Nationaal Lucht- en Ruimtevaartlaboratorium

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NLR-TP-2013-234

Prioritisation in Air Traffic Flow Management

The Design of a Flow Management Tool using a Petri-Net Approach

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Executive summary

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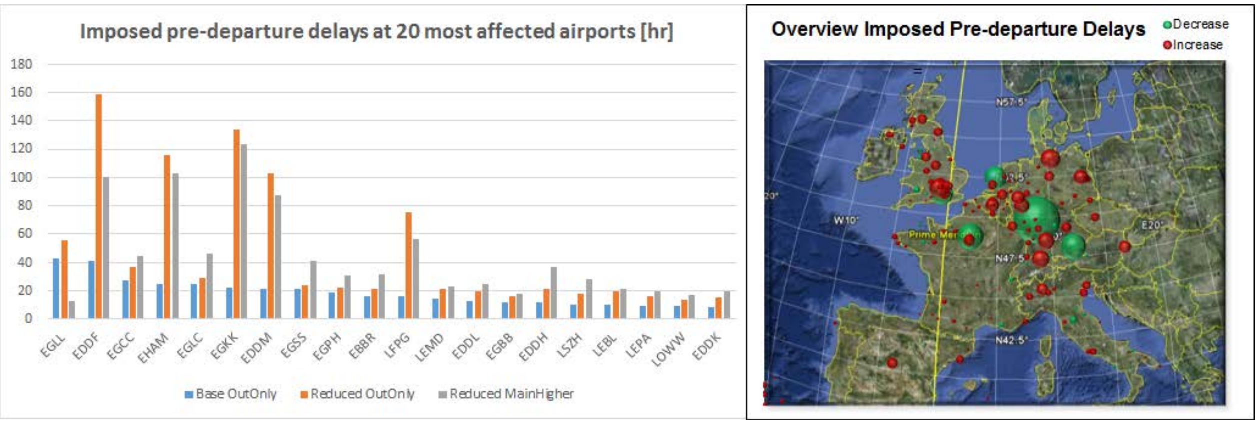

Charts presenting the differences of imposed pre-departure delays at the 20 most affected airports in the Core Area of Europe, demonstrating that 5 capacity-disrupted airports were penalised once more by imposed flow regulation delays, and that prioritisation will provide benefits compared to FC-FS regulations (MainHigher = prioritised).

Problem area
Air Transport operations are performed through an ATM network of airports connected to each other by airspace sectors. This network is vulnerable to disruption. Whenever the capacity of single or multiple nodes of this network decreases, bottlenecks and congestion will cause delays and cost-inefficiency of flight operations. SESAR developments are aiming to improve the quality of planning and regulations in case of disruption, respecting the economic value of flights.
The present research is in-line with this objective.
Specifically, large saturated airports and hub airports, depending on transfer operations, are sensitive to suffer by arrival congestion and departure delays. Schiphol, situated in the core area of Europe, is one of them.

This document describes the research and design of an enhanced prototype of an algorithm to allow improvement of ATFM regulations by optimising and prioritising the flow management of the ATM network. This prototype is used to conduct an explorative experiment to show the potential benefits of this algorithm.

Description of work
Congestion of temporarily overloaded sectors and/or airports can be prevented by assigning flights pre-departure delays, and thus spreading demand. For operations in Europe, Air Traffic Flow Management (ATFM) is accomplished by imposing constraining pre-departure delays following a First-Come First-Served (FC-FS) principle and applying these regulations on flights when arriving at congested nodes

Report no.
NLR-TP-2013-234

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Report classification
UNCLASSIFIED

Date
July 2013

Knowledge area(s)
Luchtverkeersmanagement(ATM)-en luchthavenoperaties

Descriptor(s)
Air Traffic
Air Traffic Flow Management (ATFM)
Network Analysis

This report is based on a paper to be published in Journal of Aerospace Operations, 2013, by IOS Press, affiliated with TU-Delft.

(sectors or airports), according to their planning.
The problem with FC-FS is that it ignores the cost of penalties as well as its impact on delays, queuing and congestion, and the natural solution is to develop an optimization algorithm to find a global optimum over all coherent air traffic during a day. This can be implemented ECAC-wide and over 24 hours, e.g. by optimizing a cost function, using Mixed Integer Linear Programming (MILP) techniques. However, this method is hard to apply for the European context due to the complexity of congestion problems as well as its systematic appearance. Therefore, a throughput analysis model was developed based on decoupling of the optimization problem by performing congestion analysis within a local context of space and time. The model applies a Petri-net methodology, selecting reservations of capacity for flights passing nodes, all based on 4D planning data. A first version of the model was used to demonstrate that prioritisation could be applied within this local context to improve throughput and to reduce delays. However, what was missing in the model, was:

1) a second order mechanism to apply iteration, filling up the gaps that delayed flights will create,
2) a measure to assess absolute success and to measure the amount of suppressed congestion against imposed pre-departure delays, and
3) to include flight connectivity by connecting arriving flights to departing flights and measuring possible reactionary delays.

In the present paper an enhanced model is presented, based again on Petri-net modelling techniques using an iterative approach this time, allowing reassessment of imposed pre-departure delays, and calculating a new selection of imposed delays every 10 minutes during a 24 hours period. Each time a look-ahead period is investigated on reservations for flights passing through nodes of the network, and when reservations cannot be made so-called “Waiting-time” is detected until the reservation can be made. Thereafter the “Waiting times” along 4D planned flight paths are translated into imposed pre-departure delays. With this new model it was demonstrated on a core area scenario of 24.000 flights that it was possible to suppress most of the Network “Waiting time” and to replace it by imposed pre-departure delays. The second order effects of iteration allowed to suppress now most of the waste of available capacity, and the amounts of measured “Waiting time” were comparable with the amounts of imposed delays. Also, the traceability of evaluating bottleneck behaviour was strongly improved allowing analysis of critical network aspects. Finally, a heuristic flight connectivity mechanism was applied allowing evaluating the impact of turnaround on accumulating delays occurring e.g. by loss of capacity.
This enhanced model was evaluated by processing the reference scenario as well as the disrupted scenario again, with and without prioritization of flights to/from disrupted airports. And again, successful results could be confirmed, but this time with a higher confidence level than before. The model is validated for its capability to suppress “Waiting time” and to apply prioritization.

Results and conclusions
This publication presents a prototype of an enhanced ATFM Tool with performance capabilities that go far beyond the original aims:

- The revised tool has still the aim to operate in a local context of space and time, to be efficient in performance, and moreover, to be transparent and traceable in selecting and imposing delays.
- The tool operates in a fully iterative way now, being able to convert most of the detected network “waiting time” into pre-departure imposed delay.
- The tool can select the most penalising node in a flight, can protect secondary nodes against double penalties, and can also release penalised flights by cancelling imposed delays. This helps to reach maximum achievable efficiency.
- The tool has a node access reservation feature that has been applied in variety of ways to allocate prioritised access rights. Other options are possible and may be investigated yet.
- The method of regulation by different classes of prioritisation allows for performance monitoring and post-processing analysis, supporting the transparency of operations.

Applicability
Enhanced flow management can be accomplished by replacing FC-FS ATFM by optimising and prioritising ATFM. Several prioritising options are possible, such as prioritising flights to/from disrupted airports, prioritising flights suffering reactionary delays, prioritising flights with high economic value, and other options. The assumption is that prioritisation options may provide benefits, whilst the enhanced ATFM Tool is able to balance and to protect the exclusiveness of prioritisation against possible negative impact on the overall performance of the ATM network. In other words, this yields not only demand and capacity balancing, but even balancing the prioritisation.

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This publication has been refereed by the Advisory Committee AIR TRANSPORT.

Customer	TU Delft
Contract number	6033101.1
Owner	National Aerospace Laboratory NLR
Division NLR	Air Transport
Distribution	Unimited
Classification of title	Unclassified
	July 2013

Approved by:

Author	Reviewer	Managing department
H.W.G. de Jonge 4/7/2013	R.R. Seljee (ATAP) 10/7/2013	C.S. Beers (ATAP) 18/7/2013
Date: 01/Aug/2013	Date: 01/Aug/2013	Date: 01/Aug/2013

Summary

In this article an improved Flow Management tool is proposed and evaluated. In most research currently performed on the subject of air traffic flow management, Mixed Integer Linear Programming techniques are used to come to a solution. In the approach proposed herein, a Petri-net algorithm is used to model the flow of traffic. By iteratively looking ahead in time, future reservations on capacity are made. In-air waiting times are then suppressed by imposing pre-departure delays, based on the maximum delay a flight can expect at a node along its route. The newly developed algorithms were shown to effectively suppress in-air waiting time by imposing pre-departure delays. Second-order (knock-on) network effects are also included, leading to a more efficient utilisation of capacity. Moreover, in a large European-wide scenario with a disruption at several major hub airports, prioritising flights to and from these airports was shown to considerably alleviate delays at the impacted airports. While this did come at a small cost to the total duration of imposed delays, total cost of delay was found to be reduced.

Keywords

Air Traffic Management (ATM)
Air Traffic Flow Management (ATFM)
Flow and Capacity Management
Network Analysis
Optimisation
Prioritisation
Petri-net Analysis
Model-based simulations

Contents

Abbreviations

AFP	- Airspace Flow Program
ANSP	- Aeronautic Navigation Service Provider
ATC	- Air Traffic Control
ATM	- Air Traffic Management
ATFM	- Air Traffic Flow Management
CASA	- Computer Assisted Slot Allocation
CFMU	- Central Flow Management Unit (Eurocontrol, Brussels)
DCB	- Demand and Capacity Balancing
ECAC	- European Civil Aviation Conference
FC-FS	- First-Come First Served
FM	- Flow Management
GDP	- Ground Delay Program
GUI	- Graphical User Interface
ICAO	- International Civil Aviation Organization
LA	- Look-Ahead
MILP	- Mixed Integer Linear Programming
MTOW	- Maximum Take-Off Weight
PD	- Pre-departure Delay (assigned by ATFM)
R&D	- Research & Development
SES	- Single European Sky
SESAR	- SES ATM Research programme
SWIM	- System-Wide Information Management
UDPP	- User-Driven Prioritisation Process
WT	- “Waiting Time” (measured network congestion time)
4D	- In 4 Dimensions

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1 Introduction

In tactical ATFM, the focus of this study, whenever in the near future a demand is detected that exceeds available capacity, ATFM measures, such as imposing pre-departure delays, are taken to prevent this overload and thus to ensure safety and efficiency. Because of the enormous complexity of the networks, equity/fairness considerations, connectivity, and because a flight can encounter not just one but multiple congested regions, it is extremely difficult to determine the most efficient measure. Therefore, since the early 1990s a large amount of research has been performed on this challenging topic.

Most research was focused on flow management within the US airspace and uses Mixed Integer Linear Programming (MILP) models to find an optimal solution. Because most of these models deal with only one congested sector or airport, these MILP methods are very useful to find an efficient and equitable solution. In Europe, flow management is a process in which a complete network of capacitated elements needs to be considered, in which even a small disturbance will have effects throughout the entire network, see also [1] and [2].

Therefore, NLR developed a method to model a European-wide scenario where ATFM is performed by solving overloads in its local context and imposing pre-departure delays based on a chosen method of prioritisation (See NLR, de Jonge and Seljée, [3]). Using this method it is possible to clearly see not only the local but also the European-wide consequences of different methods of prioritisation, while it is still possible to process an entire day of traffic in a reasonable amount of time.

Although the tool developed by NLR already showed promising results, several improvements and extensions were desired. Flight connectivity at the airport and more importantly second-order network effects were not yet included, thus preventing that the time gaps that were created by imposing a delay to a flight could be filled up again by other flights. Also a more efficient use of capacity was achievable. Therefore, it was conjectured that significant reductions in imposed delays could be achieved with an improved algorithm, as well as an increased level of confidence in the results obtained. The objective of research presented in this article, was to significantly extend and improve the existing flow management tool, including second-order network effects and connectivity at the airport, leading to a powerful, robust, fast and reliable tool.

This paper first describes the background and context of research, followed by a more detailed discussion of the research goal and subgoals. Next, the core Petri-net algorithm and the new flow management algorithms are explained. Thereafter, a brief outline is given of the set-up of the experiment, followed by a discussion of the results. The paper is concluded with ideas for future research and the conclusions.

2 Background and Context

According to Barnhart et al., [4], the goal of Air Traffic Flow Management is to prevent local system overloading by dynamically adjusting the flows of aircraft on a national or regional basis. In other words: matching demand with available capacity. This is performed both at the long-term strategic and at the short-term tactical level. The tactical level, just days before departure, or at the day of operations itself, is the focus of this study. Flow management measures such as imposing delays, metering (varying speed) and/or rerouting are used to prevent demand from exceeding capacity, but the most impacting measure used systematically in pre-departure flow management is the first one, to impose pre-departure delays, and this is the only measure modelled in this research.

2.1 Current ATFM Programs

Large differences exist between the European and US approach to flow management. In the US, programs such as the Ground Delay Program (GDP) and Airspace Flow Program (AFP) are used when demand is expected to exceed capacity [5]. A queue of virtual arrival slots is created and flights are assigned a slot on a First-Come, First-Served basis (FC-FS). Normally, these programs are only enacted for several hours at a time, in most cases due to severe weather. On most days only a small amount of GDPs or AFPs are used (rarely more than 6 per day) and flights do not often suffer from multiple congested regions along their path.
On the other hand, in Europe a more central approach is used in which large, frequently congested airports always use departure slots and where the Central Flow Management Unit (CFMU) centrally allocates pre-departure delays. Because Europe deals with congestion on a much more routine basis, even when disregarding weather influences, flow management in Europe is a much more complex process [2]. CFMU flow managers use the Computer Assisted Slot Allocation (CASA) system to predict future overloads and to determine the sectors which come under CASA control [6]. Flights entering a flow-controlled zone are sequenced in a FC-FS order.

2.2 Prior research

A literature study was performed on existing research. Two main research paths were distinguished: the single resource problem and the multiple resource problem. The single resource problem has been a popular area of research because of its fast computational times and because the easiness to include new developments such as airline involvement. Early models by Richetta & Odoni [1] have formed the basis for most research on the problem. In this research path, a clear focus on the American situation can be observed, but for the European situation this path of research is less applicable [2].
In particular for the single, but also for the multiple resource problem, an extensive use of MILP techniques can be observed. In early models by Vranas et al. [7] and Bertsimas & Stock-

Patterson [8], flight connectivity at airports was introduced in the model. Still, flights would encounter only one capacitated region or airport. What is probably most striking though is that possibly the most complicated network-wide ATFM problem in the world, the European airspace, received only limited attention. Only the research done by Lulli & Odoni [2] demonstrated the complex task of solving the ATFM problem in Europe. They showed how in Europe areas of congestion cannot be considered on an individual basis, but instead a true network of capacitated elements needs to be considered. This also results in a conflict between equity and efficiency. In certain cases 'fair' solutions for all participants result in a significantly higher total delay than the most efficient solution. Unfortunately, no attempt was made to apply the Bertsimas & Stock-Patterson model on a European-wide scenario.

2.3 Preliminary NLR Research

In contrast to the heavy use of MILP by other researchers, NLR (de Jonge & Seljée, [3]) has worked on a Petri-net based flow management model. The advantages of this model are that it allows for a good analysis of demand and capacity mismatches at both airports and sectors, that it can be run on a large-scale scenario, and that it allows for different methods of prioritisation instead of only a FC-FS approach.

A throughput analysis model was developed based on decoupling of the optimisation problem by performing congestion analysis within a local context of space and time. The model applies a Petri-net methodology, making reservations and selecting an order of assigning reservations to flights, all based on 4D planning data. A first version of the model was used to demonstrate that prioritisation could be applied within this local context to improve throughput and to reduce delays. In particular, under disruptive conditions with reduced capacity, prioritising flights to/from the disrupted airports significantly reduced the imposed delays at those airports. This was shown to significantly benefit the performance of these airports under these conditions. However, what was missing in the model, was:

1. a second order mechanism to apply iteration, filling up the gaps that delayed flights will create,
2. a measure to assess absolute success and to measure the amount of suppressed congestion against imposed pre-departure delays, and
3. to include flight connectivity by connecting arriving flights to departing flights and measuring possible reactionary delays (connectivity).

In the present paper an enhanced model is presented, based again on Petri-net modelling techniques but using an iterative approach this time, allowing reassessment of imposed pre-departure delays, and calculating a new selection of imposed delays every 10 minutes during a 24 hours period. In each 4-hour look-ahead period reservations on capacity are made for flights passing through nodes of the network, and when direct reservations cannot be made, so-called in-air 'waiting time' is detected. These accumulated waiting times are transformed thereafter into imposed pre-departure delays. The ability to deal with second order effects through iteration, is the reason that most of the waste of available capacity can be avoided now. Finally, a heuristic flight connectivity mechanism is applied, that also allows the evaluation of the impact of turnaround time on the accumulation of delays, occurring as a consequence of disruption by loss of capacity.

3 Requirements for advanced ATFM

This section describes the high level requirements on an advanced ATFM algorithm that is able to provide added value to future developments of ATFM in Europe in the context of SESAR, and that will satisfy in a favourable way the expectations and needs of airspace users.
Under the Single European Sky (SES) initiative, the SES ATM Research programme (SESAR) is charged with modernising the ATM system of Europe. The main lines of the advanced concept of future ATM in Europe are defined during the first activities of SESAR, the Definition Phase, and regarding pre-departure flow management, this concept defines some of the operational conditions that can be used as a starting point for future advanced Air Traffic Flow Management (ATFM) (SESAR D3 and CONOPS, [9] and [10]):

- There shall be sufficient capacity to cope with air traffic demand, and sufficient capacity shall be ensured while anticipating an accurate planning of demand, accomplished by convergent and layered planning.
- The accurate planning yields an increasingly more reliable 4D flight planning from gate to gate.
- Demand and Capacity Balancing (DCB) is the process to ensure a flight-efficient, punctual and undelayed execution of flight by all planned air traffic in Europe, in balance with available capacity.
- In case of disruption, there is defined a so-called User-Driven Prioritisation Process (UDPP) to solve the bottlenecks in ATM performance, in which the airspace users are involved in solving their temporary capacity shortfalls.
- In case of congestion and lack of capacity, the economic value of flight prevails over a First-Come First Served (FC-FS) principle to solve the problems of an undisturbed performance of air traffic as planned.

Given the characteristics of ATM in Europe with a quite heavily overloaded core area, and some areas of systematic overloads en-route, as well as a sub-network of 12 to 20 airports that are operating close to the capacity, the need was recognised to operate a process of pre-departure flow management. Control on the management of flows of air traffic is required, in particular, when ANSPs are unable to supply the extra airspace capacity needed or when airports fail for whatever reason to cope with air traffic demand. Weather is one of the more systematic reasons why airports are forced to operate as good as possible but with less capacity than needed or expected. The challenge is to offer the best throughput under these constraining conditions, and advanced ATFM is challenged to offer improvements by making best use of available capacity, superior to today's operations and possibly close to a "true" optimum of best ATM performance under constraining conditions.

Assuming balance in demand and capacity at the more strategic level – more than a week before execution of the actual flight – it is considered possible by SESAR to improve the performance of DCB by applying accurate 4D planning and better exchange of planning information between stakeholders by access to System-Wide Information Management (SWIM). Although lots of other aspects of pre-departure planning can be improved as well, the objective of this publication is to describe how the performance of ATFM can be improved in the late pre-tactical and tactical flight phase before departure, based on 4D planning information and taking into account the known in-flight traffic conditions. Enhanced ATFM shall modify then the pre-departure planning of flights in such a way that all flights can complete their mission with a high level of confidence without meeting disruptive congestion.

Today's operations performed by CFMU are successful when applying ATFM, even if enhanced 4D planning information is not available yet, and enhanced reliability of planning information by CDM is not fully implemented either. In addition, ATFM is performed on a First-Come First-Served (FC-FS) basis. Regulations are applied on the first flight arriving at an overloaded sector (network node) according to its planning, and pre-departure delays are imposed without taking into account the impact that imposed delays may have on the traffic conditions at departure or destination. Therefore, there is room for improvement, given the application of an algorithm that reacts on overloads of regulated sectors, but that ignores the circumstantial conditions, locally as well as throughout the network.

On the one hand, the impact of imposed delays can be considered as an area of improvement for the performance of the ATM Network, on the other hand the operational requirement to take into account the economic value of the flight asks for a strategy to improve ATFM and to apply a methodology that can address selective decision making instead of a FC-FS strategy. One step further, the question will have to be addressed if it is possible to replace the strategy of delay assignment on a FC-FS basis by an optimising and prioritising flow management strategy, which allows providing guidance under minimal penalising conditions.

Once, the selection and assignment of imposed pre-departure delays is possible in an optimising and prioritising way, there are several options possible allowing airspace users to select their most favourable solutions for solving congestion problems under constraining conditions. However, assessment of the impact of selected solutions on the overall ATM performance through the network is part of the solution strategy, and therefore it is not possible to simply select a preferred solution and at the same time to ensure an optimal performance of the ATM network. At all times, the proposed ATFM algorithm shall process planned flows of traffic through the congested ATM network in such a way that all individual flights are accommodated

as well as possible in adherence to their 4D planning, with the best overall performance of the ATM network as a whole. This optimisation criterion can be expressed as reaching an ATM network performance with minimum average delay and minimum spread in delay, possibly taking into account additional aspects of other costs and economic value.
This leads to a requirement of an algorithm solution strategy that allows to compare assignments of pre-departure delays of those flights that can contribute to solving the detected congestion at a node of the ATM network, and that allows to select delay assignments that meet also the optimisation criteria. Moreover, it requires to be able to quantify and analyse the penalties on ATM network performance due to imposed pre-departure delays, and it requires to be able to evaluate these solutions and penalties under changing conditions due to late flight-plan changes. We have found in that case an algorithm that satisfies high level basic requirements for operational applicability.

4 Advanced modelling and operational applicability

This section describes the operational context in which the proposed advanced ATFM algorithm will be used, and how to evaluate and assess its outcomes when processing such an algorithm. The need for flow management stems from congestion and bottlenecks in the ATM system. On the one hand, these bottlenecks occur at airports, being incidentally or systematically congested and overloaded, causing delays during flight execution and thus deviations of flights from their planning. On the other hand, these bottlenecks occur by traffic passing through airspace sectors, causing overloads and stress on ATC, which possibly reacts by decreasing the declared capacity of their sectors. The actual sector overload is experienced as workload and as traffic density in the sector, not as flight delays. The effect on operational ATM performance is therefore not measured as flight delays, but only on the long term by reduced throughput, by anticipation of possible congestion for a safe level of operations, and by protection of airspace sectors against future hazardous situations.
R&D will be able to reflect these operational effects by modelling the actual operations of processing air traffic through an ATM system of airspace and airports by fast-time simulation. Fast-time simulation is accomplished by modelling airports by their typical bottleneck behaviour, and modelling airspace by measuring conflict risks and workload effects, but not by delaying the flights more than the way the flights will deviate in real-life situations from their 4D planned operations. The outcome of these fast-time simulations is appropriate to assess the value of advanced ATFM on operational ATM performance, and thus on costs and economic benefits, but they have little added value for the analysis of congestion and bottlenecks through the ATM network. It should be noted that in this publication **no results on fast-time simulation** are published, and therefore no concrete ATM performance results are produced.

R&D will need also pure ATM network models, on the one hand, to perform advanced flow management, solving congestion whilst processing traffic flows through the ATM network, and on the other hand, by application of a network model to perform bottleneck analysis, and to assess the effectiveness of solving congestion. It should be noted that in this publication **all effort is focused on the working of an enhanced ATM network model**, and that this model is used for network performance analysis as well as **for partial validation of a prototype of advanced ATFM**, including options for optimisation and prioritisation.
The working of the ATM network model depends only on the definition of nodes, being airport and airspace sector nodes, and of air traffic demand, being represented by 4D flight plans. 4D flight plans consist of series of 4D waypoints, and the 4D distance between these 4D waypoints determine the distances between nodes of the ATM network. A scenario consists of 24 hours of traffic, assuming a quiet period during the night to separate consecutive days from each other. Further, a scenario consists of an ECAC-wide expansion, considering traffic from and to outside areas as unmanageable flows of air traffic receiving no imposed pre-departure delays. Of course, the same is applicable for departed in-flight traffic not being able anymore to receive imposed delays.
All other traffic is able to receive pre-departure imposed delays, and these **ATFM delays are calculated** by the proposed model, operating **in a flow management mode**, whilst the **effectiveness** of the calculated delays are evaluated by the same proposed model, but operating now **in a throughput analysis mode**.
The performance of throughput is measured by processing an, at least slightly, overloaded scenario through an ATM network and measuring the so-called “waiting time”. The “waiting time” is the time period that the flight is waiting for capacity that allows the flight to access the node. This “waiting time” is accumulated per flight and per node each time that it is observed that there is insufficient capacity to allow a planned flight to access and to pass a node, and this node can be a sector node as well as an airport node. **The performance of throughput is optimal if no “waiting time” remains** when processing a scenario over 24 hours.
The performance of an ATFM option is measured first by the amount of pre-departure imposed delays needed to mitigate the observed congestion, secondly by measuring the amount of “waiting time” remaining, when the adapted scenario is processed by throughput analysis again. In the ideal case, the lowest possible amount of pre-departure delays is imposed, whilst no “waiting time” is observed anymore over the full 24 hours processing time.
As stated before, the ATM network performance depends fully on 4D flight plans, sector nodes and airport nodes:

- The 4D flight plans are assumed to be available for all flights, and they exist first of all of lists of waypoints to be flown consecutively. If not delivered by airspace users, they are assumed to be produced from available ICAO flight-plans, albeit with larger uncertainty. For evaluating the proposed model, it is assumed that all flight-plans are 4D, and will have a sufficient level of confidence. In operations, flight-plans may change, in particular, due to refinement close to departure. In this experimental evaluation no flight-plan changes will occur, but the proposed ATFM model is processed frequently and is able to cope with these changes. No negative impact is expected therefore from instability of flight-plans, or other reasons for late corrective changes.

- The sector nodes are characterized by capacity limits, specifying the maximum number of flights passing the sector per hour. The number of sectors specifying the connectivity between airports seems quite huge from the point of view of what is required for network connectivity. The minimum connectivity needed to allow all planned flights to fly from origin to destination through connecting airspace sectors should be sufficient for network management, making the network more robust for overloads than using all sectors of the existing network [11]. Nevertheless, the sectors and their capacity limits are used as specified, and from experimental perspective some network saturation, even if avoidable, is helpful to support assessment of the proposed model.
- The airport nodes are characterized by simple capacity figures defining the number of movements per hour. This is not sufficient to describe the complex operations around airports, but from ATFM perspective the ambition to manage departing and arriving flows through the airports should be modest. ATFM aims to prevent bottlenecks and congestion and thus to prevent overloads. Therefore, the applicable capacity figures should match the maximum airport capacity figures, not more and not less. Any other form of regulation of airports should be considered beyond the scope of ATFM, and this is important, because too low capacity figures would suggest ATFM to reduce throughput instead of maximising throughput, whilst too high capacity figures would invoke queuing around the airport, as will be observed during ATM performance assessment by fast-time simulation (N.B. not addressed in this publication; see also [12]). Given the volatility of airport capacity, it might be required to anticipate fluctuations in airport movement capacity, caused e.g. by fluctuations in departure/arrival ratios. There is no principle problem for the proposed ATFM model to accept a refinement of airport movement capacity figures to e.g. capacity figures per hour. However, it is likely too detailed and too difficult when ATFM would aim to regulate separate departure and arrival flows, whilst ensuring no overloading and no underloading at the same time.

A first version of a Petri-Net based model was developed by NLR to evaluate enhanced ATFM operations compared to traditional FC-FS operations [12]. It could be demonstrated that one type of prioritisation could operate very beneficially compared to FC-FS regulations. In particular under disrupted conditions there was evidence of benefits due to prioritisation, i.e. some large airports (5 main airports in the core area) were assumed to suffer under reduced capacity and could benefit from prioritisation (See also “2 Background” and [12]).

This first attempt was successful, but the applicable strategy was far from complete and optimal. It was recognised that it was sufficient for a first order approach to analyse a local context in space and time, i.e. one node (airport or sector) and during a maximum time of one hour, was sufficient to identify most of the applicable "waiting time", and to convert waiting time to pre-departure imposed delays (See Figure 1). However, it was not possible to achieve full optimisation. Once imposed, a pre-departure delay could not be cancelled or reduced anymore when due to other imposed delays, it was not necessary anymore. Though, prioritisation was favourable in the applicable scenarios compared to applying FC-FS in a straightforward way, but the applicable strategy to determine imposed pre-departure delays could be improved.

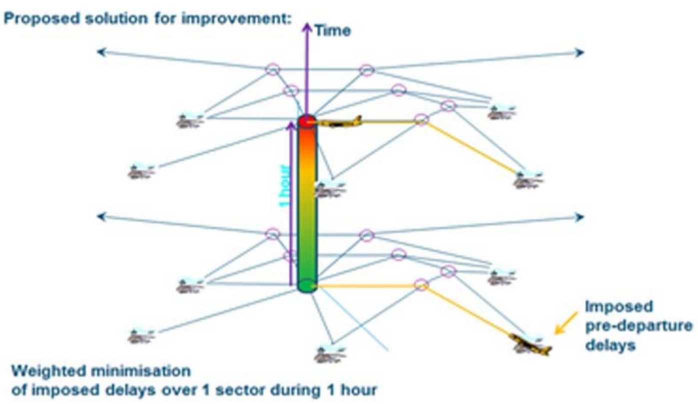

Figure 1 – Illustration of the notion of a local context applicable to the first of a petri-Net prioritising AFTM model

5 Design of FM tool, using a Petri-Net approach

The challenge is now to refine the application of a Petri-Net network analysing strategy in such a way that ATFM can be applied in an optimised way, converting almost all observed "waiting time" to the minimum needed amount of imposed pre-departure delays. This tool will be designed to use it in two ways:

1. **In support of ATM network throughput analysis**: To analyse the amount of "waiting time" needed to process air traffic demand of a given scenario through the ATM network, and
2. **In support of applying enhanced ATFM**: To process advanced ATFM options on the air traffic demand of a given scenario in such a way that the remaining "waiting time" is minimised against a minimum amount of imposed pre-departure delays.

Moreover, these options are extended with the option to include the application of reactionary delays to the network model. These reactionary delays are determined firstly, in principle, by available flight plan data, secondly, by the time needed for turnaround. Because both types of data were missing in the flight-plan data, both had to be emulated, and the emulation will never be complete and will never comprise all reactionary delay effects in real life. Nevertheless, emulation was partly successful and this option can be used to get some extra insight in case of throughput analysis of extremely disruptive ATM network behaviour.

The Flow Management Tool is discussed now from the high level process to the more detailed processes, but only the process to determine imposed flow management delays is discussed in more detail (See for a more detailed description of design, implementation and validation: van Hout, [13]):

- The modules of the Flow Management Tool
- The Flow Management algorithm
- Creating reservations on future capacity
- The main principle to determine imposed pre-departure delays
- The second principle to determine imposed delays
- The Petri-Net application by reservations and transitions

5.1 The modules of the Flow Management Tool

The Flow Management Tool (See Figure 2) consists essentially of:

- **The Simulator**: the control module, controlling a time-sequenced process to deal with time-triggered events.
- **The Model**: the heart of the tool controlling access of flights to the nodes of the ATM network.
- **The three user interface modules**:
    - **FM Console**: to perform basic controls, like start/stop on the ATFM process.
    - **FM Res.Visualiser**: to show for a chosen node how reservations are created.
    - **FM GUI**: to provide graphical output on the performance of network throughput.

The heart of the Flow Management Tool is “the Simulator”. This process takes care that the whole flow managed period of typically 24 hours is processed in a dual phased step-wise iterative process.

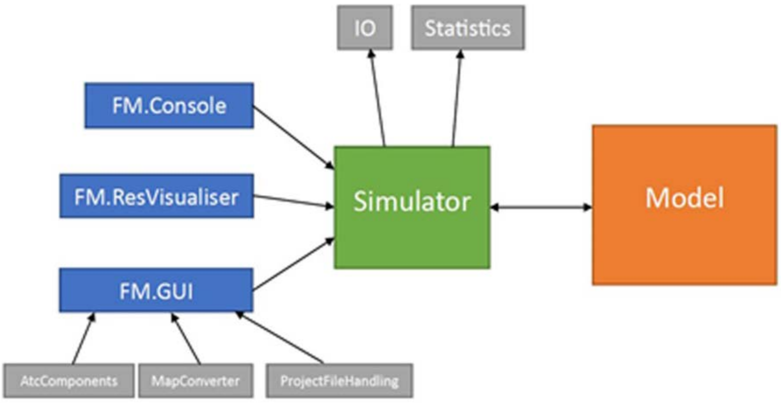

Figure 2 - Main components of the Prioritising Air Traffic Flow Management Tool

5.2 The Flow Management algorithm

The Flow Management algorithm is processed firstly in fixed time periods. This fixed time period is called the Look-Ahead (LA) period, and by default this period is set to 4 hours. The 4 hours period might have to be extended yet, but this is a non-critical issue, and for the applicable ECAC-wide scenario only 0.5% of the flights turned out to have a longer flight duration. A time period of 4 hours is needed to capture most flights that are entirely executed within this period. This is required because “waiting time” is determined per overloaded node, and the waiting time at all nodes, passed by a flight until arrival and determined in the LA period, has to be known before a pre-departure delay can be calculated and before the flight-plan can be adapted to accommodate a constraining delay.

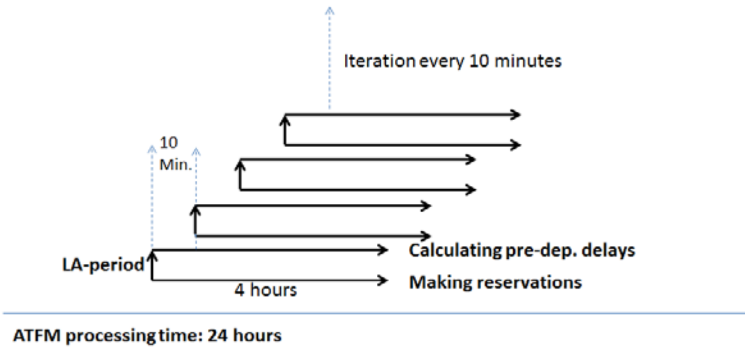

Figure 3 - Main loop of ATFM algorithm by Look Ahead period analysis

This explains also the second main point of processing the algorithm, i.e. each flight is processed twice in the LA period: once to make for each flight passing a network node a node access reservation, and checking the flight status transitions to fulfil these reservations, and secondly to deal with each flight determining the imposed pre-departure delay, including an update of the 4D planning of the flight (See Figure 3).

By default, every 10 minutes a new step is initiated to process a LA period of 4 hours. A 10 minutes period might seem to be a short period, but some tests revealed that larger intervals might lead to a strong increase of instability of planning. The number of flights that change their

status and that are added to the active time period or that leave this period, is sufficiently large to keep the interval time on this default value. This automatically implies a heavy reiterative process for all flights to pass through a process of congestion analysis. Moreover, because each flight is updated immediately after processing the LA period, and because original scheduled flight-plan data as well as updated planning data is analysed, it is possible in a next consecutive processed LA period to recalculate imposed pre-departure delays, or even to cancel them. This last feature turned out to be one of the decisive elements in gaining efficiency in the use of network-wide available capacity.
The setting of the main loop on a 4 hours LA period and a 10 minutes re-iteration interval were evaluated on sensitivity for a large core area network, including Italy and Spain (See experimental results) and the expectation is that for an ECAC-wide network the 10-min. iteration is likely to be sufficient, but the LA period has to become more than 4-hours probably.

5.3 Creating reservations on future capacity

As stated, after every 10 minutes of model time a LA period of 4 hours is initiated. In this LA period no actual flow of traffic takes place, but only reservations are created to pass through a network node. For all flights scheduled to pass a node within this period, reservations will be made. These reservations will be made based on their scheduled arrival times at each node, or in case of assigned pre-departure imposed delays, on appropriately updated arrival times.
The reservations to be made are dependent on, and are determined by, the priority assigned to the entire flight or to the flight at that node. Seven different priority classes, 1 to 7, are possible, with 1 being the highest in the applicable level of priority:

1. Reserved for VIP and/or military flights. Not used in this scenario.
2. Used for flights originating outside of the network. Because they originate from outside Europe, they cannot receive pre-departure delay and are therefore given preference.
3. Departed flights, currently in-flight.
4. Only used to create reservations in the Look-Ahead period for non-constraining flight segments of increased priority flights (see section 5.6).
5. Similar to priority class 4, but for standard priority flights instead of increased priority flights.
6. Increased priority flights.
7. Standard priority flights.

Reservations are made based on absolute priorities. This means that a higher priority flight always gets preference over a lower priority flight. Within the same priority class, flights with an earlier arrival time at the node get preference. At first the algorithm aims to make direct reservations for the same time as the planned arrival time. This will ensure no waiting time at the node. However, in case of congestion, all available capacity reservation places may already hold a reservation at the desired time. In that case the algorithm checks if an existing reservation can be overturned, for example, when it was made for a lower priority flight. If this is possible, the existing reservation is deleted and for the new flight a reservation is made at the arrival time. For the flight whose reservation was overturned, a future reservation will then be made at the earliest possible time. This is also done in case no existing reservations could be overturned for a particular flight of a lower priority.

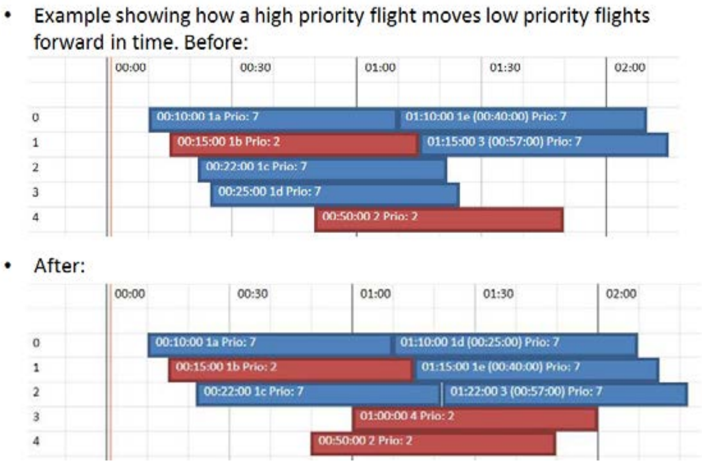

Figure 4 - Example of making a reservation for a prioritised flight during a condition of overload

The strength of this algorithm is that it is always able to make a reservation for a flight, even in periods of heavy congestion. A drawback is that with completely saturated nodes, low priority flights may receive excessive delays in order to prevent a small amount of delay for a high priority flight, leading to gaps of unused capacity between reservations (see Figure 4).

The reservations made in the LA period are used to determine in the next step whether or not a flight can enter once it arrives at a node. This makes it possible to not only swap flights, but also to impose pre-departure delay to flights when capacity is still available.

5.4 The main principle to determine imposed pre-departure delays

This process deals with the second step of processing the LA period, i.e. to determine pre-departure imposed delays. These delays are derived from the node access reservations, made during the first step. Thus, after every Look-Ahead period, it is analysed where each flight can expect the highest waiting time. The expected waiting time at this node, designated as the flight's constraining node, is then imposed as the pre-departure delay. This ensures that the flight arrives at the constraining node at exactly the time for which the reservation could be made, ensuring no waiting time at the constraining node.

Figure 5 shows this main principle. In this example a flight is scheduled to arrive at nodes A, B and C at respectively 09:00, 09:20 and 09:45. In the Look-Ahead period, reservations could be made at respectively 09:05, 09:35 and 09:45. The flight can thus expect 5 minutes of waiting time at node A and 15 minutes of waiting time at node B. Please note that these reservations have been made independently of one another. For this flight, node B is thus designated as the constraining node and 15 minutes of pre-departure delay is imposed. This imposed delay

ensures that the flight arrives at node B at exactly the time the reservation (and thus capacity) is available for the flight, preventing waiting time at node B.
The primary advantage of imposing the pre-departure delays immediately after the end of a Look-Ahead period, is that second-order network effects can be taken into account. During each Look-Ahead period, all future reservations are made completely anew. In this way the effects throughout the network are taken into account. When for example a flight passes a node at a later time due to an imposed pre-departure delay, the gap created in the reservation scheme can possibly be filled up again by another flight, preventing a delay. Therefore the Look-Ahead interval, which has significant impact on overall processing time, preferably should not be increased to more than 10 minutes. With a higher interval, there are less revisions of imposed delay for each flight, resulting in less opportunity to use available capacity optimally.
Flight connectivity is also implemented at this stage. When the option to take into account connectivity between flights is activated in the model, in addition to analysing the maximum expected waiting time for each flight, also the expected reactionary delay is analysed. This is done using the (expected) arrival time of the flight's preceding flight (with the same aircraft) and the minimum turnaround time for that type of aircraft. A simplified model is implemented to represent turnaround times based on assumptions of minimum and maximum scheduled turnaround times for different types of aircraft. Further, flights are coupled based on an heuristic principle. In case a flight's preceding flight is delayed, the flight itself can be reactionary delayed. If the expected reactionary delay is higher than the maximum expected delay, it is imposed as a pre-departure delay to ensure the aircraft is ready at the time of departure. Statistics are tracked separately for both types of delays.

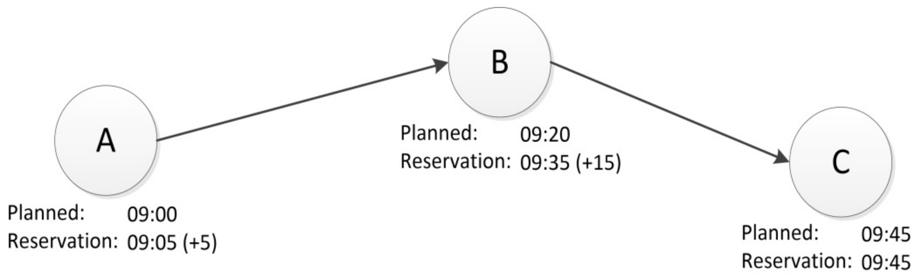

Figure 5 - An example of a node planned to arrive at nodes A, B and C at specified planned arrival times. At nodes A & B the node can expect waiting time due to the reservations being made at a later time than the scheduled arrival time.

5.5 The second principle to determine imposed delays

The node with highest observed "waiting time" determines the imposed pre-departure delay, however, also other nodes may ask for imposing delays. These nodes get a special prioritised treatment now.
In the example of

Figure 5, node B has become the flight's constraining node and 15 minutes of pre-departure delay was imposed. The goal of the imposed delay is to ensure that the flight arrives at the constraining node at the time of the reservation (09:35), preventing waiting time. However, waiting time at nodes A & C can still occur, possibly leading to the flight missing the reservation at node B. Therefore, a second principle was implemented in the algorithm: the priority is increased for a flight's non-constraining nodes. For this principle priority classes 4 and 5 are used. After the delay has been imposed, in future Look-Ahead periods all reservations for non-constraining nodes are made at the updated arrival time (including the imposed delay) and at priority levels 4 or 5 instead of 6 or 7 for respectively increased and standard priority flights. For the constraining nodes reservations are still made at the original priority and the scheduled arrival times. Because the amount of delay imposed on a flight is re-assessed after each Look-Ahead period, this allows delays to change again.
It is important to realise the meaning of expected waiting time for a reservation. In case the reservation was made for priority 6 or 7, the expected waiting time will be used to base the imposed delay on. This waiting time is thus suppressed. If a reservation for a higher priority has an expected waiting time, it will remain waiting time since the flight is either already in-air, or because the reservation is made for a flight's non-constraining node. In the latter case, the flight has already been imposed a delay to a higher expected waiting time at the flight's constraining node. This prevents all waiting time from being suppressed.

5.6 The Petri-Net application by reservations and transitions

The previous sections discussed when node access reservations were made, and how the flow management algorithm would react by calculating imposed pre-departure delays to flights. Now the making of reservations and the applicable transitions to use these reservations in the context of a Petri-Net ATM network strategy are discussed in more detail below.

Petri-net model

A basic Petri-net is a directed bipartite graph consisting of places and transitions, interconnected with directed arcs [14]. A place can contain zero or more objects, called tokens, drawn as black dots. A transition can fire if the required number of tokens is in the input place, moving the token to the output place (see Figure 6). This modelling language is well-suited for modelling air traffic since its power is in modelling objects (flights) moving between places (sectors or airports). The basic Petri-net model is extended to a Coloured Petri-net in order to be able to distinguish between flights. A further extension to a Timed

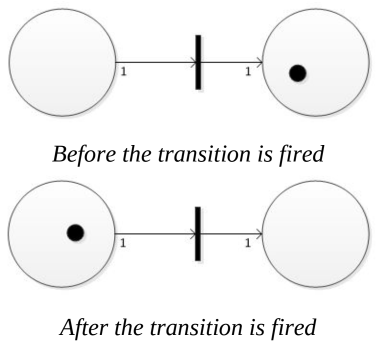

Figure 6 - A simple Petri-net model with two places and a transition

Coloured Petri-net is done to define the time at which a transition is enabled.
N.B. The core Petri-net model as well as the flow management algorithms discussed before are all programmed in the C# language, using Microsoft Visual Studio 2008 as the development environment. Instead of *tokens* directly representing flights and *places* representing nodes, also separate *Node* and *Flight objects* are used for all nodes and flights in the scenario. Each *Flight object* in turn contains *RouteNode objects* that together form the entire route that will be flown. These *RouteNode objects* contain the transit and scheduled arrival times for each element in a flight path.

Tokens and places

Node objects are split into an actual and a virtual part, each having two places. In the actual part, tokens are used to directly represent flights. There is therefore a one-to-one relation-ship between a Flight object and its actual token. When a flight (and its actual token) arrive at a node, the token first enters the ActualQueue. When it is allowed to enter the node (this can be directly or at a later point in time), the token moves to the ActualSector. When leaving (after the transit time for the node has passed), the token moves from the ActualSector to the ActualQueue of the next node along its route.
The virtual part is used to ensure that capacity (measured in flights per hour) is not exceeded. Here each token represents a unit of capacity. The VirtualQueue place represents available capacity, while the VirtualSector place represents used capacity. During the model initialisation, for each node the VirtualQueue is filled with an amount of virtual tokens equal to the node's capacity. When a flight thus enters a node (moving its actual token from the ActualQueue to the ActualSector), simultaneously a virtual token will move from the VirtualQueue to the VirtualSector. Since capacity is measured in flights per hour, exactly one hour after entry the virtual token moves back to the VirtualSector.These virtual tokens can hold reservations on future capacity. In a Look-Ahead period, as described before, reservations can be made on future capacity, making it possible to prioritise. These reservations are made on a virtual token and contain the call sign of the flight for which a reservation is made as well as the time for which the reservation becomes available.

Transitions

Transition objects are used to move tokens from one node's ActualQueue to the next node's ActualSector and to move the virtual token back to the VirtualSector when a flight virtually leaves a node. During the model initialisation, for each flight a start transition is created at its departure time. All transitions are added to a list (sorted by the time of the transition) and executed one by one, thus moving the model forward in time.
For the event in which a flight actually enters the sector, no separate transition object is used. The transition takes place by moving an actual token from the queue to the sector while simultaneously moving a virtual token from the virtual queue to the virtual sector (shown in the grey box in Figure 7). When the transition is fired that moves a flight to the next node, placing it

in the queue, immediately a check is performed to see if the flight can also enter the node. This is the case when not only capacity is available (there is/are token(s) in the virtual queue), but when there is also a reservation available for the flight (a token in the virtual queue holds a reservation for the flight at the current time). If the flight can enter, both the actual and the virtual token that holds the flight's reservation, move to respectively the actual sector and virtual sector. Two new transitions are created at this time and added to the transitions list. The first one is used to move the actual token to the next node once the transit time has passed. The second one is created for one hour into the future and is used to free up capacity again by moving the virtual token back to the VirtualSector.
In case no capacity or no reservation is available for the arriving flight, it will remain in the actual queue. Each time a 'virtual exit' takes place (a token moves back to the virtual queue), again the check is performed to determine if a flight in the actual queue can enter on the virtual token (and its reservation) that has just become available.
By processing the model during the LA period, making the reservations in a correct way, flights are ensured by the transitions as described to pass each node, and to use capacity as required. In the second step, directly following the first one, imposed delays are calculated and flight-plans adapted.

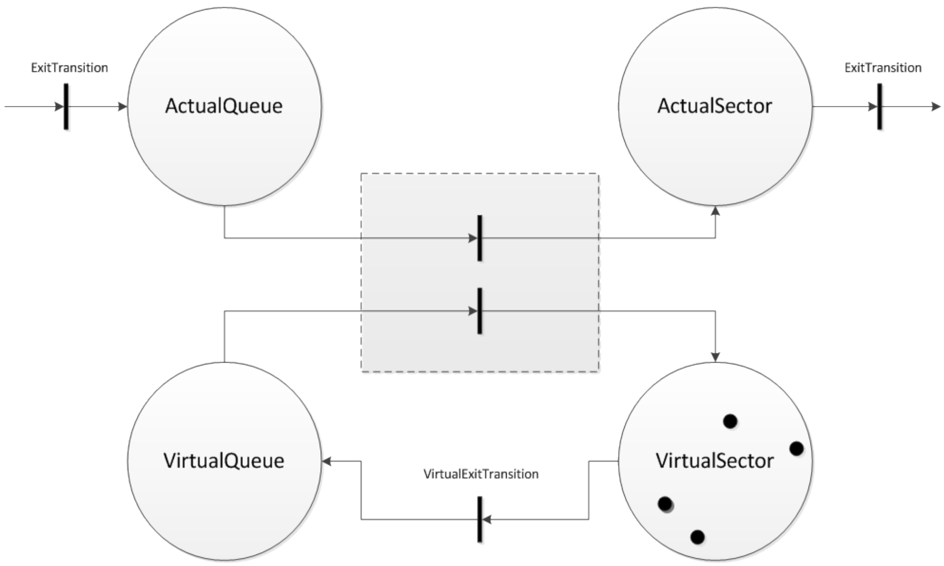

Figure 7 - The complete Petri-net system. In this example the node shown has a capacity of four and is currently completely occupied

6 Experimental Set-up and Scenario

The validation of the revised ATFM Tool was performed on the same scenario as used for previous validation experiments [12]. There are some draw-backs, i.e. the scenario dates from SESAR Definition Phase experiment (2008) and does not even include the new runway used today in Frankfurt. Also, the capacity figures for airports are not reliable, there is some artificial congestion in a few sectors due to simulation-technical reasons, and a small part of the traffic was generated instead of derived from operational flight-plan schedules. This is all irrelevant when performing network analysis only, and comparing different options of optimisation and prioritisation. Moreover, for ease of the experiment only about 70% of ECAC-wide traffic was processed by experimental runs (24.000 instead of 35.000 flights) and only an enlarged core area was considered. The simulated area comprised 15 main airports, 514 other airports and 736 airspace sectors (See Figure 8). Most importantly, the applicable scenario is representative for an ECAC-wide dense traffic scenario.

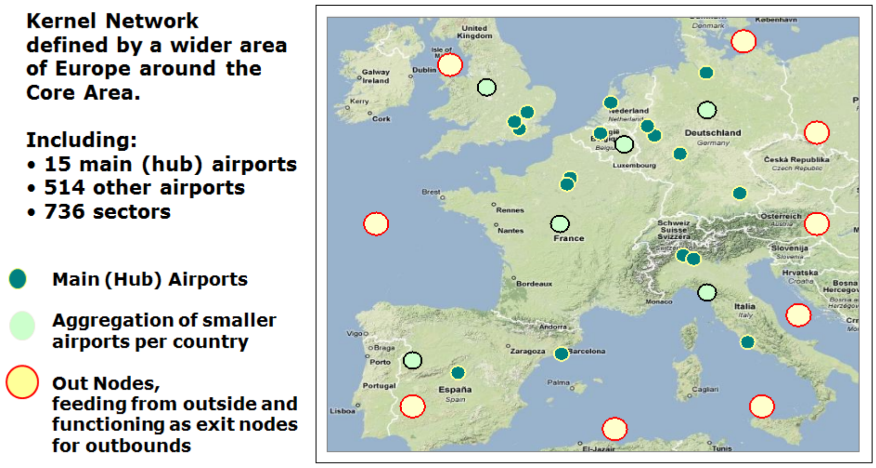

Figure 8 - Experimental scenario, including 15 main airports and 736 sectors

Nevertheless, the consequence of using this scenario is that all results are indicative and will have a relative notion only. Some extra congestion is welcome for network analysis purposes, but does not have any direct operational notion. What is important, however, is to be able to demonstrate the performance capability of the revised tool and the use of prioritisation options in ATM. In addition, the experimental set-up is sufficient to demonstrate the feasibility of the tool for operational applicability in tactical and pre-tactical ATFM before departure (See for an elaborate description of the experiment: van Hout, [13]).

The scenario is processed in two variations, called:

- **Nominal scenario**: Applying all nominal capacity figures applicable to a nominal scenario in almost perfect balance with air traffic demand.
- **Disrupted scenario**: Applying the same scenario, but with 5 airports with an assumed reduced capacity: The capacities of Amsterdam Schiphol Airport (EHAM) and Paris Charles de Gaulle (LFPG) were lowered by 30%, while the capacities of Frankfurt Airport (EDDF, 2008(!)), Munich Airport (EDDM) and London Gatwick Airport (EGKK) were reduced by 20%.

These scenarios were processed using two basic options:

- **OutOnly prioritisation**: This option comes close to a most realistic way to process ATFM FC-FS. Flights from outside the area (entering via Out-nodes) are prioritised, and not delayed, which is operationally most realistic. Though, this comes at a price in terms of some extra “waiting time” and pre-departure delays.
- **MainHigher prioritisation**: The 5 airports with reduced capacity are prioritised regarding the assignment of pre-departure delays, aiming enhanced throughput.

It is good to emphasise some of the critical differences with previous experiments [12]:

- The reference case (OutOnly prioritisation) is strongly optimised compared to the previous version. Also, FC-FS is processed optimally in terms of iteration and selection of imposed delays. The whole network is analysed including airports, the highest congestion events are selected, and full iteration is applicable, cancelling imposed delays whenever possible. It is questionable if this fully matches real operations, but probably better than the non-iterative approach of the first experiment.
- All experimental runs, even the reference case, comprise now already two options of prioritisation (by default), i.e. OutOnly prioritisation to prioritise flights entering the area, and prioritisation on non-constraining nodes avoiding waiting time to remain (described under section 5- Design of the FM Tool).
- The disrupted scenario was executed now with prioritisation of 5 airports, and in the previous experiments with 6 airports, including London Heathrow (EGLL). The reason was that prioritisation of traffic to and from EGLL would reduce imposed delays so effectively at that airport that this would lead to a non-realistic disproportional advantage. With the present version of the tool best results are obtained with 5 airports prioritised instead of 6.

This leads to the following experimental cases for discussion:

- **Nominal scenario, OutOnly prioritisation**: The reference case, assessing the performance of the revised ATFM tool to convert “waiting time” to pre-departure delays under nominal conditions, applying FC-FS.
- **Disrupted scenario, OutOnly prioritisation**: To assess the performance under a moderately disrupted scenario, applying FC-FS.
- **Disrupted scenario, MainHigher prioritisation**: To assess the performance using prioritisation to/from disrupted airports, in addition to default prioritising rules, now also the flows to and from the 5 disrupted airports are prioritised (as described under section V - Design of the FM Tool).

Each case is processed in 3 steps:

1. Assessment of the scenario on network congestion by processing the “waiting time” through the network,
2. Processing the ATFM tool, generating the imposed pre-departure delays, and

3. Assessment on remaining network congestion by processing the modified scheduled flight-plans on network congestion again, confirming the difference in performance.

In addition, some cases are analysed in the context of performance and sensitivity analysis:

- Lost capacity due to prioritisation
- Spread of delays and absolute assignment of priority
- Economic consequences
- Reactionary delays

7 Experimental Results

All experimental runs could be performed without any computational performance problems. The revised algorithm was much more efficient than the first version of the tool, and processing time on a normal PC was brought down from 6 hours to roughly 45 minutes. Most time consuming was the duplication of the full model to initiate a Look Ahead period, and to further speed up the processing performance, this can be performed easily also by a set of parallel processors. Therefore, there is no technical problem to extent validation to ECAC-wide scenarios and/or to adapt the tool settings.

The following cases are described now:

- Nominal scenario, OutOnly prioritisation
- Disrupted scenario, OutOnly prioritisation and MainHigher prioritisation
- Extra cases and Sensitivity analysis

7.1 Nominal scenario, OutOnly prioritisation

Firstly, the "waiting time" for the Nominal scenario through the network was assessed (Table 1). It should be noted that:

- 70 hours "waiting time" was added by giving priority to Out-node flights.
- Remaining congestion of Out-node flights could not be solved by "waiting time" of other flights because there were not enough other flights at that time through a low number of border nodes.
- In the Nominal scenario, almost all congestion is airspace congestion.

Secondly, the imposed delays and the remaining "waiting time" was measured (Table 2). The effect of the ATFM tool is:

- Almost all waiting time is suppressed: from 585.8 hours to 3.5 hours.
- This is achieved by an average delay of 10.9 min. of 637 flights (2.5% of the flights).
- Remaining "waiting time" could be caused e.g. by flights with more than 4 hours flight duration, and by flights with a prioritisation status such as Out-node flights and in-flight operations.

- The spread is rather high due to lack of balancing control on the distribution of imposed delays.

Table 1 - Nominal scenario, OutOnly prio, Original congestion

	Total	At airports	At sectors	Out-node flights
Waiting time [hr]	585.8	46.6	539.2	0.2
Nr. of flights with WT	3366	656	3367	4
Avg. WT per flight [min]	10.4	4.3	9.6	3.5

Table 2 - Nominal scenario, OutOnly prio, Remaining "waiting time" and imposed delays

	Total	At airports	At sectors	Out-node flights
Waiting Time [hr]	3.5	0.5	3.0	0.7
Nr. of flights with WT	39	12	27	11
Pre-departure delays [hr]	637.0	637.0		
Nr. of flights with PD	3514	3514		
Avg. PD per flight [min]	10.9	10.9		
Std. Dev. PD [min]	11.8	11.8		

The conclusion from these results is that for a nominal, balanced, non-saturated, and quite representative scenario, almost all "waiting time" can be transformed in an efficient and effective way to imposed pre-departure delays. Given all constraining conditions on solving overloads, it is not possible to transform without any inefficiency, but a modest amount of extra imposed delay hours were needed (637.0 hours) to neutralise the observed "waiting time" (585.8 hours), i.e. +9%.

7.2 Disrupted scenario, OutOnly prioritisation and MainHigher prioritisation

The second scenario is used to evaluate a manageable level of disruption, in this case by just 5 airports suffering loss of capacity, and with an acceptable decrease of capacity to enable airports to recover.

First, the "waiting time" for the Disrupted scenario through the network was assessed (Table 3). It should be noted that:

- Of course, a large part of the delay is allocated now at the airports, due to lack of capacity at the 5 disrupted airports.
- The total amount of "waiting time" increased due to missing capacity (+105%), as well as the number of flights suffering lack of capacity increased, and thus forced to accept "waiting time" (+61%).

Conclusions from applying the ATFM tool on the disrupted scenario (Table 4), are:

- The "waiting time" is suppressed effectively, even better when applying prioritisation of disrupted airports (+14% hours delay, +2% nr. Of flights).
- The disrupted airports are benefitting from prioritisation by reduced average delays (-16%) and significantly less flights receiving imposed delays (-14%).
- The overall amount of imposed delays is almost equal with and without prioritisation (+1.5%).
- The secondary airports are paying a price by suffering an increase of average delay (+12.5%), but the assumption was that the impact of these delays is less significant than for main airports with high density operations.
- The spread of delays is increasing for all traffic together, and in particular for traffic to/from secondary airports. This is a problem, but it can be mitigated probably by having better control on the distribution of delays (N.B. not yet supported by the present ATFM tool).
- In numbers:
    - 23% of the flights receive imposed delay in this disrupted scenario, of which 8% at the 5 disrupted airports.
    - At disrupted airports, there is benefit of a 27% decrease in imposed delays by applying prioritisation for these airports.

Table 3 - Disrupted scenario, OutOnly prio, Original congestion

	Total	At airports	At main airports	At sec. airports	At sectors	Out-node flights
OutOnly Prioritisation						
Waiting Time [hr]	1202.6	686.7	659.8	25.9	517.06	0.2
Nr. of flights with WT	5449	3440	3255	185	3249	4
Avg. WT per flight [min]	13.2	12.0	12.2	8.4	9.6	3.5

Table 4 - Disrupted scenario, Remaining "waiting time" and imposed delays

	Airports	Main airports	Disrupted airports	Secondary airports	Sectors
OutOnly prioritization					
Waiting time [hr]	1.1	0.9	0.7	0.2	3.4
Imposed PD [hr]	1371.1	778.8	642.0	592.3	
Nr. of flights with PD	5549	3056	2334	2493	
Avg. PD per flight [min]	14.8	15.3	16.5	14.3	
Std. Dev PD [min]	11.4	10.5	10.0	12.4	
MainHigher prioritisation					
Waiting Time [hr]	0.5	0.3	0.1	0.3	2.8
Imposed PD [hr]	1392.3	699.7	467.6	692.3	
Nr. of flights with PD	5564	2987	2014	2577	
Avg. PD per flight [min]	15.0	14.1	13.9	16.1	
Std. Dev PD [min]	14.0	11.4	8.4	16.4	

Figure 9 - Geography of disrupted scenario, comparing OutOnly prioritisation with MainHigher

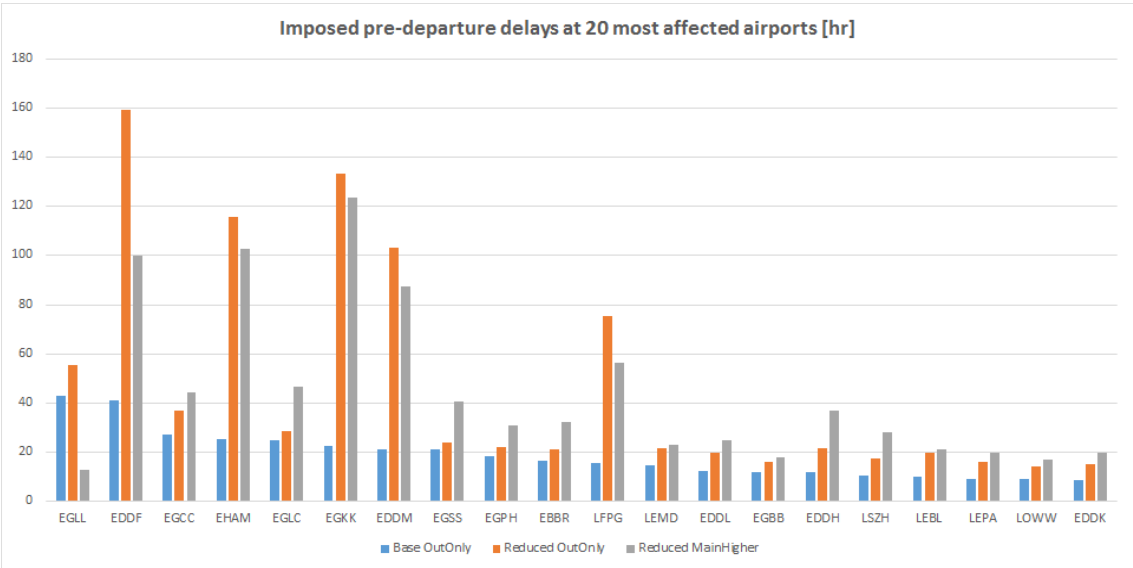

Figure 10 - Histogram 20 most affected airports of disrupted scenario, comparing OutOnly prioritisation with MainHigher

The distribution of delays can be illustrated by a graphical presentation. It is demonstrated by green circles that mainly the 5 disrupted airports are benefitting reduction of imposed delays, whilst several other airports, mainly secondary airports are penalised by increased delays (See Figure 9).
Finally, the impact of prioritisation on the 20 most congested airports is presented by an histogram, comparing the Nominal scenario with the Disrupted scenario, with and without applying prioritisation (See Figure 10). The results are at a first glance less impressive than the results in a previous publication [12], but it should not be ignored that the all-over performance of the ATFM Tool is strongly improved now, also for FC-FS operations. The effectiveness of ATFM performance is much improved now, leaving less capacity to be allocated in favour of prioritised flights. See also the discussion on “gaps” below.

7.3 Extra cases and Sensitivity analysis

The sensitivity analysis deals with:

- Loss of capacity due to prioritisation,
- spread of delays, saturation in case of congested nodes,
- economic consequences, and
- reactionary delays.

Loss of capacity due to prioritisation

The presently implemented algorithm applies prioritisation with absolute priority. This works if it is assumed that small parts of air traffic receive priorities. However, several extra levels of prioritisation were needed to implement all required functionality, working correctly. Prioritisation was applied for arriving traffic outside the area, for in-flight traffic, for secondary nodes of flights receiving imposed delays, and finally, also for priority assigned to flights to/from disrupted airports. Therefore sometimes degradation was observed due to saturation. Altogether, this may easily cause too many constraining conditions when systematically applying prioritisation in overloaded network nodes. There is no balancing mechanism, and in unfavourable cases, this forces gaps in the reservation space when searching for appropriate capacity reservations for each flight. In case of the disruptive scenario, the difference between observed “waiting time” (1202.6 hours) and imposed delays (1371.1 hours) can be interpreted as loss of capacity, and the amount of lost capacity slightly increased by prioritising 5 airports. Moreover, adding more airports being prioritised turned out to even steeply increase the amount of lost capacity (see Figure 11).

One selected way to mitigate this problem was to allow assigned delays to be reduced or even cancelled during iteration. For the disrupted scenario, including prioritisation, pre-departure imposed delays were cancelled again 730 times (6.5%). Though, this was evidently not enough to solve the problem.
Another appropriate mitigation strategy requires to balance loss of capacity against obeying the prioritisation rules, and the result can be managed by optimisation against minimal imposed delays. This is to be implemented yet.

Spread of delays and absolute assignment of priority
The same problem was encountered in a different way by analysing the effects of prioritisation of disrupted airports impacting the performance of secondary airports. Not only a significant amount of imposed delays moved from the disrupted airports to the secondary airports but also the spread of delays increased significantly, reaching a value of 16.1 min average delay with a spread of 16.4 min (see Table 3 and Table 4). This is another indication of potential problems applying prioritisation in highly loaded and saturated sectors. The sensitivity of the problem becomes evident also from the results of the disrupted scenario. With OutOnly prioritisation (FC-FS) only 15 flights received a delay of over an hour, whilst with MainHigher (prioritising the 5 disrupted airports), these figures increased to 68 flights. The more saturated the use of capacity of the node, and the more constraints being applicable, the higher the need to impose extreme pre-departure delays. An example, showing the effect of absolute prioritisation in case of saturation is shown in Figure 11.
Also, this leads to the conclusion that a more balanced way of applying prioritisation is required. From the perspective of fairness and costs, optimisation towards minimal average delay and minimal spread of delay is required.

Figure 11- Example showing difference in allocation of reservations at EDMMUR3, using OutOnly and MainHigher prioritisation

Economic consequences

All benefits of prioritisation are measured up to now in terms of reduction of “waiting time” against penalties in terms of imposed pre-departure delays. However, even if prioritisation may lead to an increase of overall imposed delays, depending on options chosen, there might still be benefits in terms of economic value. In case of the disrupted scenario, the benefits went to main airports, where relatively more wide-body aircraft fly to.

To determine the cost of delay, data from a study by Cook [15] is used. An interesting conclusion of the study was that there is a good fit between maximum take-off weight (MTOW) of an aircraft and the cost of delay. Also, at-the-gate cost figures for 15 minutes of delay for the B737-800 and B747-400 were given. These were respectively €440 and €1230 and also include passenger costs to the airline. To get a cost figure for all other aircraft types, the numbers were used in combination with the two aircraft type's MTOW in order to obtain the following general equation: $\text{Cost}_{15\text{min}} = 2.62 * \text{MTOW} + 233$

Assuming a linear cost function and using the cost per minute data for each aircraft type, the cumulative delay costs were calculated for all aircraft types, although ignoring aircraft with an MTOW of less than 15 tons. Even though prioritising the disrupted airports leads to 1.5% more total delay duration, the total cost of delay has decreased by 3.6% (See Table 5). Also, a non-linear cost function was considered, giving similar results.

Table 5 – The cost of delay for OutOnly (FC-FS) and for MainHigher (prioritisation), using a linear cost function

	OutOnly	MainHigher	Relative change
Total cost	1.94 M€	1.87 M€	-3.6%

Reactionary delays

As described in section 5, Design of the FM Tool, the processing of reactionary delays is supported in the experiment by expanding the scenario with flights connected to each other by heuristic estimates of turnaround scheduling and the applicable linkage of flight-plans. Up to 45% of the flights were connected by estimation, comprising between 50%-70% of the traffic at hub airports. The identified connectivity was judged to be feasible and reasonable (See also van Hout [13]).

Flight connectivity during turnaround was further taken into account during some specific experimental runs when processing “waiting time”, making reservations, and possibly also assigning pre-departure delays. For those runs, reactionary delays were measured and imposed delays were partly attributed to reactionary delays and partly to pre-departure imposed delays, depending on a calculated aircraft-ready status. In case of reactionary delays, the pre-departure delays due to congestion are expected to be partly covered now by the reactionary delays (See Figure 12). It should be noted further that the applicable slack times were derived from the flight scheduling, and these turned out to be dependent not only on aircraft type but also on airport size (see Table 6). As can be seen, much tighter connections are made at secondary airports.

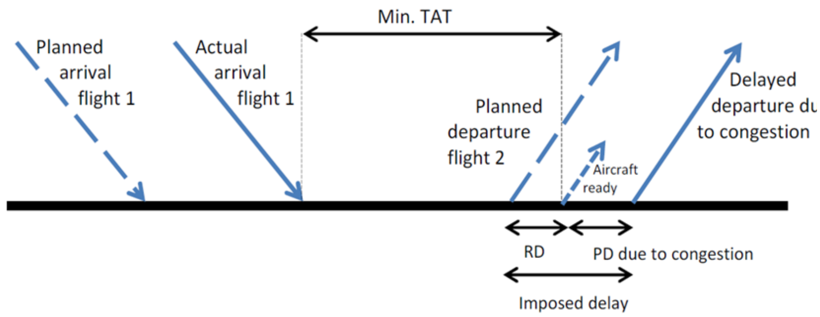

Figure 12 - Attribution of delays in case of re-planning of departures due to reactionary delays as well as imposed pre-departure delays

Table 6 – Average turnaround slack times derived from flight scheduling

	Top 15 airports	Top 5 airports	Sec. airports
Average slack time [min]	65.7	69.1	49.9

The experimental runs on reactionary delays gave relative small effects on the overall amount of imposed delays. For three measured scenarios extra reactionary delays of not more than 36 to 68 extra hours delay were measured (4%-5%). The impact on measured “waiting time” and imposed pre-departure delays was quite small, caused partly by the rather long slack times at the main airports, including the 5 disrupted airports. In fact, these slack times are quite large compared to the average imposed delay times, and these delay times are limited for the processed scenarios (See Table 2 and Table 4). The evident reason is that the amount of assumed disruption of the disrupted scenario had to be rather small, i.e. the model is not robust enough yet to process scenarios with higher levels of disruption or more disrupted airports.
One special experimental run was processed, prioritising just those flights suffering from reactionary delays. The prioritisation could reduce about 50% of the measured reactionary delays but at a price of additional imposed pre-departure delays. It was concluded that the net benefits of this mode of prioritisation were negative. However, this might be different for more

severe levels of disruption and a better method to deal with the balance between capacity needs of flights with high prioritisation rights, and flights with lower rights.

8 Future Research

The present research has shown that large-scale (ECAC-wide) Flow Management is feasible, using balanced decision making and applying optimisation and prioritisation. Nevertheless, improvement is still possible regarding the featuring of the tool and its validation:

- The present ATFM Tool is still applying prioritisation in an absolute way. This becomes risky for the performance when congested nodes tend to get saturated. A weighted delay assignment strategy would improve the quality and robustness of its performance of ATM regulations.
- There is no control on outliers at present (control on standard deviation of imposed delays), and it would provide better means to control the performance of prioritising ATFM by applying weighted optimisation (using MILP).
- When the tool is featured to apply weighted optimisation, also more dramatic disruption scenarios could be investigated, e.g. by including a saturated airport like London Heathrow (EGLL) in the list of capacity-reduced airports.

In summary, future research should address improvement of the tool by weighted optimisation and a more elaborate validation of its performance, i.e. by validation on ECAC-wide 24-hours scenarios and by more variation of applicable scenarios in traffic density and disruption of capacity.
Weighted optimisation will result in a balanced decision making, e.g. by applying MILP, to create reservations in the local context instead of the absolute algorithm currently used, and this requires the exploration and validation of extra parameters determining the weights of different elements of a cost function.

9 Conclusions

Flow Management originally just managed overloads in airspace sectors, based on a FC-FS strategy derived from flight plan information, and imposing pre-departure delays to mitigate congestion and to preserve safety. A first requirement to improve that strategy is to be able to select flights and to make choices in decision making. An efficient method was to consider groups of flights in their local context of space and time, and secondly to process the whole ATM network, including airports, to mitigate network congestion. This was sufficient in first instance to demonstrate that prioritisation could be used to deploy network capacity in a more

capacity-efficient way than by a FC-FS strategy, taking into account the impact of departure penalties on network throughput. Also, optimisation within a local context of space and time was possible now.
In this publication, a prototype of an enhanced ATFM Tool is presented that has performance capabilities that goes far beyond this original aim:

- The revised tool has still the aim to operate in a local context of space and time, and to be efficient in this way in performance, and moreover, to be transparent and traceable also in selecting and imposing pre-departure imposed delays.
- The tool operates in a fully iterative way now, being able to convert most of the detected network "waiting time" into pre-departure imposed delay, and to manage under balanced conditions, that the amount of imposed delays is not much higher than the measured "waiting time". This criterion counts as a measure of efficiency of the tool.
- The tool can select the most penalising node in a flight, can protect secondary nodes against double penalties, and can also release penalised flights by cancelling imposed delays. This helps to reach maximum achievable efficiency.
- The tool has a node access reservation feature that has been applied already in variety of ways to allocate prioritised access rights. Other options are possible and will have to be investigated yet.
- The prioritisation method is implemented as an absolute priority principle taking into account the impact of constraining imposed delays on external conditions, such as e.g. congestion at departure or destination airports, or on economic impact such as cost of flight. This works at this stage of development of the tool for moderate levels of disruption.
- The method of regulation by different classes of prioritisation allows for performance monitoring and post-processing analysis, supporting the transparency of operations.

The limitations on the present implementation of the ATFM Tool are:

- The validation was performed on a one-day traffic sample only in two variations: a nominal and a disrupted scenario. A more extensive validation process on some recent ECAC-wide 24-hours scenarios is required.
- The most constraining feature of the tool was the absolute mode to apply prioritisation. This makes it impossible to control the spread of imposed delays, and allowing thus assignment of extreme delays. This can be solved by replacing the absolute strategy by a balanced weighted optimisation strategy, taking into account minimum spread of delays. However, this asks for tuning and also agreement on sets of parameters to control the process of balanced optimisation.
- A more systematic way to analyse prioritisation principles might be needed. For example, it is difficult to overview the added economic value of prioritised flights against other

penalised delayed flights. These prioritisation classes always operate indirectly in support of their presumable benefits on operations of the ATM network elsewhere. Monitoring and analysing of these benefits is needed.

- The present ATFM tool operates on improving the performance of network throughput. It is still necessary to validate that the resulting revised scheduling provides the expected benefits in real-life operations, indeed. The first step is to validate these benefits by fast-time simulation, simulating real-life operational conditions.

Enhanced flow management can be accomplished by replacing FC-FS ATFM by optimising and prioritising ATFM. Several prioritising options are possible, such as prioritising flights to/from disrupted airports, prioritising flights suffering reactionary delays, prioritising flights with high economic value, and other options. The assumption is that some form of prioritisation may provide benefits, whilst the enhanced ATFM Tool is able to balance and to protect the exclusiveness of prioritisation against possible negative impact on the overall performance of the ATM network. In other words, this yields not only demand and capacity balancing, but even balancing the prioritisation.

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