Optimizing and Prioritizing Air Traffic Flow Management in a European Scenario

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EXECUTIVE SUMMARY

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Assigned pre-departure delays
Difference between OutOnly prioritisation and optimised prioritisation
Reduced¹ scenario

Total assigned pre-departure delays at 15 most affected airports
Reduced¹ scenario

Problem area

Air Traffic Flow Management (ATFM) aims to prevent local demand-capacity imbalances of planned air traffic by adjusting flows of flights on a national or regional basis. The goal is to regulate flows through the Air Traffic Management (ATM) network in such a way that overloads are prevented.

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Besides this, the aim of ATFM is to maximize the throughput through the network, or more precisely formulated: "The aims of ATFM are to use the existing airspace, Air Traffic Control (ATC) and airport capacity in a safe and efficient way, and to provide aircraft operators with timely, accurate information for planning and execution of an economical air transport, as close as possible to foreseen flight intention and without discrimination." (Ref. Philipp & Gainche).

Congestion by temporarily overloads of sectors and/or airports is solved in Europe by the Network Management Operations Centre (NMOC) in Brussels, the former Central Flow Management Unit (CFMU), by applying ATFM on a First-Come First-Served basis (FCFS). Their principle of operations may solve an overload at a specific node of the ATM network, but it does not allow controlling the distribution of delay assignment and it does not take into account traffic conditions elsewhere in the network.

Optimization and prioritization add value compared to FCFS. Therefore, NLR (National Aerospace Laboratory of the Netherlands) and TUD (The Technical University of Delft) have developed a prototype of an optimizing and prioritizing advanced ATFM tool. This tool applies optimization aiming for efficient regulations and controlling the distribution and assignment of pre-departure imposed delays at the same time. Prioritization is added as a relative weight factor during optimization. Prioritization may serve several objectives each with the purpose to add weight to a flight representing its specific condition regarding either network throughput or economic value.

The advanced ATFM tool, being a prototype in support of tactical ATFM operations in Europe, must demonstrate high computational performance, must be robust for varying scenarios and must be able to cope with changing conditions of capacity and demand.

Description of work

Improvement of First-Come First-Served (FCFS) ATFM was identified as solving a logistic problem: How to make best use of available resources given the demand? An advanced optimizing and prioritizing ATFM tool was developed ensuring:

1) Safety by respecting capacity constraints,
2) Cost-efficiency and punctuality by optimized use of capacity and minimized delays,
3) Optimization and fairness by control on average delay and spread of delay,
4) Support of prioritization to classes of flights or individual flights,
5) Support of high computational performance levels, and
6) Supporting the comparison and validation of different options for advanced ATFM.

The ATFM toolset, being developed, supports:

1) ECAC-wide fast-time runway-to-runway simulations enabling the validation of enhanced performance levels as the result of applying advanced ATFM options,
2) ATM network throughput analysis capability assessing the actual balance of the ATM network in space and time before and after applying FCFS ATFM or optimizing and/or prioritizing options for advanced ATFM, and
3) The ATFM prototype tool, supporting several options of optimizing and/or

4) prioritizing ATFM in addition to the more traditional option of FCFS ATFM.

Advanced optimizing and prioritizing ATFM was implemented as follows:

1) Network optimization is accomplished by a highly frequent, iterative and convergent process of re-planning the assignments of pre-departure delays throughout the network. Petri-net technology was applicable to evaluate the minimized required assignments of pre-departure delays to flights.
2) Optimization, using Mixed Integer Linear Programming (MILP) was applicable to select the most optimal distribution of slot reservations through an overloaded node during an applicable 4 hours look-ahead period. Optimization was focused on minimal average delay and spread of delay, and possibly respecting also differences in prioritization of planned flights.
3) Prioritization was implemented to honour differences in the attributed priority to flights. Flights could receive priority by being part of a class of flights, e.g. to a capacity disrupted airport, or by getting priority assigned at an individual basis, i.e. selected by the Airline Operator.

After prototype development validation had to be conducted on a large scenario, by preference an ECAC-wide scenario (around 35.000 flights). However, most of the validation experiments on optimizing and prioritizing ATFM, made use of a reduced scenario (still 25.000 flights), but large enough to experience and to mitigate airport congestion, sector congestion and coherent overload problems at several airports and sectors. The relevant experimental results were focused on:

1) **Fast-time simulation**: Some limited results of ECAC-wide simulations gave indications how to use fast-time simulation in overall validation experiments.
2) **Optimizing ATFM compared to FCFS**: The result of optimized distributing and minimizing FCFS imposed delays, executed on a disrupted scenario, was compared with straightforward FCFS as applicable at present.
3) **Optimizing and Prioritizing ATFM**: The result was assessed of prioritizing all flights from and to a set of disrupted airports and optimizing the assignment of imposed delays of all flights through overloaded nodes of the ATM network.

The present publication gives a summary of work and results of the last ten years.

Results and conclusions

NLR and TUD developed a toolset for optimizing and prioritizing flow management (ATFM) because the presently used method for regulation is not able to take into account any effect of delay beyond the context of the overloaded and regulated sector. There is evidence that FCFS regulations are less than optimal. Moreover, there was a strong wish by airspace users to get more control over management and planning of their flight operations.

The optimizing and prioritizing ATFM tool is able to facilitate prioritization, and this enables either to manage disruption, for example at airport level, in a better way, or it allows airspace users to designate some of their flights to receive priority in applicable regulations. Optimization improves the distribution of delays to flights.

The validation work by NLR and TUD demonstrated that:

- The tool is robust and operational at the level of operating a prototype ATFM tool.
- Prioritization works appropriately and can be fine-tuned to operate in fair balance with overall efficiency.
- Optimization is appropriate to manage and control the average delay as well as the spread of delay, and this is a good method to minimize delays and penalties under (moderately) disruptive conditions.
- Optimization is able, in particular, to suppress the highest imposed pre-departure delays, ensuring a better and more fair distribution of delays over the penalized flights.

The validation is far from completed, and also a more operationally focused validation might be beneficial to give more confidence in the applicability of advanced options for ATFM and to bring the tools to a higher level of maturity. Fast-time simulation is required to assess the real operational benefits of advanced options for ATFM under flight-executive conditions.

Applicability

The development of a prototype of an optimizing and prioritizing ATFM tool was successful in demonstrating feasibility of optimizing ATFM on a very large scenario, whilst reaching convergent results against acceptable computational performance levels.

The result is a powerful, robust, fast and versatile tool that can be used to analyse different methods of prioritization in flow management. The tool thus provides a solid basis for future research, enabling more extensive validation of ECAC-wide scenarios, and possibly leading to a suitable tool for operational use.

Therefore, the recommendations for future work are to validate the ATFM toolset on an operational up-to-date ECAC-wide scenario, and to evaluate in more detail the direct and indirect economic benefits of deployment of optimizing and prioritizing ATFM. It is important to combine the validation of options for optimizing and prioritizing ATFM with fast-time simulation experiments on regulated and non-regulated scenarios, assessing in this way the cost-effectiveness of advanced ATFM

Optimizing and Prioritizing Air Traffic Flow Management in a European Scenario

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Summary

Optimizing and Prioritizing Air Traffic Flow Management in a European Scenario

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NLR (National Aeronautics Laboratory of the Netherlands) and TUD (The Technical University of Delft) have developed a prototype of an optimizing and prioritizing advanced Air Traffic Flow Management (ATFM) tool. The current practice of ATFM mitigates congestion by issuing slots (CTOTs) following a First-Come First-Served (FCFS) delay assignment principle. This may solve an overload at a specific node of the Air Traffic Management (ATM) network, but it does not allow controlling the distribution of delay assignment and it does not take into account traffic conditions elsewhere in the network.

Optimization and prioritization add value compared to FCFS. The ATFM toolset applies optimization aiming for efficient regulations and, at the same time, controlling the distribution and assignment of pre-departure imposed delays. This is accomplished by optimizing towards a weighted minimum of average delay and spread of delay per network node. Delay assignment per flight is accomplished by selecting the most penalized node of a flight along its flightpath. Prioritization is added as a relative weight factor during optimization. Prioritization may serve several objectives each with the purpose to add weight to a flight representing its specific condition regarding either network throughput or economic value. An example of prioritizing network throughput is to prioritize all flights to and from a disrupted airport with the aim to avoid penalizing an airport already struggling with capacity problems, and an example of priority by economic value is allowing Airline Operators to prioritise specific flights at a specific cost. They will receive priority but balanced against the performance of the ATM network.

 The tool to process imposed delays is ready as a prototype and is used for a number of validation exercises all running basically on one scenario. The applicable scenario is a European enlarged Core Area scenario of around 25.000 flights in 24 hours.

The tool turns out to be robust under varying operational conditions and varying levels of disruption. To evaluate operational benefits, the ATFM results have to be processed on simulated operations, simulating the scenario in fast-time, and evaluating the impact of regulations on queuing and workload. This article describes the present status of research, mainly focused on the prototype of the ATFM tool, and future work, focused on fast-time simulation and validation. Also some early results of validated operational benefits are presented.

Content

Abbreviations

Acronym	Description
AFP	Airspace Flow Program (FAA)
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
CASA	Computer Assisted Slot Allocation
CDM	Cooperative Decision Making
CFMU	Central Flow Management Unit (EUROCONTROL)
CTOT	Calculated Take-Off Time
DRAP	Dynamic Research Allocation Program
ECAC	European Civil Aviation Conference
FAA	Federal Aviation Authorities (USA)
FCFS	First-Come First-Served
FPPR	First Plan Penalising Regulation principle
GDP	Ground Delay Program (FAA)
ICAO	International Civil Aviation Organization
MILP	Mixed Integer Linear Programming
NAM	Network Analysis Model
NLR	National Aerospace Laboratory of the Netherlands
NMOC	Network Management Operations Centre (EUROCONTROL)
RBS	Ration By Scheduling
SESAR	Single European Sky ATM Research program (EU)
TMA	Terminal Maneuvering Area
TUD	The Technical University of Delft
UDPP	User Driven Prioritisation Process (SESAR)

1   Introduction

Congestion by temporarily overloads of sectors and/or airports is solved in Europe by the Network Management Operations Centre (NMOC) in Brussels, the former Central Flow Management Unit (CFMU), by applying Air Traffic Flow Management (ATFM) on a First-Come First-Served basis (FCFS). The CFMU started its operations in 1994, led by EUROCONTROL in Brussels. Its mission was to manage flows of air traffic through the ATM network, and amongst others avoiding overloads in the late tactical phase of flow management by issuing pre-departure slots, Calculated Take-Off Times (CTOTs). Re-routing is in this context rarely applicable as a measure taken by NMOC because the overloads will be solved in terms of delays against calculated minimal costs, whilst the costs of re-routing can be calculated by the Airline Operator only. If applicable, this will ask for specific coordination.

The present practice of First-Come First-Served (FCFS) ATFM can be improved. NLR and TUD are developing a prototype of an ATFM toolset that will offer added value in terms of flight economy, control on the performance of air traffic flows through the ATM network and, in some cases, enhanced interoperability to airspace users. This is achieved by offering options to give priority to flights being part of a flow management regulation. For example, a specific category of flights is prioritized, such as all flights flying from and to one or more disrupted airports, e.g. suffering loss of runway capacity. In that case, no individual intervention per flight is needed, however, prioritization of individual flights at a certain cost is also possible. Airline Operators may select prioritization of certain flights and this will help them to protect their most costly and/or time-critical flights against imposed delays.

The ATFM tool performs also an optimization process, evaluating all possible imposed delays through all congested and overloaded nodes of the ATM network. Optimization per node is accomplished using Mixed Integer Linear Programming (MILP). This process performs optimization against an objective function optimizing towards minimal average delay and minimal spread of delays (avoiding excessive delays). Moreover, the prioritization is taken into account by increased weight factors for prioritized flights. Furthermore, the impact of congestion on performance of the ATM network is taken into account by iteration. Test results demonstrate that the algorithm works efficiently and beneficial, making most efficient use of the capacity available in the ATM network.

The tool to calculate imposed delays is ready as a prototype and has been used in several validation experiments. The applicable scenario is a European enlarged Core Area scenario of around 25.000 flights (UK, France, Germany, BENELUX, Switzerland, Spain and Italy), more than 700 sectors, and more than 500 airports, of which 15 can be considered as major airports. The

tool turns out to be robust under varying operational conditions, varying the available capacity of some airports of the scenario (See Figure 1).
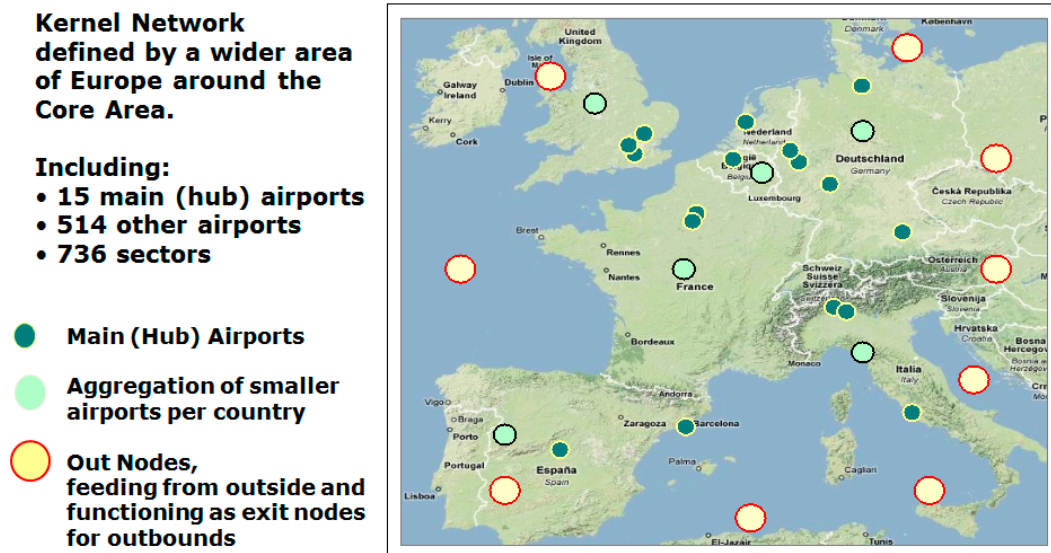

Kernel Network defined by a wider area of Europe around the Core Area.

Including:
- 15 main (hub) airports
- 514 other airports
- 736 sectors

● Main (Hub) Airports

● Aggregation of smaller airports per country

⊙ Out Nodes, feeding from outside and functioning as exit nodes for outbounds

Figure 1: Experimental scenario, the larger European core area (UK, France, Germany, BENELUX, Switzerland, Spain and Italy)

There are some major limitations in evaluating and validating the ATFM Prioritization and Optimization tool. This relates to the operational performance of flights under imposed restrictions as well as the related economic costs and the impact of delay on operations of airports and airline operators. The tool calculates imposed delays, based on demand and declared capacity of sectors and airports of the ATM network. However, at the level of flow management as applicable in this research, planning and execution of departure and in-flight operations are unmanaged. These operations have to be simulated separately. The real benefits of ATFM can be assessed in a more elaborate way by coupling the processing of the optimizing and prioritizing ATFM tool to runway-to-runway fast-time simulations at a European scale. There is some experience with this type of simulations already but more validation work has to be done yet. This article describes the present status, mainly focused on the prototype of the ATFM tool, and, future work, mainly focused on fast-time simulation and validation.

A.   Statement of problem

Congestion in the ATM network occurs by overloads of sector and/or airport nodes of this network. The overloads are detected by monitoring the detailed flight planning, in the best case, a 4D planning at the long-term (strategic), or short-term at the day of operation (tactical), and by comparing the demand with available capacity (declared sector or airport capacity). Once an

overloaded node is designated for regulations, overloads are solved by issuing slots, Calculated Take-Off Times (CTOTs), imposing pre-departure delays. Flights through more than one regulated node receive the highest calculated delay along their planned flightpath, solving the overload at the most constraining node. This delay assignment method follows a FCFS principle, identified as a First Plan Penalising Regulation principle (FPPR).

The FPPR principle is straightforward and fair, and benefits the safety of operations, however, there are serious problems with the method in terms of costs and efficiency:

1) The delay assignment, not optimal at the overloaded node, might induce inefficiency in use of available capacity.

2) The delay assignment does not take into account any constraining condition or any other possibly negative impact on use of capacity resources along the planned flightpath.

3) The delay assignment does not take into account any induced cost impact or any other economic side effect; the criticality of imposed delays on airport and airlines operations is ignored.

4) The delay assignment has no control on average delay or spread of delays, and as such, there is no attempt to minimize overall negative costs and penalties due to loss of capacity e.g. by disruption.

A technical problem of finding a solution for the negative effects of a FCFS solving strategy is that any form of optimization and prioritization requires an enlarged scope of analysis of congestion problems. Because imposed pre-departure delays impact the whole flight, the solution strategy requires preferably an ATM-network broad scope. Moreover, the strategy has a significant impact on the performance of airline network operations, including turnaround.

B.   Literature

According to Bertsimas, (Ref. 1), ATFM aims to prevent local demand-capacity imbalances by adjusting flows of aircraft on a national or regional basis. The goal is to regulate flows through the network in such a way that overloads are prevented. Besides this, the aim of ATFM is to maximize the throughput through the ATM network. A complete definition of ATFM is given by Philipp & Gainche (Ref. 2), which declares: *"The aims of ATFM are to use the existing airspace, Air Traffic Control (ATC) and airport capacity in a safe and efficient way, and to provide aircraft operators with timely, accurate information for planning and execution of an economical air transport, as close as possible to foreseen flight intention and without discrimination."*

How to implement a feasible operational system for ATFM depends on local conditions as well as stakeholder agreements on ATM management and control issues. Regarding this, the differences

between operations in the USA and Europe are remarkable. In the USA, the focus is on flow management solving specific bottlenecks, either overloaded airports or congested and disrupted airspace areas. The programs to solve these problems are identified as the Ground Delay Program (GDP) and the Airspace Flow Program (AFP). Specific methods are developed allowing prioritization regarding delayed flights, such as precedence Ration By Scheduling (RBS) and exemption RBS, but both methods may lead to inefficient use of airspace capacities. It may occur according to Barnhart (Ref. 3), that regulations at overloaded sectors are ignored. The methods applicable to both programs belong to the research paths identified as "single" resource problems, whilst the European approach for ATFM has to be addressed as a "multiple resource problem", addressing the entire ATM network. See also van Hout (Ref. 4).

Besides capacity constraints at airports, the European network has to deal with capacity constraints at the en-route airspace sectors as well. According to Lulli & Odoni, (Ref. 5): *"Air traffic flow management in Europe has to deal as much with capacity constraints in en-route airspace as with the more usual capacity constraints at airports."* The authors describe the European ATFM problem as follows: *"Given an airspace, consisting of a set of airports, airways, and sectors, each with its own capacity for each time period, t, over a time horizon of T periods, and given a schedule of flights through the airspace system during T, assign ground and airborne delays to the flights in a way that satisfies all the capacity constraints while minimizing a function of the cost of the total delay assigned."* A complete problem definition is given which also comprises the assessment of airborne delays. Moreover, the aim should be to minimize total cost of delay. Finally, the authors want to address the complexity of finding a balance between the objectives of efficiency (minimizing cost of delay) and equity (making sure that there is no bias against certain flights, airlines or origin/destination pairs). In this way a principle is formulated aiming to support the research of present-day ATFM in Europe for a more advanced mode of operations, compliant with some of the ambitions of the Single European Sky ATM Research (SESAR) program.

One attempt to improve ATFM operations in Europe is made by Duong et al. (Ref. 6) by introducing Absorption Areas to find a solution for the limitations of the CASA algorithm (Computer Assisted Slot Allocation), applicable at present by NMOC. CASA searches in flight plan information to identify the sectors in which demand exceeds capacity. Then, demand-capacity balancing regulations are activated. All flights that enter the regulated sectors are listed and the CASA algorithm sequences them in the order they would have arrived considering the original flight scheme, a FCFS principle. From the computed flight sequence, the CTOT is computed for each flight. In this way, each flight gets assigned a -5 to +10 minutes departure slot, and should

adhere to it. In the paper of Duong et al., the notion "alea" is introduced. Events that cause a disruption of the planning are identified as operational aleas, and examples of such aleas are bad weather conditions or unexpected technical failures. To solve these so-called aleas of planned flights, the authors introduce Absorption Areas: *"An absorption area is a number of slots left unfilled during the slot allocation process, allowing the absorption of such disturbances with least modification of the planning."* The present research by NLR and TUD aims to develop a mechanism with similar objectives as proposed, but including other features such as prioritization and optimization. The difference is that disruption is mitigated by creating gaps in their approach, whilst gaps are managed as efficiently as possible and minimised in our approach.

The problem of resource allocation as addressed by ATFM is also discussed in a publication by Bertsimas et al., (Ref. 7). According to this paper, the characteristic elements of a so-called general Dynamic Resource Allocation Problem (DRAP), are: *"a set of resources R and a set of requests I belonging to a set of owners O that need to be processed by these resources over a time horizon T. Each request i needs to be completed by a certain time and it can be completed by using alternative sets of resources. Different allocations of resources to requests over time result in delays if the request is completed after its desired time. The overall goal is to allocate resources to requests over time in order to complete the requests as efficiently as possible (minimum delay), potentially using alternative resources and ensuring that the distribution of delays amongst these request (and implicitly their owners) is fair."* Scheduling constraints are used to complete the definition of the problem to be solved. The constraints are forcing the scheduled requests and ensure that the capacity of the resources is not overloaded. In this paper, the authors show that their model is flexible because it can handle different object functions, different resources and different notions of fairness.

The paper of Barnhart et al. (Ref. 3), offers an integer programming method dealing with multiple resource ATFM problems, and addressing the principle of fairness. Because of the multiple resource problem, a trade-off is needed between the original schedule order and the total system delay. Five measures of fairness for a multiple resource problem are defined:

1) Fairness should be measured with respect to the original schedule order.
2) Fairness measure should be applicable to a single flight as well as the overall schedule.
3) Deviation from fairness should be consistent between resources.
4) No flight should expect to receive less delay than what would be caused by the most congested resource along its route.
5) Measure of flight's deviation from original schedule should be calculated relative to the total delay assigned to the flight.

From this, a metric is defined that can evaluate fairness. Their implementation is applicable to a US context with several GDP's and AFP's.

Special requirements on ATFM solutions are formulated by SESAR (Ref. 8). On the one hand, SESAR formulates in its operational concept (Ref. 9), the principle that the economic value of a flight should prevail over a FCFS-principle, which allows solutions prioritizing flights or flows if it is beneficial to the economy of operations, on the other hand SESAR formulates a concept of a User Driven Prioritisation Process (UDPP). UDPP is defined as *"a process during periods of reduced capacity in which the service provider declares the available capacity, and users, interacting collaboratively and collectively with the provider, propose specific flights to fill it."* (Ref. 8). UDPP enables airlines to be involved in the decision making process during a period of reduced capacity. The NMOC will come up with an initial order of flights during the ATFM regulation. As a reaction on this, airlines may communicate their preferred order to the NMOC. This enables the airlines to give certain flights priority and increase their net profit.

The present publication aims at presenting a toolset that addresses the ATFM problem in the European context offering capabilities to be applicable on ECAC-wide (European Civil Aviation Conference) scenarios, and satisfying the essential requirements of referenced literature, described above. Specifically, the prioritisation and the optimisation of ATFM measures are addressed, whilst options to apply UDPP are possible although in balance with the overall performance of the ATM network.

C.   Research question

The problems with a FCFS-principle are solving a logistic problem: How to make best use of available resources given the demand? Due to the wide impact of departure planning constraints on ATM network operations, airport and airline operations, the next question is how to find an optimizing model maintaining a sufficient broad scope, but yet feasible to be processed while respecting stakeholder's ownership? In a highly competitive world, balancing access to resources should be fair and transparent in terms of operational performance and penalties, whilst control on flight planning and free access to resources should be respected as much as possible.

The intent of this research is to demonstrate feasibility by development of a prototype of an advanced flow management tool. Its most principal requirements are that the tool ensures:

1) safety by respecting capacity constraints at sector and airport level,

2) cost-efficiency and punctuality by finding an optimum in use of available capacity, while minimizing delays,

3) ATFM optimization and fairness by control on minimum average delay as well as control on minimum spread of delay,

4) flight prioritization, either by specific individual flights and/or by a category of flights, such as flights to and from airports suffering disruption and thus degraded capacity,

5) That the toolset shall be capable to process different scenarios with different levels of degraded capacity and to validate the operational and computational performance of advanced ATFM, and

6) That the toolset shall be capable to compare the validation results of implementation of different advanced ATFM features.

N.B. Flight prioritization is not fair as such, but the application might be considered as fair as long as the conditions for prioritization are agreed amongst stakeholders and as far as the costs for prioritization are in balance with the benefits received.

The present research is focused on finding answers for the required coherence of operations in time and space, finding proper quantities to identify congestion, the quality of a solution, and the performance of planned operations. The measure of operational performance is related in first instance to capacity and throughput, but has to be measured ultimately in terms of economy.

2 Concept, Design and Implementation

In response to the research question, NLR and TUD have developed a prototype of an ATFM toolset. In support of long-term improvement of European ATM network operations, this will offer added value in terms of flight economy, control on the performance of air traffic flows through the ATM network and, in some cases, enhanced interoperability to airspace users. This is achieved by flow optimization and by offering options to give priority to selected flights participating in a flow management regulation. It is possible to use prioritization on the one hand to prioritize categories of flights, e.g. all flights flying from and to a disrupted airport, suffering loss of capacity. In that case, all concerned flights are selected and there is no need for individual intervention.

On the other hand, it is possible also allowing prioritization of individual flights at a certain cost. Airline Operators may be permitted to select flights and to assign ATFM-priority to these flights. This will help Airline Operators to protect their most costly and/or time-critical flights against imposed delays. Further, the toolset is intended in the first place to support flow management during the tactical phase of planning, requiring high computational performance capabilities, and short-term response on changes in planning. The toolset supports:

1) ECAC-wide fast-time simulation
2) Throughput analysis capability (the Network Analysis Model: NAM)
3) The ATFM prototype tool, supporting optimizing and prioritising ATFM

Flow Management in Europe operates on ECAC-wide air traffic, and there is coherence in traffic over a period of 24 hours. Flights arriving from destination airports outside the ECAC area are not flow managed, and the same holds for in-flight traffic. Flow management takes place before departure.

All flights in a scenario are planned by International Civil Aviation Organization (ICAO) flightplans, and in line with SESAR, availability of 4D flight planning is assumed. The validation experiments are processed without including any submitted change of flightplan, but the ATFM tool is designed to operate adequately irrespective of flightplan changes. These flightplans represent the preferred executive planning of the Airline Operator, and are not changed by flow management, except for the departure time, if forced by lack of capacity along the flightpath. In that case, the flight is delayed by shifting the planning in time.

When processing flows of air traffic, the undisturbed execution of flights is constrained by capacity limitations. Each node of the network is characterised by declared capacity, an hourly capacity, and flow management will protect the network against overloads by imposing pre-departure delays to planned flights. ATFM aims to make best use of available capacity, but exceeding the capacity is prohibited at all times, except when non-flow managed flights are causing the overload. The hourly capacity numbers of sectors and airports are assumed to be constant over the day at this stage of prototyping, which is not realistic. The ATFM tool works on fixed numbers but the algorithm is able to cope with varying capacity figures. All applicable validation scenarios operate therefore also with airports operating with one runway configuration with a fixed capacity over the day. This is considered not to be a critical factor for validation.

In case during fast-time simulation (the first tool), the declared capacity of a sector is exceeded, the exceeding flight is assumed to create excessive workload which affects safety but which will cause hardly any delay. In case the declared capacity of the airport is exceeded, the flight will experience delay and will deviate from its planning. This difference in reactivity creates a problem that requires fast-time simulation to validate the operational result of processing flow management on a scenario, but this asks also for a second tool, a Network Analysis Model (NAM) tool to analyse the ATM network on congestion and bottlenecks in the network. The difference with fast-time simulation is that the NAM tool will process the flightplans equally for all nodes creating "waiting time" at each node, sector or airport, where capacity falls short. The NAM tool identifies bottlenecks that should be solved for undisturbed throughput of air traffic through the network, whilst fast-time simulation validates against which delays and which costs air traffic can be operated in a simulated environment, simulating "real" operations. The NAM tool is used to validate if advanced ATFM is able to be effective in supressing "waiting time", and the most basic

requirement for each implementation of advanced ATFM is that almost all "waiting time" is suppressed indeed.

The third tool is the Optimizing and Prioritizing ATFM tool. This tool is basically an extension of the NAM tool. All nodes with identified overloads require measures to suppress the "waiting time" by selecting flights and by imposing pre-departure delays to the planning of those flights. Different options are implemented and are discussed below and described in more detail in Damhuis et al. (Ref. 10 and 11).

A.   Fast-time simulations

The first step in development of an Optimizing and Prioritizing ATFM toolset was to assess an appropriate reference scenario, and to perform fast-time simulation and FCFS ATFM on this scenario as practised today. An ECAC-wide reference scenario was obtained from the SESAR Definition Phase in 2006, based on traffic from a perfect day in July, 2005 (Ref. 12 and 13). The interest of SESAR was first of all to demonstrate the feasibility to deal with strongly increased traffic levels for the medium-term future (2012 and 2020), amongst others, by applying advanced ATFM. Increased traffic was obtained by cloning flights, providing scenarios for 2005 (later lightly increased to 2008 levels of traffic), 2012 (+50%) and 2020 (+70%).

In this project, three successive steps were performed successfully:

1) the ability to perform fast-time simulations on a non-regulated scenario, then

2) to apply simple FCFS ATFM aiming to suppress overloads, and then

3) to perform fast-time simulation again, and this time with enhanced operational performance characteristics.

The project was not successful in suppressing delays by advanced ATFM. The increased traffic levels were extreme, whilst the capacity of the network could hardly be changed. Advanced features were not able to provide benefits compensating such a significant increase of air traffic. In addition, it was underestimated how carefully and balanced the strategic scheduling process takes place. The ultimate scheduling, in particular for the slotted airports, shall be in balance most of the time with available capacity. Nevertheless, most European airports will experience degraded performance levels from time to time, e.g. due to adverse weather conditions. This is most critical for the major hub airports, operating close to their maximum performance levels. For this reason it was decided to focus on airport disruption rather than future increase of traffic volumes, and to support an ATFM process that supports maximum possible throughput under disrupted conditions. This will be more realistic and may support the development of a more sustainable level of operations, in particular for the congested hub airports in Europe.

Fast-time simulations at the scale of ECAC-wide scenarios are runway-to-runway simulations. Flights are assumed to depart in compliance with their planning, possibly including imposed ATFM delays and possibly including delays due to modelled turnaround effects. Flights are executed by following their flightplan, flying under guidance of simulated control by ATC. Actual flight-time, departure and arrival delays compared to the original flightplan are the performance indicators, whilst workload is the performance indicator for the load of the sector. The flight-time through a sector is determined by sector-entry and sector-exit waypoints.

By processing flightplans fully unconstrained and in fast-time, 4D flightplans could be created representing ideal 4D trajectories. All other constrained fast-time simulation runs would produce the more realistic performance of flight operations under control of ATC measures. These were applicable to further experimental validation.

B. Airport Capacity and the Network Analysis Model (NAM)

Regarding ATFM regulations, the most critical element is the airport capacity. The declared capacity is assumed to be one single number of movements per hour. The actual capacity, even of a single runway configuration, may vary significantly due to changing departure/arrival waves and patterns, flying segregated, alternating or in bunches (arrival sequences). These are considered to be local effects on planning and control, and at the level of pre-departure tactical ATFM the capacity number shall represent the sustainable overall capacity figure per hour. There might be also a difference between declared capacity and physical capacity, for example due to noise regulations and/or other environmental constraints. The declared capacity has to represent in that case the physically realised operational capacity, otherwise ATFM will act with adverse effects for the actually realised capacity of the airport. Constraining throughput to implement and effectuate local regulation measures is considered to be beyond the scope of ATFM. Rather, local scheduling and planning are assumed to ensure these kind of regulations.

On the other hand, a too high declared airport capacity figure has the risk to induce local departure and arrival queuing with negative effects on observed flight delays. Moreover, the airport capacity has to be compliant with the capacity of the Terminal Manoeuvring Area (TMA) to ensure undisturbed throughput.

In the SESAR project (Ref. 12 and 13) there were problems with inconsistencies between declared airport capacity figures and actually simulated operations. Amongst others, this was a cause of local queuing and significant deviations from planning, making it difficult to analyse the effectiveness of ATFM measures. The NAM-tool will produce objective figures ("waiting time") that represent the level of, or remaining level of, congestion at a node, compared to its applicable declared capacity figure.

Although remaining "waiting time" is an adequate key performance indicator of overload of a node after applying ATFM, it ensures only compliance with the capacity, ensuring probably safety and also a safe level of workload required.

C.   FCFS ATFM as a reference model

At present, the operational ATFM process scans a scenario for overloaded nodes, determined to be regulated, and applies FCFS regulations. The assigned CTOT might be revised and the ATFM process is optimized by manual intervention. The CTOT is frozen before push-back.

With full support of automation this process could be completed and possibly optimized by use of high precision up-to-date 4D planning data, by continuously flow managing the entire ATM network, and by increasing the frequency of the monitoring and slot assignment loop. Also, Cooperative Decision Making (CDM) plays an important role in establishing an enhanced process of ATFM. These are short-term improvements under development by SESAR.

FCFS is the straightforward way to suppress congestion detected in an overloaded node. Due to the coherence of congestion through the network, it is already good practise at present to take into account network-wide effects. This is done now systematically with the FCFS option of the ATFM toolset, giving efficient FCFS results. However, the real challenge was to find a more beneficial strategy to suppress congestion within the overloaded node. All flights passing through that node at roughly the same time, are the real competitors in sharing available capacity, which raise the following questions:

1) Is it possible to find a more optimal strategy for assignment of delays than FCFS?
2) Is it possible to take into account the context of operations, responding on the question if delay assignment has negative impact elsewhere?
3) Is it possible to find a more fair strategy by striving not only for minimal delay, but also for a minimal spread in delay, reducing the amount of delay assigned per delayed flight?

This last point takes into account that several short delays are less penalizing than one excessive delay, and that raises the question if it is possible to actively control the spread of delays.

D.   Optimizing ATFM

Ideal 4D planning and network-wide FCFS ATFM is chosen as the reference scenario to evaluate new long-term advanced ATFM applications. Due to the size and the length of a scenario and due to the requirement to cope with planning updates, an iteratively optimizing and converging ATFM process is preferred. Secondly, there is a need for iteration because imposed delays by pre-departure slot assignments are determined by congestion in one specific overloaded node, the

most penalizing node along the flightpath of a regulated flight. Delay assignment and changes in flight planning are causing gaps in the deployed capacity in other nodes and that capacity has to be made available for minimizing the imposed delays. This is accomplished by iteration (See Figure 2).
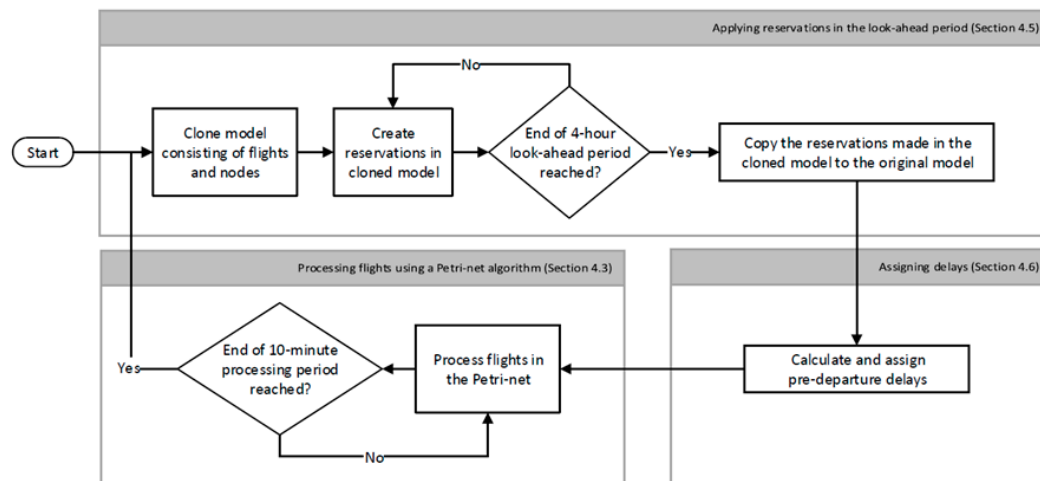

Figure 2: Flow chart of the core algorithm

Early experiments with the enlarged core area scenario (~25.000 flights) gave evidence about the frequency of iteration and the size of the iteration step. The step size has to be sufficient to manage a full flight from take-off to touch-down or, in case of long-haul flights to or from a so-called "out-node", entering or leaving the flow-managed area of the scenario. In case of the enlarged core area scenario a 4 hours look-ahead period was sufficient to process more than 99% of the applicable air traffic, but a longer look-ahead period of up to 6 hours or more may be required for an ECAC-wide scenario. Because copying the scenario temporarily is one of the most computing-intensive activities, an increase of the look-ahead period is feasible and has probably a mostly linear degrading effect on computational performance.

The frequency of the process is high in order to get sufficient convergence in stability of delay assignments and planning. The remaining "waiting time" is an indicator of convergence and stability. Enhanced ATFM is pro-cessed in the experiments with a step-size of 10 minutes. This relatively small time step is required probably due to the changes of the scenario caused by frozen flightplans and new upcoming flightplans within each look-ahead period. A larger step-size gave unstable and degraded results (Ref. 4).
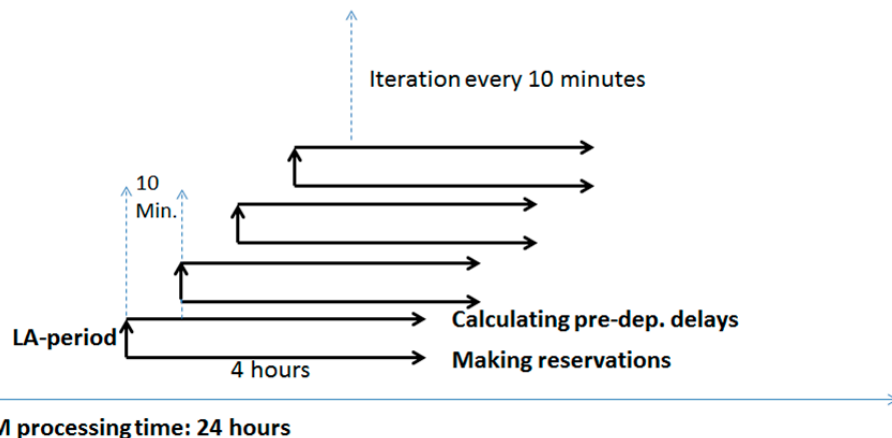
Figure 3: Main iteration loop processing all overloaded nodes of the ATM network each 10 minutes over 24 hours

The size of the process is determined now by the size of the ATM network, the 10-minutes step-size and the number of congested nodes to be processed on suppressing the overloads (See Figure 3). With the applicable enlarged core area scenario with roughly 500 airports and 700 sectors, the number of processed nodes could raise easily above 2000, depending on applicable levels of disruption. This turned out not to create any computational performance problem.

Processing nodes during each look-ahead period gives more than enough context to compare alternatives for accepting delays. An optimization module was developed, based on MILP, using a binary integer programming formulation, to calculate the optimal distribution of delays for each node. In this context "optimal" means optimizing towards a weighted minimum of average delay and spread of delay. The weight factor determines the emphasis on controlling the average or the spread, and the spread of delay was reduced by introducing a "minimax" function reducing the maximum amount of assigned delay. Implicitly, this optimization process allows also distributing a large delay and splitting the assignment of delay over several flights. The implementation was successful in reducing imposed delays compared to FCFS for the applicable scenarios. Also a reasonable balance between average and spread of delays was accomplished choosing appropriate weight factors. See for more details Damhuis et al., (Ref. 10 and 11).

E.   Optimizing and Prioritizing ATFM

Optimization within the context of operations at a node is focused on prohibiting overloads against minimal penalties. It doesn't take into account the context of operations elsewhere or the economic value of a flight. Within the context of planned operations at a node, there is no knowledge on this issue. Several attempts were made to incorporate prioritization in order to incorporate other cost elements in the ATFM optimization process.

The first option for solving congestion of an overloaded node was to give absolute priority over non-prioritized flights to a special class of flights and avoiding assignment of pre-departure delay. The absolute priority was assumed to be assigned to those flights departing from or arriving at a major or hub airport suffering disruption due to a strong decrease of declared capacity for whatever reason such as adverse weather conditions, incidents or strikes. To overcome the difficulty to take into account the specific costs of each flight in terms of delay and economic penalties due to local disruption, prioritisation could support undisturbed throughput at the penalized airports as much as possible.

The assigned priority is absolute, except that higher priority is still applicable to all arriving long-haul flights, and to all in-flight air traffic. Moreover, also the priority flights are not allowed to exceed the capacity at the node, and in case of local overloads, these flights will still receive penalties by assignment of pre-departure delays. Finally, there was a technical issue with the penalized flights. These flights could reduce their assigned penalty by benefitting from gaps in the network-wide slot assignment scheme. Whenever these reductions were applicable, they were issued with an extra high priority in order to avoid instable oscillation during the iterative ATFM process. Altogether, absolute priority was not a guarantee to receive no delay assignments, but it was a guarantee of systematically receiving less delay than without priority. During implementation, it was realised that two negative effects could not be controlled:

1) Too many prioritised flights would slowly deteriorate to equal performance as non-prioritised flights.
2) Too many prioritised flights may prohibit planning non-prioritised flights, and this could lead to excessive delay assignment to non-prioritised flights.

The concept of absolute prioritization was implemented successfully, and some validation experiments demonstrated beneficial effects for operations of a class of (limitedly) disrupted airports. See for more details of concept, implementation and validation, van Hout (Ref. 4 and 14).

The next option was to implement a fully optimized concept, combining optimization towards minimized delays with weighted optimization of prioritization. All prioritized flights received weight factors to give these flights a better chance to pass undisturbedly through congested nodes along their flightpath. At the same time, weight factors ensure an optimal distribution, minimizing average delay and spread of delay.

The implementation of this option was validated and turned out to be robust for levels of disruption and the participating amount of prioritised flights. The benefits are evident under moderately disrupted conditions, however, also under heavily disrupted conditions, optimized ATFM still operates correctly, although being less beneficial to delayed flights. The opportunities

to profit from a favourable allocation of imposed delays are missing due to saturation. In case of heavy disruption, almost all flights will be delayed, and there is no room for any beneficial ordering. The best possible ordering of penalized flights per congested node is fully determined by the generalized formulated optimization criteria, expressed in the applicable objective function. This function benefits part of the traffic more than other parts according to rationally determined fractions. See for more details of concept, implementation and validation, Damhuis (Ref. 10 and 11).

The system described above yields altogether an implementation of 7 different classes of flights, as summarized in Table 1. Priority level 7 (and 5) was used for non-prioritized flights, planned for departure. Priority level 6 (and 4) was used in the validation experiments to give priority to a class of flights departing from and arriving at a number of disrupted airports. There is no limitation to select these flights and to make use of priority rights as long as there is agreement amongst stakeholders how to use level 6, and against which price. The priority rights might be used, for example, also to prioritise economically high-valued flights. However, this works only appropriately and as intended, if the total number of prioritized flights through congested nodes is low compared to the total amount of air traffic.

Options to control the assignment of priority could be, for example, to allocate budgets of priority rights to airline operators, or to agree on prices that are in balance with the expected average or nominal improvement of performance per flight. And in that case, assessment of performance improvements is always possible by executing what-if simulation experiments varying the prioritization weight factors as well as the selection of priority assignment to planned flights of the applicable scenario.

Table 1: Priority levels applicable to Optimized and Prioritized ATFM

Prio	Type of flights	Comment
1	VIP, and military	Not used, not flow-managed
2	Arriving long-haul flights	Not flow-managed, absolute priority
3	In-flight air traffic, en-route	Not flow-managed, or flow-managed previously, absolute priority
4	Extra prio to already penalized prio flights	Extra priority in non-constraining nodes to force stability
5	Extra prio to non-prio flights	Extra priority in non-constraining nodes to force stability
6	Priority flights	A designated class of flights, receiving imposed pre-departure delay through overloaded nodes of the network with systematically less probability than other non-prioritized flights
7	Non-priority flights	Standard non-prioritized flights

Finally, it was considered interesting to make use of the direct and indirect costs of flights in selecting priority rights. This requires extending the notion of priority level 6 flights to a continuum of priority rights. However, this has two major draw-backs:

1) The airline operator internal operating costs become explicitly part of a flow management regulation. The problem is that airline operators are not expected to be prepared to submit any details on costs and deployment of their planned operations, and if they should submit these data it will be difficult to exclude manipulation.

2) The extension of priority rights to the level of flight-individual rights will be prohibitive for transparency on the performance of prioritizing ATFM. In the current implementation of the prototype tool, there are two distinct classes of flights: non-priority and priority flights. This implies that it is possible to evaluate by what-if simulations the impact of optimization and prioritization on both classes of flights. It is complicated enough to analyse these effects distributed over the day, distributed over departure and destination airports, and over prioritised and non-prioritised classes of flights. With more continuous priority rights it becomes difficult to evaluate the impact of priority on throughput and performance.

Therefore, no costs are directly part of the optimization and prioritization process, however, cost aspects were taken into account to a limited extent in some of the validation experiments and the evaluation of results (Ref. 10 and 11).

3 Some Experimental Results

Validation takes place on a large scenario, by preference ECAC-wide (around 35.000 flights). However, most of the validation experiments for development of optimizing and prioritizing ATFM, made use of a reduced scenario (still 25.000 flights), but large enough to experience airport congestion, sector congestion and coherent overload problems at several airports and sectors. The relevant experimental results are focused on:

1) **Fast-time simulation**: Some limited results of ECAC-wide simulations gave indications how to use fast-time in overall validation experiments for the Optimizing and Prioritizing ATFM toolset.

2) **Optimizing ATFM compared to FCFS**: The result of distributing and minimizing FCFS imposed delays executed on a disrupted scenario, compared to straightforward FCFS as applicable at present.

3) **Optimizing and Prioritizing ATFM**: The result of prioritizing all flights from and to a disrupted airport and optimizing the assignment of imposed delays of all flights through overloaded nodes of the ATM network.

A. Fast-time simulation

Fast-time simulation was the pre-requisite to be able to initiate the ATFM research. ATFM was mandatory to manage the flows of air traffic through ECAC-wide scenarios. The research for SESAR was not successful in managing strongly increased volumes of air traffic but much could be learned about regulating overloads.

The most relevant result was achieved with a 2012 scenario (+50% air traffic). The distribution of imposed pre-departure delay were increasing over the day, showing a strong effect of saturation (Figure 4).
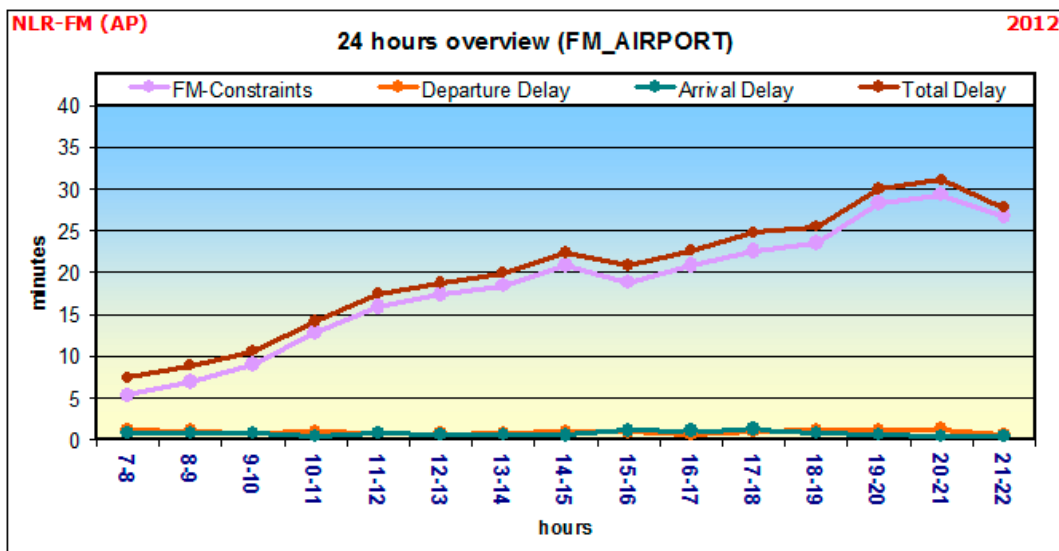

Figure 4: Accumulation of total delay and ATFM delay for an ECAC-wide scenario over 24 hours (2012)

Due to unexpected queuing at airport level, the workload at sector level was not decreasing sufficiently. The most sensitive key performance indicators for workload were: the percentage of capacity usage and the calculated workload. For the most relevant 600 sectors the maximum hourly period was observed and for each sector the value of max. workload and max. percentage of capacity used, was plotted (Figure 5).
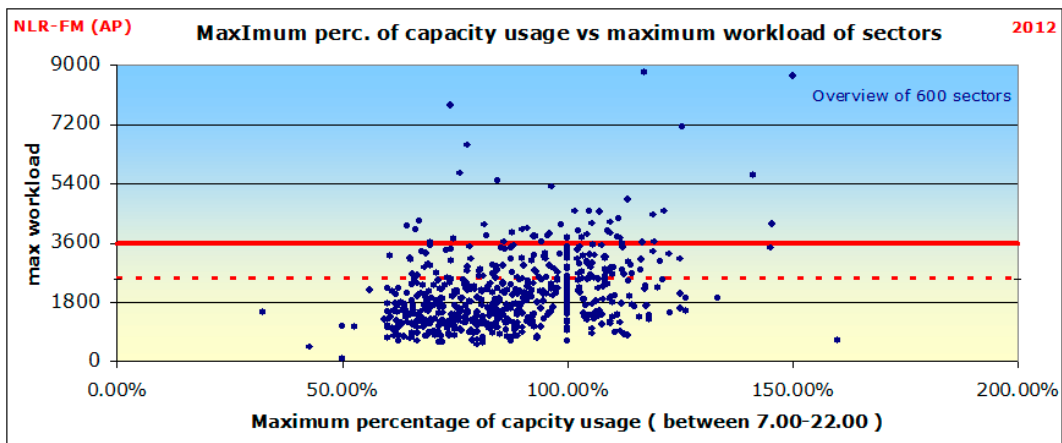
Figure 5: Plot of values of hourly period of max. workload and max. percentage of capacity usage of 600 sectors for an ECAC-wide scenario over 24 hours (2012)

The results are not relevant for the anticipated future, but the fast-time simulation facility and the method to analyse operational results of applying ATFM are very useful for future validation.

B.   Optimizing ATFM compared to FCFS

Just the summarizing overall result is presented of the (moderately) "Reduced" scenario. This scenario yields ATFM on the enlarged core area scenario (2008), comprising 5 capacity-reduced airports, i.e. LFPG (-30%), EHAM (-30%), EDDF (-20%), EDDM (-20%) and EGKK (-20%). Capacity reduction is chosen such that saturation is avoided, and that cancelations are not mandatory yet. Optimizing FCFS, aiming at improvement of the distribution of imposed delays at each overloaded node, turns out not to improve significantly the average delay (03:31 min.) and even not the spread of delay (08:41 min.). Nevertheless, improvement is achieved in a better spread of delays by suppressing the number of highest imposed pre-departure delays (a change of 13 flights with more than 90 min. delay for FCFS ("OutOnly") to 2 flights for FCFS-Optimized ("OutOnly-optimised"). Also the number of penalized flights slightly decreased for this scenario (-113 (-2%)) (See also Figure 6, and see for more details, Damhuis, Ref. 10.)
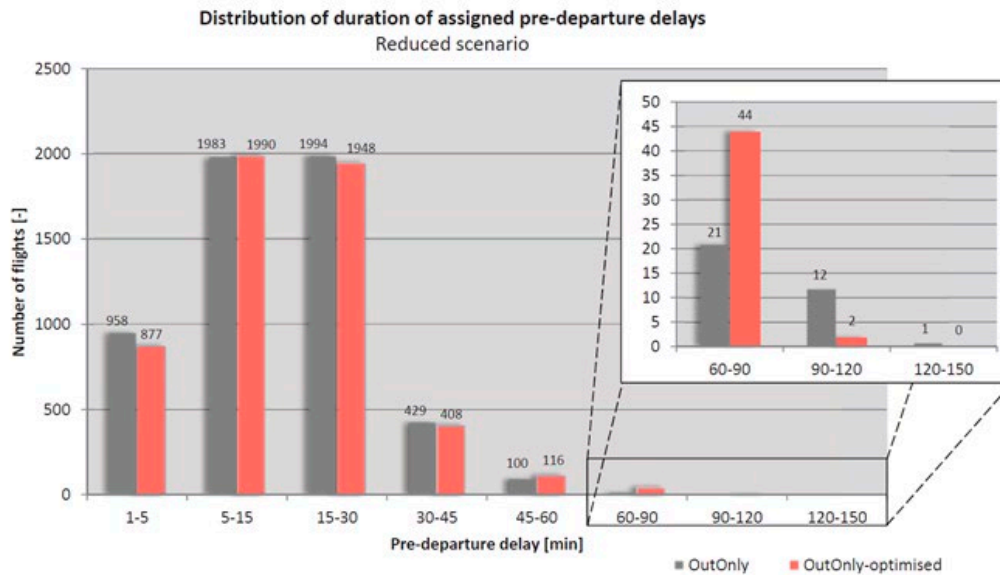
Figure 6: Distribution of the duration of assigned pre-departure delays for the reduced scenario, comparing FCFS (OutOnly) with FCFS-optimized (OutOnly-optimised)

C. Optimizing and Prioritizing ATFM

The summarizing results are presented of the "Reduced+" scenario. This scenario yields ATFM on the enlarged core area scenario (2008) as well, however, this time comprising 7 capacity-reduced airports, i.e. LFPG (-30%), EHAM (-30%), EDDF (-20%), EDDM (-20%) and EGKK (-20%), EGLL (-15%) and LFPO (-45%). Capacity reduction is still moderate, although EGLL operates anyhow close to saturation.

According to Table 2 around 4500 flights are suffering around 890 hours delay, mainly allocated at flights to and from the disrupted airports. To solve the overloads around 6300 flights had to be penalized with imposed delays. Optimization is now effective indeed and is able to reduce the total number of imposed hours of delay with 114 hours, achieved by better filling the gaps. This is illustrated for one example node at one moment of optimization by Figure 7.
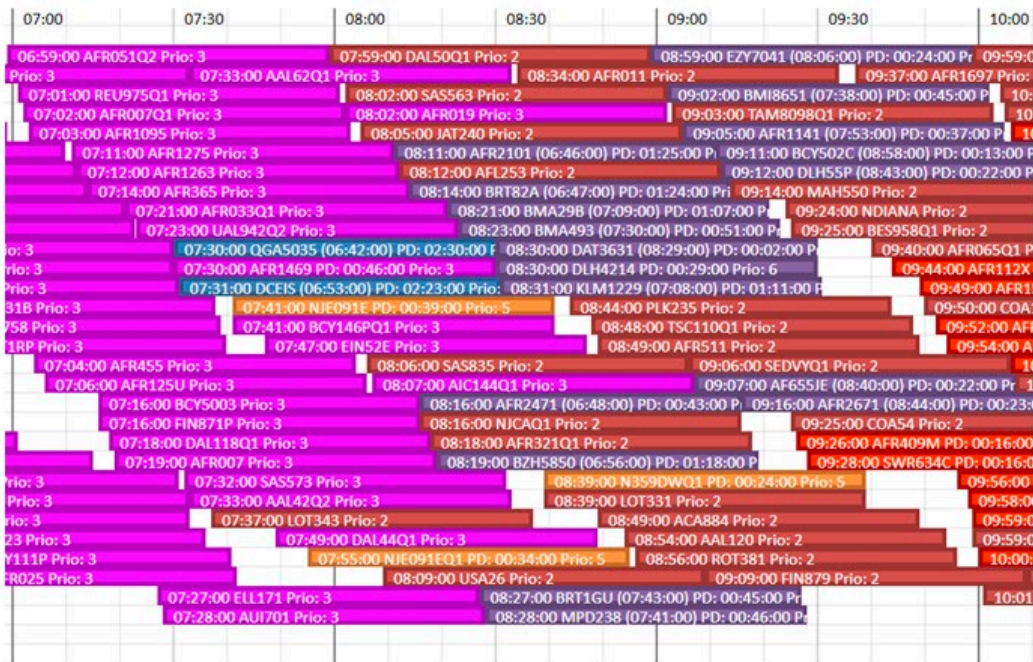
Figure 7: Example of making slot reservations for an overloaded node, using optimization and prioritization (different colors for different priorities)

The assignments of imposed delays have been improved now compared to FCFS reducing the pressure on disrupted airports with almost 200 hours delay. The optimized delay assignment is more balanced now than when applying absolute prioritization, but this is dependent of course on the choice of appropriate parameter settings in the objective function for optimization.

Table 2: Summary of results comparing FCFS ATFM with Optimizing and Prioritizing ATFM

Before applying ATFM		At all airports	Main airports	Main airports (disrupted)	Secundary airports
Overloads	Waiting time [hr.]	897	871	867	27
	Nr. of flights	4529	4352	4227	177
After applying ATFM		At all airports	Main airports	Main airports (disrupted)	Secundary airports
FCFS	Pre-dep delay [hr.]	1761	1029	862	732
Prioritization	Pre-dep delay [hr.]	1766	833	633	934
Optimization and Prioritization	Pre-dep delay [hr.]	1647	864	687	783

The overall result yields optimization to be successful in applying prioritization, but without paying a price in average delay over all flights (04:19 min.) and spread of delay (09:32 min.). Again there was a significant improvement, not only in less penalizing disrupted airports, but also in reduction of the maximum assigned pre-departure delay decreasing from 02:47 hr. to 01:54 hr. for the optimized scenario (a reduction of 23 flights with imposed delay above 01:54 hr.).

The benefits for the disrupted airports is best illustrated by showing a geographic distribution (Figure 9) and a histogram showing imposed pre-departure delays of 15 most affected airports (Figure 8) for the three different options of applying ATFM: FCFS ("OutOnly"), absolute prioritization ("MainHigher") and optimization combined with prioritization ("Optimised").
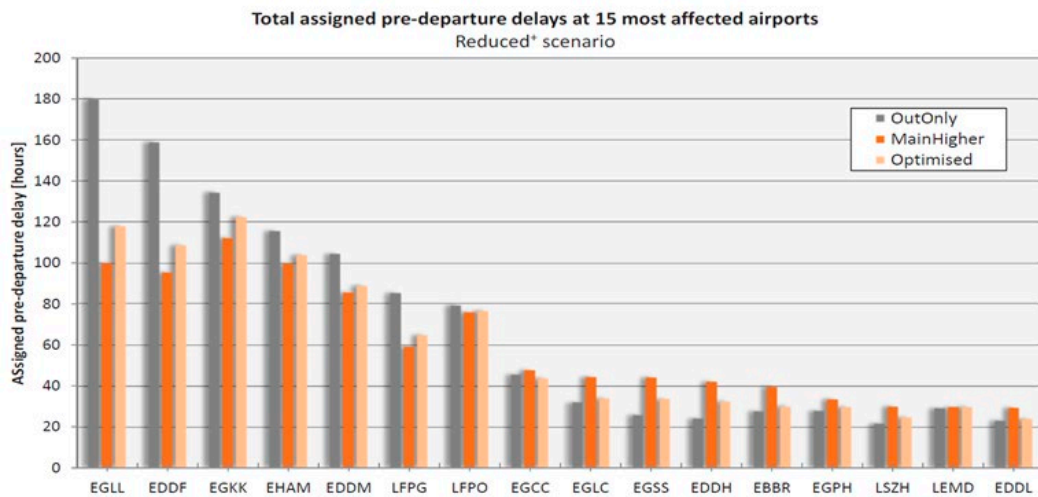

Figure 8: Total assigned pre-departure delay at 15 most affected airports for the reduced+ scenario, using FCFS ("OutOnly"), absolute prioritization ("MainHigher") and optimization and prioritization ("Optimised")
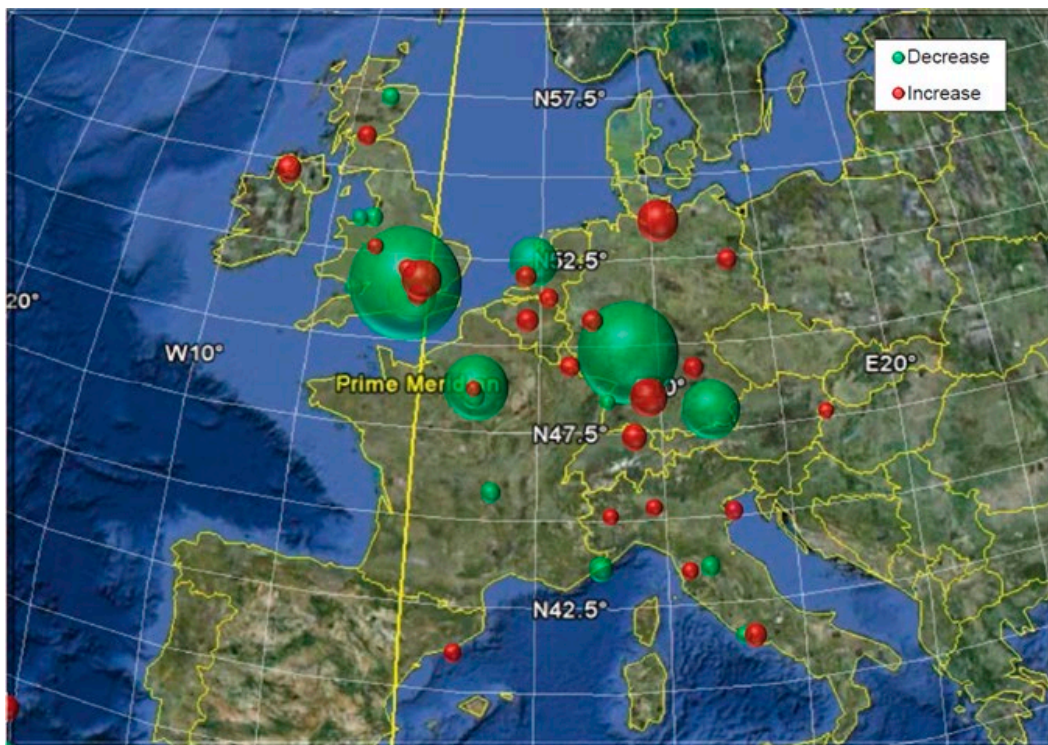

Figure 9: Geographical distribution of differences in assigned pre-departure delays at airports between FCFS and optimised prioritisation for the reduced+ scenario
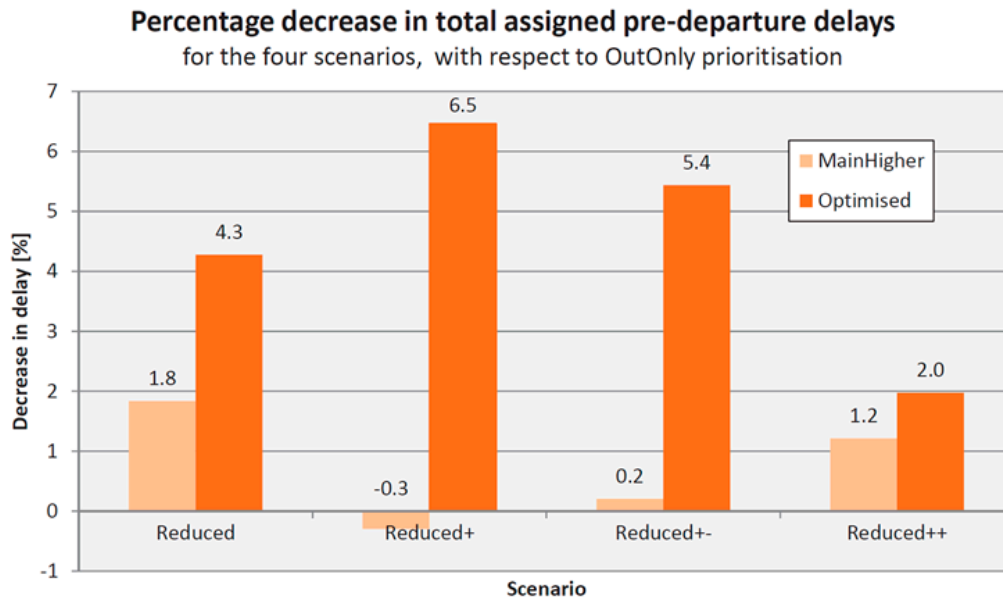
Figure 10: Decrease of total assigned pre-departure delays for the four scenarios, compared to FCFS ("OutOnly")

Finally, a histogram is presented that shows some trends in effectiveness of applying options for optimization and prioritization in ATFM, depending on the degree of disruption of the scenario. Far from being exhaustive, the result shows the trend for 4 scenarios with an increasing level of disruption by loss of airport capacity. All results are compared with FCFS results, and all results show a decrease of the required amount of imposed pre-departure delays by using optimization. The decrease, and therefore the effectiveness of optimization, is optimal with some evidence for "quite moderate" levels of disruption (the Reduced+ scenario). (See Figure 10.)

4   Conclusions and Recommendations for future work

NLR and TUD developed a toolset for optimizing and prioritizing flow management (ATFM) because the presently used method for regulation is not able to take into account any effect of delay beyond the context of the overloaded and regulated sector. There is evidence that FCFS regulations are less than optimal. Moreover, there was a strong wish by airspace users to get more control over management and planning of their flight operations.
The optimizing and prioritizing ATFM tool is able to facilitate prioritization, and this enables either to manage disruption, for example at airport level, in a better way, or it allows airspace users to designate some of their flights to receive priority in applicable regulations.
The validation work by NLR and TUD demonstrated that:

- The tool is robust and operational at the level of operating a prototype ATFM tool.
- Prioritization works appropriately and can be fine-tuned to operate in fair balance with overall efficiency.
- Optimization is appropriate to manage and control the average delay as well as the spread of delay, and this is a good method to minimize delays and penalties under (moderately) disruptive conditions.
- Optimization is able, in particular, to suppress the highest imposed pre-departure delays, ensuring a better and more fair distribution of delays over the penalized flights.

The validation is far from completed, and also a more operationally focused validation might be beneficial to give more confidence and to bring these tools to a higher level of maturity. Therefore, the recommendations for future work are:
- To validate the working of the toolset on an ECAC-wide up-to-date scenario,
- To extent the scenarios with more realistic hourly capacity figures and to take into account reactionary delays,
- To better evaluate economic effects and indirectly related cost aspects,
- To evaluate the fine-tuning of the objective function for optimization, and to validate operational applicability, and
- To validate operational benefits by an extensive program of validation by fast-time simulation, using the optimising and prioritising ATFM tool.

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