(TC,UFXF,UH)	0
PARI2MILAN	(TS,UP,TUUT)	0
PARI3MILAN	(TC,UFXF,UE)	30
PARI1ROME	(TC,UFXF,UH)	0
PARI2ROME	(TS,UP,TUUT)	30
PARI3ROME	(TC,UFXF,UE)	30
PARI1BOLO	(TC,UFXF,UH)	0
PARI2BOLO	(TS,UP,TUUT)	60
PARI3BOLO	(TC,UFXF,UE)	50
PARI1VERO	(TC,UFXF,UH)	0
PARI2VERO	(TS,UP,TUUT)	20
PARI3VERO	(TC,UFXF,UE)	30
PARI1VENI	(TC,UFXF,UH)	0

PARI2VENI	(TS,UP,TUUT)	20
PARI3VENI	(TC,UFXF,UE)	30
PARI1NAPO	(TC,UFXF,UH)	0
PARI2NAPO	(TS,UP,TUUT)	30
PARI3NAPO	(TC,UFXF,UE)	30
PARI1gPISA	(TC,UFXF,UH)	0
PARI2gPISA	(TS,UP,TUUT)	20
PARI3gPISA	(TC,UFXF,UE)	30
MILAN1PARI	(TUUT,AR,AO)	0
MILAN2PARI	(UH,UFXF,AR,AO)	140
ROME1PARI	(TUUT,AR,AO)	0
ROME2PARI	(UH,UFXF,AR,AO)	110
BOLO1PARI	(TUUT,AR,AO)	0
BOLO2PARI	(UH,UFXF,AR,AO)	90
VERO1PARI	(TUUT,AR,AO)	0
VERO2PARI	(UH,UFXF,AR,AO)	60
VENI1PARI	(TUUT,AR,AO)	0
VENI2PARI	(UH,UFXF,AR,AO)	0
NAPO1PARI	(TUUT,AR,AO)	0
NAPO2PARI	(UH,UFXF,AR,AO)	60
gPISA1PARI	(TUUT,AR,AO)	0
gPISA2PARI	(UH,UFXF,AR,AO)	110
PARI1BORDX	(TS,UP,C2L2F2,Z1N1H1)	0
PARI2BORDX	(TS,UP,C1L1F1,Z1N1H1)	160
PARI1MARS	(TS,PV1,PV2,UGUW)	0
PARI2MARS	(TS,PV1,UGUW)	70
PARI1NICE	(TS,PV1,PV2,UGUW,UA)	0
PARI2NICE	(TS,PV1,UGUW,UA)	120
TOU1PARIg	(Z1N1H1,C1L1F1,C2L2F2,UX,UK,TH, TP)	0
TOU2PARIg	(Z1N1H1,C1L1F1,UX,UK,TH,TP)	210
TOU1PARIo	(Z1N1H1,C1L1F1,C2L2F2,UX,TW)	0
TOU2PARIo	(Z1N1H1,C1L1F1,UX,TW)	170
BRUX1MADR	(TE,UYUR,UZ,ZU,UP,C2L2F2,Z2)	0
BRUX2MADR	(TE,UYUR,UZ,UP,C1L1F1,Z1N1H1)	370
BRUX1MALAG	(TE.UYUR,UZ,ZU,UP.C2L2F2,Z2)	0
BRUX2MALAG	(TE.UYUR,UZ,UP,C1L1F1,Z1N1H1)	370

AMSwG1MADR	(UYUR,UZ,ZU,UP,C2L2F2,Z2)	0
AMSwG2MADR	(UYUR,UZ,UP,C1L1F1,Z1N1H1)	370
AMSwG1MALA	(UYUR,UZ,ZU,UP,C2L2F2,Z2)	0
AMSwG2MALA	(UYUR,UZ,UP,C1L1F1,Z1N1H1)	370
FRANK1MADR	(UGUW,N2H2,Z2)	0
FRANK2MADR	(UYUR,UZ,ZU,UP,C2L2F2,Z2)	0
FRANK3MADR	(UA,UM)	20
FRANK1MALA	(UGUW,N2H2,Z2)	0
FRANK2MALA	(UYUR,UZ,ZU,UP,C2L2F2,Z2)	0
FRANK3MALA	(UA,UM)	10
MUNI1MADR	(UGUW,N2H2,Z2)	0
MUNI2MADR	(UA,UM)	20
STTUT1MADR	(UGUW,N2H2,Z2)	0
STTUT2MADR	(UA,UM)	20
MiUK1MALAG	(JSMS,QUQS,AS,GUGS)	0
MiUK2MALAG	(JSMS,NUNS,GUGS)	20
gLOND1MADR	(JSMS,QUQS,AS,GUGS)	0
gLOND2MADR	(JSMS,NUNS,GUGS)	50
gLOND1MALA	(JSMS,QUQS,AS,GUGS)	0
gLOND2MALA	(JSMS,NUNS,GUGS)	20
NthUK1MADR	(QUQS,AS,GUGS)	0
NthUK2MADR	(KUXU,C2L2F2,N2H2)	10
NthUK1MALA	(QUQS,AS,GUGS)	0
NthUK2MALA	(KUXU,C2L2F2,N2H2)	10
SCOT1MALA	(QUQS,AS,GUGS)	0
SCOT2MALA	(KUXU,C2L2F2,N2H2)	10
MUNI1CANA	(UGUW,N2H2,Z2)	0
MUNI2CANA	(UGUW,Z1N1H1)	230
STTUT1CANA	(UGUW,N2H2,Z2)	0
STTUT2CANA	(UGUW,Z1N1H1)	230
SthGE1CANA	(UGUW,N2H2,Z2)	0
SthGE2CANA	(UGUW,Z1N1H1)	230
W1GER1CANA	(UYUR,UZ,ZU,KUXU,NUNS,GUGS)	0
W1GER2CANA	(UYUR,UZ,ZU,KUXU,NUNS,AS)	110
FRANK1CANA	(UYUR,UZ,ZU,KUXU,NUNS,GUGS)	0
FRANK2CANA	(UYUR,UZ,ZU,KUXU,NUNS,AS)	110
HAMB1CANA	(UYUR,UZ,ZU,KUXU,NUNS,GUGS)	0

HAMB2CANA	(UYUR,UZ,ZU,KUXU,NUNS,AS)	110
W2GER1CANA	(UYUR,UZ,ZU,KUXU,NUNS,GUGS)	0
W2GER2CANA	(UYUR,UZ,ZU,KUXU,NUNS,AS)	110
MidUK1CANA	(JSMS,QUQS,AS)	0
MidUK2CANA	(JSMS,QUQS,AS,GUGS)	2300
LOND1CANA	(JSMS,QUQS,AS)	0
LOND2CANA	(JSMS,QUQS,AS,GUGS)	2300
NthUK1CANA	(QUQS,AS)	0
NthUK2CANA	(QUQS,AS,GUGS)	2300
WstUK1CANA	(QUQS,AS)	0
WstUK2CANA	(QUQS,AS,GUGS)	2300
SCOT1CANA	(QUQS,AS)	0
SCOT2CANA	(QUQS,AS,GUGS)	2300

Table E-4: Traffic Flows Crossing French Upper Airspace - Departures Scheduled per Hour on 25/04/96 from 03:00 to 22:00

	3h	4h	5h	6h	7h	8h	9h	10h	11h	12h	13h	14h	15h	16h	17h	18h	19h	20h	21h	Total
NthUK-BALE	0	0	1	0	1	0	2	0	0	1	0	0	1	0	0	0	0	0	0	6
SthUK-BALE	0	0	0	2	0	2	0	0	0	0	1	0	0	1	0	0	0	0	0	6
NthUK-BARC	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	2
SthUK-BARC	0	0	0	0	0	1	1	0	1	0	1	1	0	0	0	2	0	0	0	7
NthUK-ALIC	0	0	0	3	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	5
SthUK-ALIC	0	0	0	0	1	0	0	0	1	0	1	0	3	1	0	0	0	0	0	7
STUTT-BALE	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2
FRANK-BALE	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	2
ZUR-BALE	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2
WstGE-BALE	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
SthGE-BARC	0	0	0	0	0	1	1	0	2	0	1	0	1	0	2	1	0	0	0	9
NthGE-BARC	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	2
STUTT-BARC	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3
ZUR-BARC	0	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	4
GENE-BARC	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	2
WstGE-BARC	1	0	0	0	1	1	0	0	1	0	0	0	1	0	0	0	0	0	0	5
BARC-WstGE	0	0	0	0	0	0	1	0	0	1	1	0	0	0	1	0	0	1	0	5
BALE-WstGE	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2
BARC-BRUX	0	0	1	0	2	1	0	0	0	1	0	1	0	1	0	0	0	0	0	7
BARC-AMS	0	0	1	0	0	1	1	0	0	1	0	2	0	0	0	0	0	0	0	6
ALIC-BRUX	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2
ALIC-AMS	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
BARC-SthGE	0	0	1	1	0	2	0	1	1	1	0	1	0	1	0	0	0	0	0	9
BARC-STUTT	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	3
BARC-NthGE	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2
BARC-ZUR	0	0	0	0	1	0	0	0	0	2	0	1	0	0	0	0	1	0	0	5
BARC-GENE	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
BALE-SthGE	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	3
BALE-STUTT	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2

Table E-4: Traffic Flows Crossing French Upper Airspace - Departures Scheduled per Hour on 25/04/96 from 03:00 to 22:00

BALE-ZUR	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	3
ALIC-SthGE	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	2
ALIC-GENE	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
BARC-LOND	0	0	0	0	2	0	0	0	1	2	0	1	0	3	0	0	0	0	0	9
BARC-NthUK	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2
BALE-LOND	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	0	0	0	5
BALE-NthUK	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	3
BALE-MidUK	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
ALIC-LOND	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	1	0	0	0	4
ALIC-NthUK	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	4
ALIC-MidUK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
ALIC-HumUK	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
ALIC-GLAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
ALIC-arLON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2
MADR-FRANK	0	1	0	0	1	1	0	1	0	0	0	1	0	0	1	0	0	0	0	6
MADR-STUTT	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	2
MADR-MUNI	1	0	0	1	1	0	0	0	0	0	3	0	0	0	0	0	0	0	0	6
MADR-GENE	0	0	0	1	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	4
MADR-ZUR	0	0	1	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	5
MADR-WstGE	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	4
ATH-MADR	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
ATH-LISB	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
ROME-MADR	0	0	0	2	1	0	0	0	1	1	0	0	0	1	1	0	0	0	0	7
ROME-LISB	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2
MILAN-MADR	0	0	2	0	0	1	0	0	2	0	2	0	0	1	0	1	0	0	0	9
MILAN-LISB	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	3
GENO-MADR	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
VENI-MADR	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
LISB-ATH	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
MADR-ROME	0	0	1	0	1	0	0	2	0	0	0	1	1	0	0	1	0	0	0	7
LISB-ROME	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	2

Table E-4: Traffic Flows Crossing French Upper Airspace - Departures Scheduled per Hour on 25/04/96 from 03:00 to 22:00

MADR-MILAN	0	1	1	0	1	0	0	0	1	0	0	1	0	1	2	0	0	0	0	8
MADR-BOLO	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
MADR-VENI	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
LISB-MILAN	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	3
NthUK-SWT	0	0	0	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	4
LUTON-ZUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
BRUX-SWT	0	0	2	0	0	2	2	1	0	0	2	0	2	0	2	0	0	2	0	15
AMS-SWT	0	0	0	1	1	0	0	1	0	1	0	0	0	0	2	1	0	0	0	7
gLOND-GENE	0	0	0	0	3	1	1	0	0	1	1	2	0	1	1	2	1	0	0	14
gLOND-ZUR	0	0	0	3	2	1	1	2	2	0	1	1	1	3	1	3	0	0	0	21
SWT-BRUX	0	0	2	0	2	0	0	2	0	1	1	1	1	0	1	0	2	0	0	13
SWT-AMS	0	0	1	0	0	0	1	0	0	0	0	1	0	2	1	0	0	0	0	6
GENE-NthUK	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3
GENE-gLOND	0	0	1	3	0	0	1	1	1	0	1	1	1	2	2	1	0	0	0	15
ZUR-NthUK	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	4
ZUR-gLOND	0	0	1	4	0	2	2	2	0	2	0	2	3	1	0	1	1	0	0	21
NthUK-MILA	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	3
NthUK-PISA	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
BOURN-TORI	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
BOURN-BOLO	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
LOND-MILAN	0	0	0	3	2	4	0	0	2	2	0	1	2	2	1	3	1	0	0	23
LOND-gPISA	0	0	0	0	0	2	2	1	0	0	0	0	0	0	0	1	1	0	0	7
LOND-ROME	0	0	0	2	2	0	0	2	1	0	2	2	0	2	0	1	0	0	0	14
LOND-NAPO	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	2
LOND-VERO	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	2
MILAN-LOND	0	0	1	2	0	1	3	1	2	1	0	2	2	2	0	3	0	0	0	20
MILA-NthUK	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	3
MILAN-STAN	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	3
VERO-GATW	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2
ROME-LOND	0	0	0	2	1	1	2	2	0	1	1	0	1	1	1	0	0	0	0	13
NAPO-GATW	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2

Table E-4: Traffic Flows Crossing French Upper Airspace - Departures Scheduled per Hour on 25/04/96 from 03:00 to 22:00

gPIS-SthUK	0	0	2	1	0	0	1	0	1	1	1	0	1	0	0	2	0	0	0	10
gPISA-STAN	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2
PARI-MILAN	0	0	3	1	2	2	1	1	1	0	0	1	4	2	1	2	1	0	0	22
PARI-ROME	0	0	1	1	0	2	0	2	2	1	0	3	0	2	1	1	1	0	0	17
PARI-BOLO	0	0	0	2	0	0	1	0	1	0	0	1	0	2	0	0	0	0	0	7
PARI-VERO	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	0	0	3
PARI-VENI	0	0	0	1	0	1	1	1	0	1	0	0	1	0	2	0	0	0	0	8
PARI-NAPO	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	3
PARI-gPISA	0	0	0	0	0	2	1	0	0	0	1	0	0	1	1	1	0	0	0	7
MILAN-PARI	0	0	4	2	1	2	1	1	1	2	0	2	2	1	4	1	1	0	0	25
ROME-PARI	1	0	1	1	1	1	1	1	1	0	1	0	4	1	0	1	1	0	0	16
BOLO-PARI	0	0	1	1	0	1	0	0	0	1	1	0	0	0	1	1	0	0	0	7
VERO-PARI	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	3
VENI-PARI	0	0	1	1	0	1	0	1	0	0	0	1	0	1	1	0	0	0	0	7
NAPO-PARI	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	3
gPISA-PARI	0	0	0	2	0	0	0	0	1	1	0	0	1	1	0	0	1	0	0	7
PARI-BORDX	1	0	3	4	2	2	1	3	3	2	4	3	1	4	5	2	1	1	2	44
PARI-MARS	0	3	3	2	2	0	2	3	2	2	2	3	4	1	4	2	7	0	2	44
PARI-NICE	0	0	4	2	2	4	1	3	1	2	2	5	1	3	4	3	1	0	0	38
TOU-PARIg	1	1	0	0	0	1	0	1	0	0	1	0	0	0	1	2	1	1	1	11
TOU-PARIo	0	2	3	0	4	1	1	2	2	0	2	2	4	2	1	4	0	0	0	30
BRUX-MADR	0	0	0	1	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	4
BRUX-MALAG	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2
AMSwG-MADR	1	0	0	2	0	1	0	0	1	0	0	3	0	0	2	0	0	0	0	10
AMSwG-MALA	1	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	4
FRANK-MADR	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	1	0	0	0	5
FRANK-MALA	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	3
MUNI-MADR	0	0	0	0	2	0	2	0	0	0	0	0	0	1	1	0	0	0	0	6
STTUT-MADR	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2
MiUK-MALAG	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
gLOND-MADR	0	0	0	1	1	1	2	1	1	1	1	1	1	1	0	3	2	0	0	17

Table E-4: Traffic Flows Crossing French Upper Airspace - Departures Scheduled per Hour on 25/04/96 from 03:00 to 22:00

gLOND-MALA	0	0	0	1	3	0	3	0	0	1	0	1	1	2	0	0	0	0	0	12
NthUK-MADR	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	3
NthUK-MALA	0	0	0	5	0	0	0	0	0	0	0	1	2	0	1	0	0	0	0	9
SCOT-MALA	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
MUNI-CANA	2	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
STTUT-CANA	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3
SthGE-CANA	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
W1GER-CANA	2	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	5
FRANK-CANA	1	0	0	3	0	1	1	3	0	1	0	0	0	0	0	0	0	0	0	10
HAMB-CANA	1	0	1	1	2	0	0	1	1	0	0	0	0	0	0	0	0	0	0	7
W2GER-CANA	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
MidUK-CANA	0	0	1	0	0	2	0	0	1	1	0	1	0	1	0	0	0	0	0	7
LOND-CANA	0	0	1	2	0	1	0	2	1	1	0	0	2	1	0	1	0	0	0	12
NthUK-CANA	0	0	0	5	1	0	1	0	0	2	0	1	0	0	1	0	0	1	0	12
WstUK-CANA	0	0	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	4
SCOT-CANA	0	0	0	0	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0	4
OthsOS	5	2	7	3	5	3	5	3	6	2	4	4	2	2	0	1	1	0	1	56
OthsQUQS	10	11	19	16	15	13	18	13	33	17	9	11	16	9	8	9	10	7	6	250
OthsAS	0	0	2	11	8	20	9	15	25	14	9	11	9	13	8	10	12	10	4	190
OthsGUGS	1	1	4	4	8	11	6	14	29	18	23	13	14	6	11	17	17	11	2	210
OthsNUNS	6	6	19	19	21	20	24	24	26	28	32	20	23	12	15	21	18	13	11	358
OthsJSMS	4	8	19	13	15	13	20	24	34	23	20	19	23	10	15	11	16	8	4	299
OthsKUXU	6	10	13	14	14	9	12	13	9	11	13	12	15	9	9	10	9	8	4	200
OthsUK	2	5	15	20	8	14	16	13	22	12	12	8	11	5	10	6	15	6	6	206
OthsTH	2	6	11	20	13	16	17	17	16	17	9	14	15	16	16	9	19	5	11	249
OthsTW	1	5	31	16	12	9	17	8	9	14	15	13	14	25	19	19	6	3	2	238
OthsUP	0	7	18	10	10	8	8	5	9	7	8	9	11	12	10	11	8	6	5	162
OthsUZ	6	8	16	19	24	17	22	30	27	22	24	15	26	17	14	21	15	12	9	344
OthsTP	3	4	11	22	16	21	13	6	6	10	6	17	15	12	20	8	12	8	7	217
OthsTUUT	3	15	22	21	14	17	13	26	22	19	17	20	20	26	20	20	16	4	7	322
OthsTB	0	7	14	17	16	10	11	11	15	11	13	9	14	23	19	21	10	4	3	228

Table E-4: Traffic Flows Crossing French Upper Airspace - Departures Scheduled per Hour on 25/04/96 from 03:00 to 22:00

OthsTC	1	6	26	13	23	23	13	14	20	15	11	11	16	17	27	21	19	6	6	288
OthsTE	1	9	19	28	22	17	20	13	20	14	19	19	27	33	24	18	21	6	9	339
OthsTN	2	2	18	23	17	16	18	16	21	14	17	12	14	14	24	27	13	1	1	270
OthsTS	0	5	23	20	20	13	16	13	17	20	12	12	25	19	22	17	17	1	2	274
OthsAO	8	16	43	33	25	26	30	33	32	22	30	30	44	42	32	27	24	7	11	515
OthsAR	9	9	23	18	16	13	21	18	16	14	15	20	27	19	14	18	13	4	9	296
OthsUX	3	4	9	5	5	10	9	12	16	12	12	4	14	7	11	14	7	2	3	159
OthsXNUN	3	2	17	24	11	13	12	19	32	23	20	14	15	23	28	20	19	7	3	305
OthsUYUR	6	4	25	29	29	19	26	20	33	31	27	18	28	26	27	27	21	7	4	407
OthsUFXF	7	10	32	18	14	25	15	20	23	17	13	21	23	10	25	15	17	8	1	314
OthsUE	3	14	25	17	15	24	21	16	17	16	18	17	21	18	22	16	16	9	7	312
OthsUH	5	7	31	13	20	20	20	23	16	10	19	20	24	16	18	20	14	6	4	306
OthsZU	5	8	14	18	20	13	16	22	24	16	20	12	17	14	12	17	12	9	7	276
OthsPV1	1	2	16	12	20	14	11	12	13	14	14	7	19	11	13	15	12	4	3	213
OthsPV2	0	2	12	12	14	10	15	11	17	13	15	6	14	12	11	16	7	5	1	193
OthsN2H2	1	3	3	3	12	12	13	14	16	17	11	22	18	14	10	6	7	3	2	187
OthsZ2	2	2	5	5	10	11	15	15	12	18	16	25	22	11	10	10	8	4	4	205
OthsZ1N1H1	3	3	12	12	24	17	11	39	16	24	15	21	31	23	23	20	20	12	7	333
OthsC1L1F1	2	6	19	16	18	16	10	26	19	14	21	17	22	22	27	23	11	11	4	304
OthsC2L2F2	5	4	15	18	15	17	17	19	16	17	22	18	26	14	19	18	15	6	6	287
OthsUGUW	8	14	43	27	42	42	44	55	41	47	54	40	48	49	39	30	41	14	13	691
OthsUA	3	3	11	13	17	23	16	20	17	18	17	10	17	17	10	13	10	5	3	243
OthsUM	2	4	12	7	14	18	14	12	24	13	22	11	16	10	19	8	13	4	4	227
OthsUS	2	3	16	12	25	26	24	26	28	18	17	21	28	19	17	15	11	5	5	318
OthsUD	2	2	2	3	6	15	4	12	16	11	11	6	7	7	13	0	11	1	5	134

Table E-4: Traffic Flows Crossing French Upper Airspace - Departures Scheduled per Hour on 25/04/96 from 03:00 to 22:00

OthsK	1	2	6	2	12	17	14	17	12	9	8	6	17	7	0	8	8	2	0	148
Total	150	251	759	709	729	732	714	798	881	732	733	681	870	732	754	698	597	262	211	11993

Notes:

1. To include all the flights which would be in French airspace at 03:00, and depending on the time they would take to get to French airspace, departures up to two hours before 03:00 were considered. However, there were no departures for these flows between 01:00 and 03:00.
2. The total flights is 3582. However, all flights which do not belong to a flow are counted as frequently as the sectors they cross in the French Upper airspace. This accounts for the 11993 total.

Appendix F - Output from the Models

This appendix complements Chapter 8, describing output from the models which was not included in Chapter 8 because it is too detailed.

Table F-1: Comparison of Flights Re-routed

	DEL2	DEL1	BALD1	BALD2	BALD3	ALL
UK to Balearics,Barcelona and Alicante	***7***	***6***	***0***	***0***	***12***	***0***
NthUK-BALE	0	6	0	0	6	0
SthUK-BALE	0	0	0	0	6	0
SthUK-BARC	7	0	0	0	0	0
Germany(exc.west) and Swit. to Balearics and Barcelona	***2***	***2***	***2***	***2***	***2***	***2***
FRANK-BALE	2	2	2	2	2	2
W. Germany to Balearics and Barcelona	***7***	***5***	***5***	***5***	***5***	***5***
WstGE-BALE	2	0	0	0	0	0
WstGE-BARC	5	5	5	5	5	5
Barcelona and Balearics to W. Germany	***2***	***2***	***0***	***0***	***0***	***0***
BALE-WstGE	2	2	0	0	0	0
Barcelona and Alicante to Brussels and Amsterdam	***0***	***9***	***8***	***8***	***10***	***0***
BARC-BRUX	0	7	0	0	0	0
BARC-AMS	0	0	6	6	6	0
ALIC-BRUX	0	0	0	0	2	0
ALIC-AMS	0	2	2	2	2	0
Barcelona, Balearics and Alicante to Germany and Switzerland	***3***	***0***	***3***	***3***	***0***	***0***
BALE-SthGE	3	0	3	3	0	0
Barcelona, Balearics and Alicante to UK	***19***	***6***	***12***	***12***	***1***	***1***
BARC-LOND	9	0	0	0	0	0
BARC-NthUK	0	0	2	2	0	0
BALE-LOND	5	5	5	5	0	0
ALIC-NthUK	4	0	4	4	0	0
ALIC-MidUK	0	0	0	0	0	0
ALIC-HumUK	1	1	1	1	1	1
Madrid to Frankfurt and Stuttgart	***2***	***2***	***8***	***8***	***6***	***0***
MADR-FRANK	0	0	6	6	6	0
MADR-STUTT	2	2	2	2	0	0
Madrid to Southeast Germany and Switzerland	***0***	***0***	***0***	***0***	***0***	***0***
Madrid to W. Germany	***0***	***0***	***0***	***0***	***0***	***0***
Athens and Rome to Lisbon and Madrid	***0***	***0***	***0***	***0***	***0***	***0***
North Italy to Lisbon and Madrid	***0***	***0***	***0***	***0***	***0***	***0***
Lisbon and Madrid to Athens and Rome	***0***	***0***	***0***	***0***	***0***	***0***

Lisbon and Madrid to North Italy	***0***	***0***	***0***	***0***	***0***	***0***
UK (exc. London),Brussels and Amsterdam to Swit.	***0***	***0***	***15***	***15***	***15***	***0***
BRUX-SWT	0	0	15	15	15	0
London to Switzerland	***21***	***21***	***21***	***21***	***21***	***21***
gLOND-ZUR	21	21	21	21	21	21
Swit. to Brussels and Amsterdam	***6***	***6***	***0***	***0***	***0***	***0***
SWT-AMS	6	6	0	0	0	0
Geneva to UK	***18***	***18***	***18***	***18***	***18***	***18***
GENE-NthUK	3	3	3	3	3	3
GENE-gLOND	15	15	15	15	15	15
Zurich to UK	***21***	***0***	***21***	***21***	***21***	***0***
ZUR-gLOND	21	0	21	21	21	0
UK to Italy	***3***	***1***	***4***	***4***	***6***	***0***
NthUK-MILAN	0	0	3	3	3	0
NthUK-PISA	1	0	1	1	1	0
BOURN-TORI	1	1	0	0	0	0
BOURN-BOLO	1	0	0	0	0	0
LOND-NAPO		0	0	0	2	0
Italy to UK	***2***	***4***	***4***	***4***	***4***	***2***
VERO-GATW	0	0	2	2	2	0
NAPO-GATW	0	2	0	0	0	0
gPISA-STAN	2	2	2	2	2	2
Paris to Italy	***67***	***67***	***57***	***57***	***54***	***54***
PARI-MILAN	22	22	22	22	22	22
PARI-ROME	17	17	17	17	17	17
PARI-BOLO	7	7	0	0	0	0
PARI-VERO	3	3	0	0	0	0
PARI-VENI	8	8	8	8	8	8
PARI-NAPO	3	3	3	3	0	0
PARI-gPISA	7	7	7	7	7	7
Italy to Paris	***0***	***0***	***7***	***7***	***0***	***0***
gPISA-PARIS	0	0	7	7	0	0
Paris to Toulouse	***0***	***0***	***0***	***0***	***0***	***0***
Paris to Marseilles and Nice	***82***	***82***	***82***	***82***	***44***	***44***
PARI-MARS	44	44	44	44	44	44
PARI-NICE	38	38	38	38	0	0
Toulouse to Paris	***30***	***30***	***30***	***30***	***0***	***0***
TOU-PARIo	30	30	30	30	0	0
Brussels,Amsterdam and W Germany to Madrid and Malaga	***4***	***6***	***4***	***0***	***4***	***0***
BRUX-MADR	4	4	4	0	4	0
BRUX-MALAG	0	2	0	0	0	0
Germany (exc. West) to Madrid and Malaga	***16***	***16***	***16***	***16***	***11***	***11***
FRANK-MADR	5	5	5	5	0	0
FRANK-MALA	3	3	3	3	3	3
MUNI-MADR	6	6	6	6	6	6
STTUT-MADR	2	2	2	2	2	2
UK to Madrid and Malaga	***29***	***29***	***29***	***29***	***17***	***17***
gLOND-MADR	17	17	17	17	17	17
gLOND-MALA	12	12	12	12	0	0
South Germany to Canary Islands	***0***	***0***	***0***	***0***	***0***	***0***

Germany (exc. South) to Canary Islands	***10***	***0***	***0***	***0***	***0***	***0***
FRANK-CANA	10	0	0	0	0	0
UK to Canary Islands	***0***	***0***	***0***	***0***	***0***	***0***
Total Flights Re-routed	351	312	346	342	251	175

Appendix G - Output from Models in Chapter 9

This appendix complements Chapter 9, describing output from the models which was not included in Chapter 9 because it is too detailed.

Table G-1 DELINTX2- Flights Re-routed

Flow Group	Flow	DELINTX2	DELINT2
UK to Balearics, Barcelona and Alicante	NthUK-BALE	1	
	SthUK-BALE	1	
	SthUK-BARC		7
	NthUK-ALIC	1	
Germany(exc.west) and Switzerland to Balearics and Barcelona	FRANK-BALE	1	2
	SthGE-BARC	1	
West Germany to Balearics and Barcelona	WstGe-BALE	1	2
	WstGe-BARC	4	5
Barcelona and Balearics to West Germany	BALE-WstGE		2
Barcelona and Alicante to Brussels and Amsterdam	BARC-BRUX	1	
	BARC-AMS	1	
	ALIC-AMS	1	
Barcelona,Balearics and Alicante to Germany and Switzerland	BALE-SthGE		3
Barcelona, Balearics and Alicante to UK	BARC-LOND		9
	BARC-NthUK	1	
	BALE-LOND		5
	ALIC-NthUK		4
	ALIC-HumUK		1
Madrid to South Germany	MADR-FRANK	1	
	MADR-STUTT	2	2
UK(exc London),Brussels and Amsterdam to Switzerland	BRUX-SWT	2	
	AMS-SWT	2	
London to Switzerland	gLOND-ZUR	21	21
Switzerland to Brussels and Amsterdam	SWT-AMS	1	6
Geneva to UK	GENE-NthUK	3	3
	GENE-gLOND	15	15
Zurich to UK	ZUR-NthUK	1	
	ZUR-gLOND	3	21
UK to Italy	NthUK-PISA	1	1
	BOURN-TORI		1
	BOURN-BOLO		1
	LOND-MILAN	1	
	LOND-gPISA	1	
	LOND-ROME	5	

Table G-1 DELINTX2- Flights Re-routed

Italy to UK	MILAN-LOND	2	
	VERO-GATW	1	
	ROME-LOND	2	
	NAPO-GATW	1	
	gPISA-SthUK	1	
	gPISA-STAN	1	2
Paris to Italy	PARI-MILAN	18	22
	PARI-ROME	13	17
	PARI-BOLO	2	7
	PARI-VERO	2	3
	PARI-VENI	6	8
	PARI-NAPO	1	3
	PARI-gPISA	4	7
Italy to Paris	VENI-PARI	1	
Paris to Toulouse	PARI-BORDX	10	
Paris to Marseilles and Nice	PARI-MARS	29	44
	PARI-NICE	15	38
Toulouse to Paris(Charles de Gaulle and Orly)	TOU-PARIo	4	30
Brussels, Amsterdam and West Germany to Madrid and Malaga	BRUX-MADR		4
	AMSwG-MADR	2	
South Germany to Madrid and Malaga	FRANK-MADR	2	5
	FRANK-MALA	1	3
	MUNI-MADR	3	6
	STTUT-MADR	2	2
UK to Madrid and Malaga	MiUK-MALAG	1	
	gLOND-MADR	1	17
	gLOND-MALA	4	12
Germany (exc South) to Canary Islands	FRANK-CANA	1	10
Total Flights Re-routed		203	351

Table G-2 BALDISTX Flights Re-routed

Flow Group	Flows	BALDISTX	BALDIST1
UK to Balearics,Barcelona and Alicante	NthUK-BALE	6	
	NthUK-BARC	2	
	NthUK-ALIC	5	
	SthUK-BALE	6	
	SthUK-ALIC	7	
Germany(exc.west) and Switzerland to Balearics and Barcelona	FRANK-BALE	2	2
West Germany to Balearics and Barcelona	WstGE-BARC		5
Barcelona and Balearics to West Germany	BARC-WstGE	5	
Barcelona and Alicante to Brussels and Amsterdam	BARC-AMS	6	6
	ALIC-AMS	2	2

Table G-2 BALDISTX Flights Re-routed

Barcelona, Balearics and Alicante to Germany and Switzerland	BALE-SthGE	3	3
	ALIC-SthGE	2	
Barcelona, Balearics and Alicante to UK	BARC-NthUK		2
	BALE-LOND		5
	ALIC-NthUK		4
	ALIC-HumUK	1	1
Madrid to South Germany	MADR-FRANK	6	6
	MADR-STUTT	2	2
Athens and Rome to Lisbon and Madrid	ATH-MADR	1	
	ATH-LISB	1	
	ROME-MADR	7	
	ROME-LISB	2	
North Italy to Lisbon and Madrid	MILAN-MADR	9	
	MILAN-LISB	3	
	GENO-MADR	1	
	VENI-MADR	1	
Lisbon and Madrid to Athens and Rome	MADR-ROME	7	
	LISB-ROME	2	
Lisbon and Madrid to North Italy	MADR-MILAN	8	
	MADR-BOLO	1	
	MADR-VENI	1	
	LISB-MILAN	3	
UK(exc London),Brussels and Amsterdam to Switzerland	NthUK-SWT	4	
	LUTON-ZUR	1	
	BRUX-SWT	15	15
	AMS-SWT	7	
London to Switzerland	gLOND-ZUR	21	21
Switzerland to Brussels and Amsterdam	SWT-BRUX	13	
	SWT-AMS	6	
Geneva to UK	GENE-NthUK	3	3
	GENE-gLOND	15	15
Zurich to UK	ZUR-gLOND		21
UK to Italy	NthUK-MILAN		3
	NthUK-PISA	1	1
	BOURN-TORI	1	
	LOND-NAPO	2	
Italy to UK	VERO-GATW	2	2
	NAPO-GATW	2	
	gPISA-STAN	2	2
Paris to Italy	PARI-MILAN	22	22
	PARI-ROME	17	17
	PARI-BOLO	7	
	PARI-VENI	8	8
	PARI-NAPO	3	3
	PARI-gPISA	7	7

Table G-2 BALDISTX Flights Re-routed

Italy to Paris	ROME-PARIS	16	
	BOLO-PARIS	7	
	gPISA-PARIS	7	7
Paris to Toulouse	PARIS-BORD	44	
Paris to Marseilles and Nice	PARI-MARS		44
	PARI-NICE	38	38
Toulouse to Paris(Charles de Gaulle and Orly)	TOU-PARIo		30
Brussels,Amsterdam and West Germany to Madrid and Malaga	BRUX-MADR		4
South Germany to Madrid and Malaga	FRANK-MADR	5	5
	FRANK-MALA	3	3
	MUNI-MADR		6
	STTUT-MADR	2	2
UK to Madrid and Malaga	gLOND-MADR		17
	gLOND-MALA		12
	SCOT-MALA	2	
UK to Canary Islands	MidUK-CANA	7	
	NthUK-CANA	12	
	WstUK-CANA	4	
	SCOT-CANA	4	
Total		412	346