



Executive summary

Optimisation and Prioritisation of Flows of Air Traffic through an ATM Network

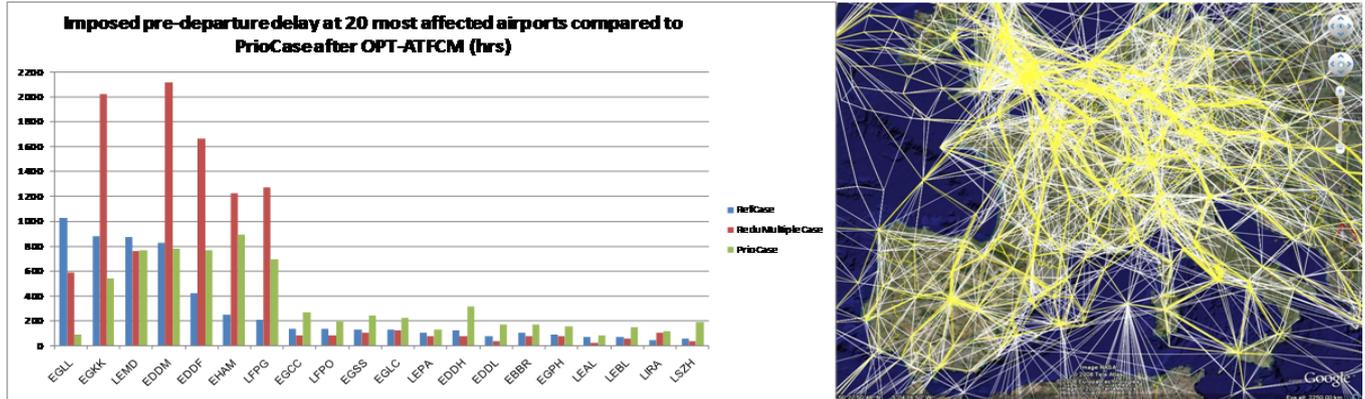


Chart presenting the differences of imposed pre-departure delays at the 20 most affected airports, demonstrating that 5 capacity-disrupted airports were penalised once more by imposed flow regulation delays, and that this could be suppressed by applying prioritisation

Problem area

Air Transport operations are performed through a network of airports connected to each other by airspace sectors. This network is vulnerable to disruption. Whenever the capacity of single or multiple nodes in this ATM 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 to improve the quality of regulations in case of disruption, respecting the economic value of flights. The present research is in-line with this objective.

Specifically, large congested 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 a prototype of an algorithm to allow improvement of ATM regulations by optimising and prioritising the 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

A prototype for ATFM regulations has been developed, based on a Petri-net strategy to select a subset of flights involved in a bottleneck. At a congested node, an airport or airspace sector, optimisation and prioritisation of regulations may take place within this local context of space and time. The result is a weighted minimisation of imposed

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delays, whilst respecting available capacity and maximising through-put through the network.

A small experiment is set up and conducted:

- To show the sensitivity of the ATM Network for incidental decrease of capacity, and the impact of congestion on the performance of large, hub airports,
- To show the feasibility of replacing a First-Come – First-Served regulation principle by an optimising and prioritising strategy, and
- To show for one example the potential benefits of prioritisation, i.e. to prioritise flows to/from congested hub airports.

The applicable algorithm assumes availability of up-to-date 4D planning available, in compliance with SESAR, and assumes a coordination process available to accept regulations and to ensure balanced decision making. The guiding principle is to search for overall optimisation of throughput, and to minimise “Waiting time” at congested nodes. “Waiting time” means in this context waiting for access to a network node (in the air and/or on the ground) and this waiting time is suppressed by imposed pre-departure delays at airports. This suppression shall occur against minimised imposed delays, and aims to make optimal use of available capacity of the ATM network.

Results and conclusions

The experiment was performed on a prototype platform, programmed in Visual-Studio 2008 and C#, which ensures sufficient computing efficiency to deal with ECAC-wide scenarios. Part of this ECAC-wide sample, around the Core Area, was processed on this platform and analysed on throughput characteristics as well as required pre-departure imposed delays to mitigate disruption.

The analysis showed for:

- **ATFCM Reference scenario:** In a representative and balanced scenario, there is sufficient capacity to mitigate incidental disruption by regulations.
- **Bottlenecks:** Most waiting time is measured in the core area, and the most congested as well as the most penalised airports are all hub airports, which are again predominantly allocated in the core area.
- **Sensitivity analysis:** Two disruptive events were evaluated on their impact on network throughput: a one-airport and a five-airports decrease of capacity with 20% to 30%.
- **Outcome:** Most remarkable conclusion is that a First-Come – First-Served mechanism tends to solve disruption where it is detected. The pre-departure

delays tend to be imposed at the airports with reduced capacity, penalising these airports again. This enforces the negative impact on overall network performance.

- **Enhanced ATFCM by prioritisation:** The five-airports case was evaluated on the impact of prioritising flows to/from the six (!) most saturated airports. (London-Heathrow, EGLL, was added because imposed delays tended to be moved otherwise to an already overloaded airport.)
- **Outcome:** Re-allocation of imposed pre-departure delays caused an improved overall performance of the ATM Network. However, main and hub airports showed very strong and significant enhanced performance, whilst the amount of imposed pre-departure delay reduced with 40% for these airports.

In conclusion

The objective of this project was to perform an explorative validation experiment on the ATM Network that demonstrates options available for advanced ATFCM to provide benefits to ATM users in Europe, and the experiment showed that optimisation and prioritisation by ATFCM can be facilitated in a beneficial way.

- The problems around bottle-necks and network congestion are focussed on the performance of hub airport operations. Most of these airports are situated in the core area of Europe, such as also Schiphol.
- Advanced regulation procedures that optimise and prioritise ATFCM are feasible means to mitigate disruption and to maximise throughput. Prioritisation can be used to increase throughput and to distribute penalties more evenly.

Applicability

Enhanced ATFCM has the potential to improve cost-efficiency of operations by changing in-flight delays to ground delays, and to improve overall throughput. Prioritisation can be used to optimise city-pair connectivity, and in particular within and around the core area of Europe.

This requires availability of accurate planning data, and accurate capacity figures of airports as well as airspace sectors. In this experiment, both, demand and capacity figures can be considered as representative figures; however, they have not been verified. Therefore, all outcomes are indicative yet. Nevertheless, the outcomes show large potential benefits of enhanced ATFCM to improve the cost-effectiveness of Air Transport operations in Europe.



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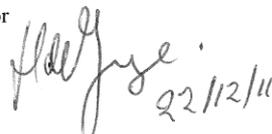
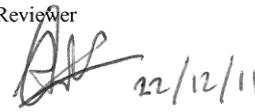
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Summary

Air Transport operations are performed through a network of airports connected by airspace sectors. This network is vulnerable to disruption. Whenever the capacity of single or multiple nodes in this ATM 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 to improve the quality of regulations of traffic flows through this network in case of disruption, respecting the economic value of flights. Specifically, large congested hub airports are sensitive to suffer from arrival congestion and departure delays, and in addition, the Core Area is the most sensitive part of Europe. Most of the congested hub airports are situated there.

The research in this paper addresses the design and development of a prototype of an algorithm to allow improvement of ATM regulations by optimising and prioritising the management of the ATM network. This prototype is used to conduct an explorative experiment to show the potential benefits of this algorithm. The most remarkable results demonstrated that re-allocation of imposed pre-departure delays caused an improvement of overall performance of the ATM Network by applying prioritisation. However, more important, both, main and hub airports, showed very significant enhanced performance, whilst imposed pre-departure delays could be reduced for the selected scenario with major reductions up to 40% for the disrupted airports.

Contents

1	Introduction	7
2	Background and Context	8
2.1	Context	8
2.2	The current scenario	8
2.3	Problems in the ATM network today	10
2.4	Mitigation of congestion in the ATM network	10
3	Demand and Capacity Balancing of an ATM Network	11
3.1	Balancing the network	11
3.2	Balancing the ATM network and Optimisation	14
3.3	Analysing optimised throughput through the network	15
4	Validation of enhanced ATFCM, an Experimental Plan	16
4.1	Validation aims	16
4.2	The Scenario	17
4.3	The tools and the algorithm	19
4.4	The Key Performance Areas (KPAs) and Metrics	20
5	Conduct of Experiment	20
5.1	The ATFM Reference scenario	21
5.2	Compliance with today's regulations	22
5.3	Sensitivity analysis by capacity deficiency	22
5.4	Options for enhanced ATFM by prioritisation	24
6	Conclusions and Recommendations	28
	References	30
	About the Authors	31

Abbreviations

Abbreviation	Description
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
CFMU	Central Flow Management Unit
DCB	Demand & Capacity Balancing
DOD	SESAR Detailed Operational Description (developed by EPISODE-3)
EC	European Commission
ECAC	European Civil Aviation Conference
FC-FS	First Come – First Served
FM	Flow Management
FTS	Fast-Time Simulation
ICAO	International Civil Aviation Organisation
KPA	Key Performance Area
KPI	Key Performance Indicator
NAM	Network Analysis Model
NLR	National Aerospace Laboratory of the Netherlands
NOP	Network Operations Plan
OPT-ATFM	Optimising Air Traffic Flow Management
PC	Personal Computer
PRG	Performance Review Group (EUROCONTROL)
R&D	Research & Development
RBT	Reference Business Trajectory
SBT	System managed Business Trajectory
SES	Single European Sky
SESAR	Single European Sky ATM Research
TAAM [®]	Total Airport and Airspace Model [®] (Fast-time simulation tool)
TMA	Terminal Manoeuvring Area
UK	United Kingdom



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1 Introduction

This paper describes the research and design of a prototype of an algorithm to allow improvement of Air Traffic Flow Management (ATFM) regulations by optimising and prioritising these regulations within an ATM network. This prototype is used to conduct an explorative experiment to show the potential benefits of this algorithm [Ref. 1].

The experimental objectives are:

- To analyse city-pair connectivity and the performance of the ATM network in light of this connectivity,
- To investigate the sensitivity of city-pairs for congestion, disruption and other capacity constraining conditions, and
- To analyse which planning strategy could help to solve congestion and to mitigate disruption by throughput optimisation.

A network analysis model has been developed to perform enhanced ATFM, and this report elaborates its potential to contribute in solving today's problems in the ATM network, and in particular to solve congestion around saturated hub airports. Application of this algorithm could facilitate enhanced ATFM operations under saturated operational conditions to solve congestion, and the algorithm will be able:

- To select a local context in space and time and to determine if an overload condition occurs.
- To impose a pre-departure delay that solves the overload condition, whilst being able to assess the impact on other flight operations.
- To apply optimisation towards minimised imposed delays, whilst solving the overload conditions.
- To apply optimisation towards the economic value of flight by prioritisation, taking into account the identification of high valued flows or high valued individual flights.
- To provide output that allows evaluating the consequences of delay assignments on the performance of individual flights, classes of flights and on the overall performance of flight operations, under constraining conditions.

Some R&D results are presented to demonstrate the potential of these tools to validate ATM benefits and how these benefits can be assessed by applying the tools on a representative ATM network for Air Transport operations in Europe. The objective is to convince ATM users of the benefits that can be obtained by regulating departure flows in a different way than today by use of enhanced ATFM algorithms. This will be achieved by applying ATFM with maximum throughput, best achievable efficiency and minimum impact on flight performance. The measured benefits turned out to be significant and the tools to evaluate them will provide

contributions to find the answers on questions about enhanced city-pair network connectivity, ATM network performance and options to mitigate disruption.

2 Background and Context

2.1 Context

It is recognised by the Single European Sky (SES) initiative that deficiencies in design and use of the ATM network are amongst the major problems for Air Traffic Management (ATM) in Europe. Fragmentation and lack of integration are responsible for low performance of the ATM network. Enhanced ATM in Europe has the potential to reduce fuel consumption and emissions by about 10% per flight [Ref. 2 and 3], and the European Commission (EC) promotes that *“...the use of transparent and efficient rules will provide a flexible and timely management of air traffic flows at European level and will optimise the use of air routes.”* [Ref. 3]. This justifies considering optimisation of performance of the ATM network as a major contributor to enhanced Air Transport operations.

The principles of an operational concept for management, planning and operations of an ATM network were developed within the context of SESAR. The main concept elements are put together in the description of the SESAR Operational Concept [Ref. 4 and 5], and this concept is worked out in more detail in the Episode-3 project, providing the Detailed Operational Descriptions [DODs, Ref. 10 and 11]. These DODs are to be detailed further during the SESAR Development Phase. The essentials regarding network management are summarised also in two reports by NLR [Ref. 12 and 13]. This study focuses on a critical element of this concept by addressing the principles to apply Air Traffic Flow Management (ATFM).

2.2 The current scenario

Air Transport operations are performed through a network of airports connected to each other by airspace sectors. This network is vulnerable to disruption. Whenever the capacity of single or multiple nodes in this ATM network decreases, bottlenecks and congestion will cause delays and (cost)-inefficient flight operations. SESAR developments aim to improve the quality of planning and to improve the quality of regulations in case of disruption, respecting the economic value of flights [Ref. 4 and 5]. Specifically, large congested airports and hub airports, depending on transfer operations, are sensitive to suffer from arrival congestion and departure delays, and for example, Schiphol, situated in the core area of Europe, is one of them.

The resilience of the European ATM network is critical due to its sensitivity for network congestion. One evident cause of congestion is the allocation of dense flows through the Core Area of Europe, feeding its hub airports in that area (see Figure 1). Apart from dense flows, bottlenecks are caused by several properties characterising the ATM network and its deployment, for example:

- Traffic takes place between a large number of airports but only traffic from and to a relative small number of major hub airports is involved in the most congested bottlenecks. These airports are suffering the major part of in-flight delays and have to accept also the major part of imposed pre-departure delays to mitigate those in-flight delays [Ref. 6 and 7].
- The network determined by these congested airports are part of a sub-network, characterised by traffic scheduled over the day, including peak hour air traffic demand due to the scheduling of Airlines' network operations and the connectivity between those major hub airports.
- In case of disruption, these airports are vulnerable moreover, because the traffic turns out to be sensitive also for reactionary delays. Disruption shows knock-on effects over the day, as analysed for example by the Performance Review Group (PRG) of EUROCONTROL [Ref. 8 and 9].

The ATM Network and the Bottlenecks

Network defined by:

- non-optimal number of sectors
- non-optimal distribution of air traffic

Problems:

- Specific sector nodes with overload problems
- Very thick and very thin traffic flows
- Airports nodes very small, very large and sometimes very congested

Conclusion:

- Network is super critical
- Solving bottlenecks to make Network robust
- More robust network by aggregation

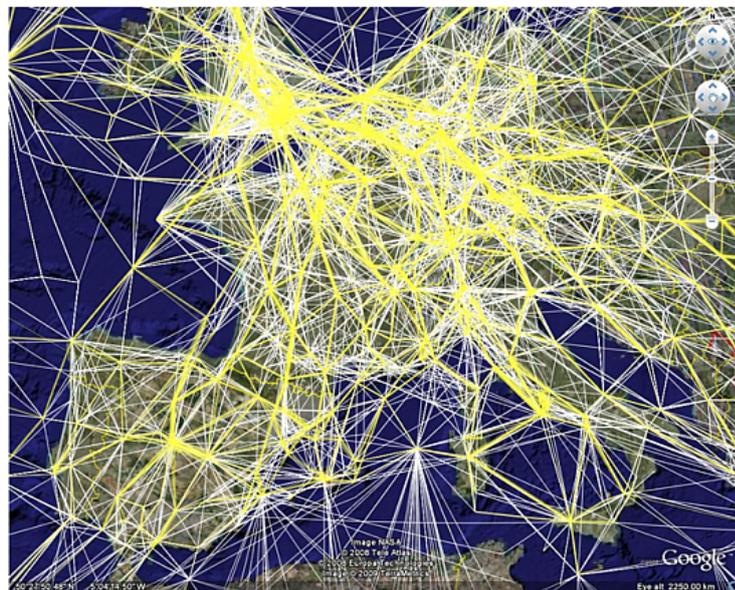


Figure 1 - The ATM network defined by airport nodes, sector nodes and air traffic through these nodes

2.3 Problems in the ATM network today

The European ATM network often operates under overloaded and congested conditions. There are many reasons for economically inefficient behaviour of this network. The reasons are stemming from the bottlenecks within this network, e.g.:

- Some airports are systematically overloaded. They operate as a critical hub airport, whilst it is difficult to expand their capacity, such as e.g.: London Heathrow, Gatwick, Frankfurt and Roma Fiumicino.
- Some airports are subject to highly invariable unbalanced operational conditions due to capacity variations by changing weather conditions, such as, for example, London Heathrow and Amsterdam Schiphol.
- Some airports are suffering from limited capacity to enter the TMA, caused by e.g. lack of airspace due to national borders, military airspace, and/or access requirements from other nearby operating airports.
- Some ATS-routes are critical due to en-route capacity constraints, for example London – Frankfurt and London – Paris East-West routes, and the North-West – South-East routes over the Netherlands and Germany, and, in general, parts of the routes through the core area [Ref. 8 and 9].
- In addition, there is also a seasonal dependency, working day versus weekend, a daily hourly dependency and a dependency on special events.

Summarising, the ATM network operates often at a critical level, and this criticality may relate to airport as well as airspace capacity constraining conditions.

2.4 Mitigation of congestion in the ATM network

To mitigate congestion, the CFMU started its operations in Brussels in 1993 to manage and monitor the ATM network and they were very successful in enlarging the realised capacity of this network by applying ATFM regulations on overloaded sectors. However, the CFMU limits its regulatory operations to airspace sectors mainly, whilst all regulations are based on rough planning information derived from unspecific and not always up-to-date flightplan information. Therefore, the performance of DCB regulations can be improved by solving inefficiencies of these operations and the management of the ATM network, assuming the availability of accurate and up-to-date 4D planning data.¹

The need for flow management stems from an unevenly distributed load of the network through network nodes in space and time. The mitigation of congestion by ATFM takes place by issuing delays to flights yet to depart; however, imposed delays can be better issued to flights that have small impact on overall network performance than on flights with high impact, and better to

¹ It is one of the main themes of SESAR to initiate a transition from planning by ICAO flightplans to 4D trajectory-based operations, and also to extend bottleneck monitoring activities to the monitoring of the balance of demand and capacity of the entire ATM network.

impose the smallest amount of delay to solve congestion. This leads to a selective optimisation process, selecting flights to accept delays by minimising the amount of imposed delay and minimising the impact on other traffic. Another option to mitigate congestion is re-routing, which is always route and airspace specific and therefore need to be considered in the context of the Airlines' network deployment considerations. Re-routing is not addressed in this paper.

To mitigate congestion, selective assignment of delays can be applied also by taking into account differences in priority. These prioritisation differences can be assigned for ex-ample by selection based on the economic value of flight. The result is a **weighted minimisation of imposed delays**,

applying priority differences between flights within a **local context of time and space**, i.e. selecting constraints for those flights involved in a bottleneck (see Figure 3). Validation has to assess under which conditions this principle can be applied with significant benefits for prioritised flights and without significant impact on the overall performance of the ATM network.

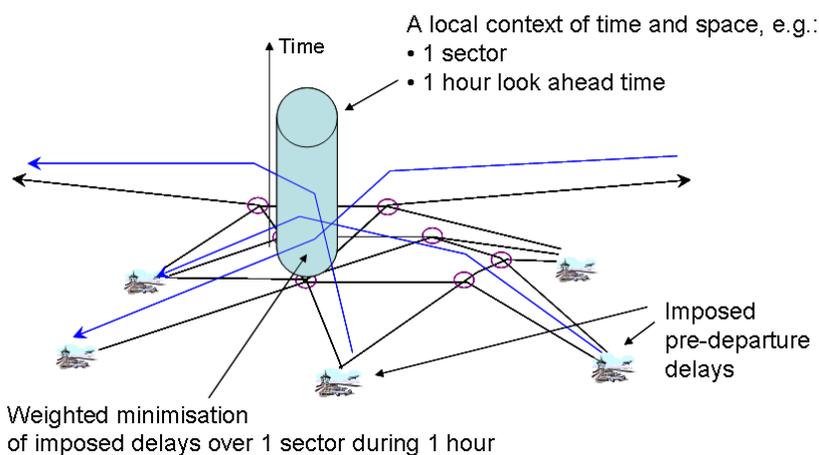


Figure 2 - Principle of operation of Optimising and Prioritising ATFM in a local context of space and time

3 Demand and Capacity Balancing of an ATM Network

This section describes how to manage and analyse the ECAC-wide ATM network, and how the research of this paper addressed this subject. The ATM network is considered regarding the analysis of bottlenecks and critical network throughput as well as regarding the tools' operations to manage and to analyse this network.

3.1 Balancing the network

The need for a process of Demand and Capacity Balancing (DCB) is understood because civil commercial air traffic in Europe is operated within a complex context of operations with limited resources available. High density traffic flows are accommodating city-pair connectivity in the core area of Europe, operating from often saturated airports and creating congestion and

bottlenecks while proceeding through the network. Starting from the principles of convergent layered planning, and aiming to support the planning of air transport operations in a collaborative way, performance of DCB requires a full understanding of the specified demand and capacities of the ATM network:

- **Air Traffic demand:** Specification of demand consists of scheduled ICAO flightplans. These plans are characterised by departure, destination, a list of waypoints and a planned cruise altitude mainly, as well as a scheduled departure and arrival time. These ICAO flightplans are converted by trajectory prediction to 4D flightplans, the SBTs/RBTs (of SESAR), and these flightplans are predicted following their planned routes, and assumed to fly most efficient trajectories along these routes. In real-life, the airspace user will supply a 4D trajectory; in the present experimental environment fast-time simulation provides these trajectories. Optimal 4D-trajectory plans are obtained by avoiding any inefficiency as result of conflict detection, conflict resolution and separation, and these 4D trajectories are stored as RBTs. The total number of 4D planned RBTs through Europe is around 32.000 flights in 24 hours, representing roughly present-day's operations [Ref. 6 and 7].
- **Airports and airport capacity:** Two capacity constrained parts of the ATM network determine the throughput: airports and airspace. The airports are strongly varying in imposing capacity constraints on network operations. On the one hand, air traffic demand varying over the day, is causing constraining conditions. On the other hand, physical constraints like runway capacity, weather conditions and operational constraints determine the airports' capacity bottlenecks and associated congestion problems. The total number of airports in Europe is more than 500, of which 133 airports can be characterised as significant airports, and around 20 as large and major hub airports. The performance assessment study of SESAR Definition Phase showed that ~50% of flight-executive delays per day were allocated at 20 airports and the most significant delays appeared at the 10 largest hub airports [Ref. 6 and 7]. Airports' capacity figures are specified as "sustainable" declared capacity and sometimes also as "ceiling" peak-capacity. For demand regulation purposes the peak-capacity figures are applied, and if not available, the sustainable capacity. The airport capacity is increased by 10% hourly capacity to take into account uncertainty in departure/arrival demand and other uncertainties such as unbalanced demand distribution due to runway configuration usage procedures. The objective is to use capacity figures precisely matching the physical airport capacity, and even then, there are marginal variations possible. Airport capacity figures have still to be considered carefully:
 - Too high capacity figures will disable any throughput regulating performance capability, and too much planned air traffic will cause bottlenecks and inefficiency of operations, measuring (in-flight) delays.
 - Too low capacity figures, for example justified by environmental or noise policy motives, may regulate the throughput more constraining than physically required. The result will be lower throughput than physically possible and thus

low throughput performance figures, which is not desirable from the point of view of the present research.

- **Sectors and sector capacity:** The second capacity constrained part of the network concerns airspace restrictions. RBTs are following routes through volumes of airspace, and these volumes are associated with airspace sectors. These sectors are constrained by different criteria, such as for example the controller workload, the complexity of the sector and the size of the airspace sector volume. These capacity constraints are characterised by declared capacity figures and available figures were applied as made available and unmodified in the experiment, assuming to represent the physical capacity, indeed. All sectors were considered to be “open” and thus accessible.

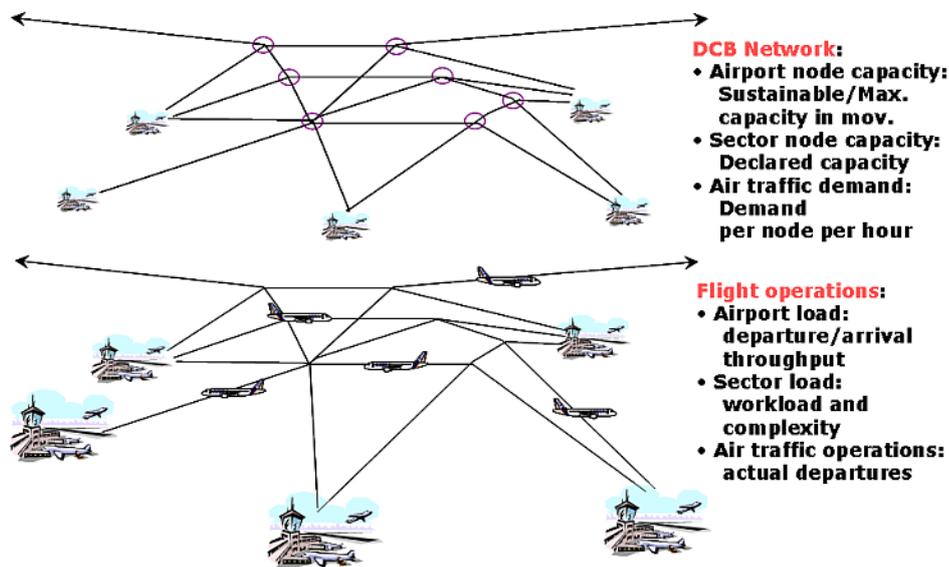


Figure 3 - Illustrative representation of the double network: the (logical, DCB) ATM network representation and the (fast-time simulated) "real-life" operational representation of the Network

The ATM network is characterised in this way by air traffic demand, airport capacity figures and sector capacity figures, whilst the planning by 4D trajectory prediction determines the required city-pair connectivity and the routing from airport to airport through sectors. A major problem of this network is, that airport nodes and airspace volumes (sector nodes), although characterised by similar simple capacity numbers, are totally different in their impact on network behaviour. Airport nodes are directly constrained by congestion; a bottleneck is detected for example because aircraft are waiting for access to a runway, and this access time is measured as “delay”. Sector nodes, however, are not performing directly as capacity constrained nodes. If a sector gets overloaded, the controller has to solve his/her problems and only afterwards it might be discussed to reduce the declared capacity. There is no option to “wait” in the air and to accept delay, unless holding patterns or re-routings are added and executed. This last option is less interesting when investigating capacity and efficiency optimised performance

of the ATM network. Therefore, we discern two networks, the logical DCB ATM network and the “real-life” operational network. Both networks behave differently! (See Figure 3)

3.2 Balancing the ATM network and Optimisation

The present-day policy of CFMU to apply regulations originates from its mission to mitigate congestion when the planning of demand and capacity through the network suffers from identified overloads. Once a node of the network is identified as overloaded, and when regulations apply, flights get departure slots assigned following a principle of first arrival at the sector according to their planning. There are no regulations applicable for the total network by default and airports are not regulated as long as scheduled flights are not evidently causing overloads, not solved at airport level.

The concept of SESAR, under guidance of the principle of convergent layered planning, aims to develop a concept for more systematic management of the ATM network, supported by a Central Network Management function. This function will monitor the balance of demand and capacity through the whole network, and the aim to monitor the full network, implies also to include the airports and their bottlenecks in this process.

Improvement of ATFM, compared to the today’s flow regulation process, stems firstly from a complete and accurately (layered) planning of network capacities and flight-plan information (RBTs). Secondly, the principle to identify overloaded network nodes and to select flights for applying regulations, can be subject of improvement. SESAR formulates a principle that the economic value of a flight will prevail over the traditional First-Come – First-Served (FC-FS) principle, and this principle is subject of research in this paper [Ref. 5]:

- **Traditional ATFM** (flow management) applies regulations by **FC-FS** of planned arrivals at a network node, assigned for regulations.
- **Optimised ATFM** applies regulations by selecting over a time period at an overloaded node and will select those flights for constraint assignments that will **minimise the amount of imposed delays** and that will minimise the impact on other traffic.
- **Prioritised ATFM** applies regulations by selective assignment of imposed delays, taking into account differences in priority. These prioritisation differences may be derived from e.g. differences of the economic value of flights. The result is a **weighted minimisation of imposed delays**, applying priority differences between flights within a local context of time and space, i.e. selecting constraints for those flights involved in a bottleneck (see Figure 2).

Validation has to assess under which conditions this principle can be applied with significant benefits for prioritised flights and without significant negative impact on the overall performance of the ATM network.

This paper presents some results by applying optimisation and prioritisation of ATFM.

3.3 Analysing optimised throughput through the network

Given the fact that nodes of the ATM network (airports and sectors) are so unequal in their operating characteristics, delays and related throughput problems often cannot be attributed straightforwardly to specific node capacity problems. For example, airport and airspace dependency problems, and even a concatenation of bottlenecks, may emerge, and precisely these dependencies may increase congestion problems. A primary requirement is therefore to understand the performance of the ATM network as if it was operating like an ideal network, where demand is just balanced against capacity. This is the reason to separate performance assessment of the ATM network in two clearly segregated parts (See Figure 3):

- **Network throughput analysis**, assessing throughput through the ATM network by analysing the network in terms of capacity per node and demand per node. The throughput analysis is performed by a Petri-net modelled Network Analysis Model (NAM) [See further Ref. 1]. The throughput constraints are characterised by measured “**waiting time**”, accumulated each time a flight has to wait for access to a node when no capacity is available at that time at that node. N.B., it should be noted that this “waiting time” has no direct relationship with “delay”; it is just an indicator of overload at a node.
- **Network ATM performance analysis**, assessing the operational performance of the ATM network by its capability to accommodate demand through realistically modelled network nodes, i.e. airports and airspace volumes. The performance analysis is done by a Fast-Time Simulation tool (FTS), such as e.g. TAAM[®] or AIRTOP[®]. The performance, related to capacity, is measured mainly as maximum achievable **throughput** through runways of airports, as **queuing delays** around runways and as calculated **workload** due to traffic load through sectors [See also Ref. 1].

The experiment presented in this paper is based on **network throughput analysis** only, assuming that the demand and capacity figures are representing the true operational conditions of the ATM network. The consequence is that this paper addresses the assessment of different solutions to solve imbalances between demand and capacity, comparing differences in throughput by different regulations. However, the research did not validate whether the network performance matches the ATM operational performance by assessment of the associated delays and workload. The added value of this paper must be found in successfully demonstrating opportunities to improve network throughput based on available demand and capacity figures.

4 Validation of enhanced ATFCM, an Experimental Plan

An explorative experiment was executed to demonstrate the validity of the ATFM model developed by NLR to evaluate DCB measures and to apply flow management. The results demonstrate the added value to optimise air traffic flow regulations, and the interest of this model for future research. The experiment consisted of a set of experimental runs:

1. **ATFCM Reference scenario:** It was shown that the model can be used to evaluate a present-day ATM scenario, that congestion in the ATM network can be understood, and that measures to mitigate congestion can be assessed on their impact on network throughput and network performance.
2. **Compliance with today's regulations:** The model was assessed on its ability to perform slot regulation procedures with comparable performance characteristics as present-day applicable FC-FS ATFM.
3. **Sensitivity analysis:** The ATM network is sensitive to bottlenecks, and in practice, airports often suffer from reduced capacity e.g. due to severe weather conditions. The model and the scenario were assessed on the impact of reduced capacity on performance at some nodes, i.e. in particular airports.
4. **Options for enhanced ATFM:** The model can be used to evaluate options that will demonstrate that optimising and prioritising ATFM regulation procedures may provide positive control on throughput characteristics with significant benefits for the Air Transport industry. One specific option for prioritisation was assessed on achievable benefits.

This paper will focus on the last two points, i.e. sensitivity analysis to analyse the bottlenecks and their characteristics, and enhanced ATFM to investigate one option for prioritisation of traffic flows under disruptive conditions. The results of the first two points, assessment of a reference scenario and compliance with today's regulations, are input to the last two points, and results are briefly summarised. An extensive analysis is available in the NLR report, NLR-CR-2011-379 [Ref. 1].

4.1 Validation aims

The experiment had to demonstrate feasibility and applicability of optimisation and prioritisation by assignment of imposed pre-departure delays. This was accomplished by a step-wise partial validation process.

The **ATFCM Reference scenario** was demonstrated to be representative. The objective was to understand that:

- The scenario represents a nominal day of air traffic through Europe, indeed.
- The scenario is manageable to be processed with the ATFM prototyping software and feasible to be processed on an ordinary PC-system with acceptable processing time.

- The processing results can be analysed and will show the bottlenecks as well as the characteristics of measures to solve these bottlenecks.
- The prototype software and the processing results can be used as a reference for other more advanced options to mitigate congestion by ATFM.

Some experimental runs aimed to perform sensitivity analysis and some were conducted to measure the effect of prioritisation. A temporary change of capacity was evaluated, assuming incidental disruption of the ATM network at a few well-identified nodes of the network. This case was analysed to demonstrate its wider impact on network performance and to create a reference case to explore optimisation by ATFM:

- In first instance, only reduction of capacity at one airport was evaluated, i.e. capacity reduction at Schiphol.
- Assumed capacity reduction at a few airports was considered more challenging. The impact of capacity reduction at five airports, i.e. EHAM, EGKK, LFPG, EDDF and EDDM, was assessed with capacity reduction percentages of -20% to -30%.
- The effect of prioritisation was evaluated by modifying the FC-FS rules by an option to prioritise flows to and from a selected set of congested airports.

4.2 The Scenario

The most relevant requirements for an appropriate scenario were:

- The scenario had to be representative. The experimental objectives yield assessment of an algorithm and the feasibility to process air traffic demand through an ATM network, and therefore direct comparison with “real-life” operations was not required.
- A present-day scenario was preferred because it is both, balanced and realistic, in its operational characteristics.
- Some demand overloads were required to allow regulations to be effective but excessive overloads and lack of spare capacity, reduce realism as well as the possibilities to improve operations.

After some trial runs and evaluation of observed congestion patterns, a reference scenario was selected:

- **The ATM network:** The network is determined by the waypoints of all flightplans of air traffic demand through Europe. The capacity is determined by sector capacities and airport capacities of 2008. (See Figure 1, page 9.)
- **Kernel Network:** A Kernel Network was selected covering more than only the Core area, but not an ECAC-wide network. The advantage of selecting only part of the ECAC wide network is reduced processing time allowing more sensitivity analyses; the disadvantage is to be less complete and less representative. Measured and calculated congestion is expected to be higher for a Kernel Network than for an ECAC-wide network.

- **Representative Scenario:** The selected scenario, referring to the Kernel Network, comprises 24 hours of traffic, with congestion periods of traffic to and from the hub airports mainly. The selected scenario comprises 15 main airports (see Figure 4), and the scenario is derived from air traffic of a busy day in 2008 [Ref. 1, 6, 7 and 14].
- **Reactionary delays:** This scenario consists of single flightplans only, and by lack of connectivity information, no reactionary delays are part of the observed results. Unfortunately, there was no option to add flightplan linkage information to this experiment.

The properties of this **Kernel Network** scenario are summarised in the following table, Table 1.

Table 1 - Summary of Kernel Network scenario properties

Description	Nr. of entities	Comment
The nominal day scenario comprises ECAC-wide	32.000 flights	
The selected Kernel Network comprises	24.600 flights	Decrease of 23%
Most busy period of the day (06:00/07:00 to 22:00 hour)	20.946 flights	This period was extended to include most of the traffic arriving at the busy early hours of the day by including all arrivals after 06:00/07:00, arriving within the selected area.
Nr. of sector nodes (airspace vol.)	736	
Nr. of airport nodes	514	
Nr. of feeder nodes	9	Exit/Entry path of all flights leaving and entering the Kernel Network.
Nr. of main airports	15	9 hubs and 6 other large airports
Traffic through main airports	11.221 flights	53%



Figure 4 - Overview of Kernel Network Area, representing the most relevant part of the ECAC-wide scenario for analysis of bottlenecks

4.3 The tools and the algorithm

The tools and the algorithm had to address issues concerning network throughput and optimising the throughput. The key issues were:

- **ATM Network:** What represents the ATM network, and do we understand the relationship between airport and sector capacities on the one hand, and air traffic demand on the other hand?
- **Bottleneck behaviour:** Are we able to analyse and manage the network in such a way that bottleneck behaviour is minimised whilst the network still represents the physical ATM network as it is operated in real-life?
- **Effective throughput:** How do we analyse the ATM network, and given scheduled air traffic demand, do we understand the optimisation of throughput through the network in space (a sectorised network) and time (a day of traffic) by modelling and processing planned flight operations through this network?

To answer these questions two new tools were developed, prototyping an innovative network analysis model, i.e. a Network Analysis Model (NAM) and an OPT-ATFM (Optimising ATFM) tool:

- **The NAM tool** is a light tool and performs network throughput assessment only, performing validation within the limited scope of the research actually undertaken, i.e. to balance demand against capacity and to investigate throughput through the network, constrained by capacity limitations only.
- **OPT-ATFM** is a prototype typically for those flow regulation applications that can not be applied yet today, i.e. to replace FC-FS by optimised and prioritised decision making.

These prototype models for ATM regulations have been developed, based on a Petri-net strategy to select a subset of flights involved in a bottleneck. At a congested node, an airport or airspace sector, optimisation and prioritisation of regulations may take place within a local context of space (one node) and time (a pre-determined prediction period, e.g. one hour look-ahead prediction time). (See Figure 3, page 13.) The outcome is obtained by iteration, because each calculated regulation could have impact on planning and regulation measures elsewhere. The result is a weighted minimisation of imposed delays, whilst respecting available capacity and maximising throughput through the network.

The tools were developed on a prototype platform, programmed in Visual-Studio 2008 and C#. This implementation is sufficiently powerful to process part of a nominal day of traffic of an ECAC-wide sample, around the Core Area, within roughly 24 hours. Air traffic was processed and analysed on throughput characteristics, as well as on required pre-departure constraining delays to mitigate disruption.

Together, these tools allow performing sensitivity analysis on the performance of a network representation of the European ATM network. The Kernel Network was used as a representative sub-network, and the results can be used to assess operational improvement of network operations, later on, by fast-time simulation.

4.4 The Key Performance Areas (KPA) and Metrics

The Key Performance Areas (KPA) relevant to expressing the effectiveness of applying ATFCM, are Capacity (throughput, delay and workload, i.e. by ATC) and Efficiency (distance of flight and flight duration). At this stage, only ATFM was assessed, and only on throughput characteristics. The origin of congestion stems from overloads per node and per hourly period, and the relevant metrics, measured by network analysis runs during the busy hours of the day (from 06:00/07:00 to 22:00 hours), are:

- The total and hourly capacity per node,
- The total and hourly demand per node, and the peak load demand per node,
- The total amount of demand overload per hour, and
- The total amount of hourly spare capacity, available to cope with delayed demand.

The measured quantities (KPI) are:

- Total number of flights with a waiting period,
- Total “waiting time” over the day in hours, measuring the deficiencies of capacity during periods of overload at a node (sector or airport),
- Total “waiting time” over the day at the 15 most saturated airports,
- Total pre-departure delay over the day at the 20 most affected airports, measuring the delay required to mitigate “waiting time”
- Hourly distributions of total “waiting time” per run and per airport,
- Hourly distributions of total pre-departure delay for most flow managed airports,
- Key figures of measured total and average “waiting time” and imposed pre-departure delays for each run.
- Geographical overviews of total “waiting time” and imposed pre-departure delays per node (airport or sector) and per run.

5 Conduct of Experiment

The experimental runs are all runs, performed over the Kernel Network, comprising most major airports of Europe, and being representative for the whole ECAC-wide ATM Network. All experimental runs were processed by applying the Network Analysis Model (NAM) and OPT-ATFM, several times to evaluate results by iterative processing.

Further, the scenarios did not comprise any form of linking flights to the physical existence of aircraft, as well as the modelling of use of aircraft to perform several flights per day in a feasible but cost-efficient way. Therefore, and also by missing the modelling of other flight dependencies, there are no measurements of reactionary delays, and late arrivals have no impact on related departures. Also, assessment of operational performance by fast-time simulation was not part of the experiment. However, based on experience of the past [Ref. 6 and 7], there is sufficient confidence that the DCB assessed scenario can be adapted to perform benefits assessment on operational network performance as well.

The experimental runs comprised the following ones:

- The ATFM Reference scenario
- Compliance with today's regulations
- Sensitivity analysis by capacity deficiency
- Options for enhanced ATFM by prioritisation

5.1 The ATFM Reference scenario

The balance of demand and capacity is analysed of a present-day scenario of an ATM network under nominal operational conditions. The most severe bottlenecks are identified as those nodes of the network that shows signs of saturation.

The applicable 24-hours scenario was processed three times by NAM, assessing performance of throughput, and two times by OPT-

ATFM, applying Flow Management on a selected period per overloaded node. The results demonstrated that the iteration process was effective to suppress "waiting time" and to assign "pre-departure delay" (see Figure 5).

The result of assessment of the Reference scenario was:

- 80%-90% of these flights are flights to or from one of the 15 main airports.

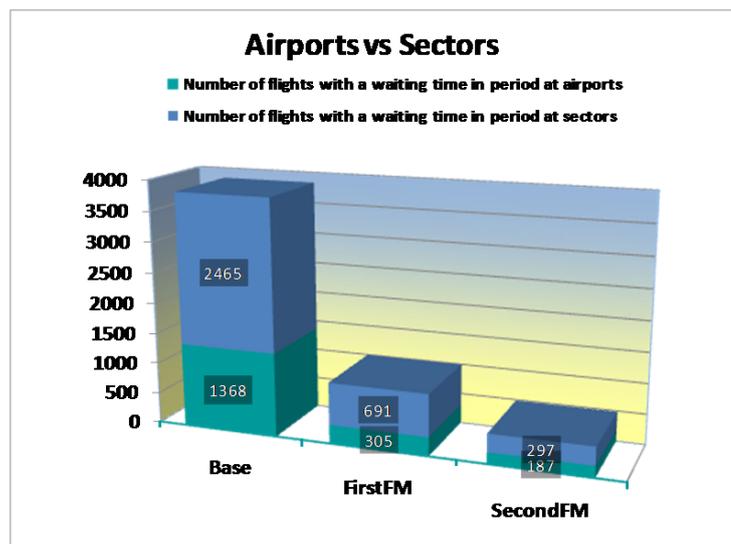


Figure 5 - Throughput problems measured by accumulating "number of flights with a waiting time", partitioned by airports versus sectors, and flow managed 2x by OPT-ATFM



- The Kernel ATM network is definitely not saturated; network “waiting time” is reduced effectively at all congested nodes. For this nominal Reference scenario, the most congested nodes were: LEMD, EGKK, EGLL, EDDM and EDDF, and only some congestion of EDDM could not be suppressed. The reasons were probably saturation in nearby sectors and flights entering the network from outside the selected Kernel Network.
- The airports receiving most of the imposed pre-departure delays were: EGLL, EGKK, LEMD, EDDM and EDDF. These airports show some evidence of being saturated by air traffic demand.

The outcome of this scenario is the reference case for the disrupted scenarios discussed hereafter.

5.2 Compliance with today’s regulations

The network analysis results of the ATM Reference scenario were compared with network analysis results of previous experiments, being assessed for compliance with “real-life” operations [Ref. 6 and 7]. There were some differences in results, making a precise comparison difficult:

- The present experiment addresses the Kernel Network instead of the whole ECAC-wide Network. The observed congestion is higher for just the Core Area, of course.
- Airport capacity figures are used but there is no confirmation of operational validity. It might be necessary to refine the airport declared capacity figures for operational use possibly even to figures specified per hour or per period of the day.
- The present experiment made use of one airport capacity figure per airport. The previous experiment for SESAR used figures split for departure and arrival flows. It seems, however, that this might be overly constraining.
- The experiment of SESAR assessed traffic loads during a time interval from 07:00 to 22:00 for the busiest hours of the day; however, the available traffic sample showed a heavy morning peak from 06:00 to 07:00 in the morning for UK departing traffic. This was not ignored in the present congestion assessment experiment.

The comparison showed how difficult it is to compare different scenarios from different experiments; nevertheless, the results gave confidence in the applicability of the present model on the condition of at least carefully tuning applicable capacity figures.

5.3 Sensitivity analysis by capacity deficiency

Two cases of an unbalance in demand and capacity by disruption were investigated:

- Incidental disruption, e.g. due to weather, by decrease of capacity at EHAM with 30%. This yields a decrease of declared capacity from 108 mov/hour to 76 (84, including 10% tolerance) (See Figure 6.)
- Incidental disruption by decrease of capacity at 5 selected airports: EHAM (-30%), EDDF (-20%), EDDM (-20%), EGKK (-20%) and LFPG (-30%).

The first case, EHAM disrupted, causes delays of peak hour traffic. These delays are impacting the congestion at other airports, however, only a few other airports suffer significant increase of delay. The congestion at airspace sector level even decreases, because the bottleneck at EHAM airport works as a sort of dose filter on upstream sectors.

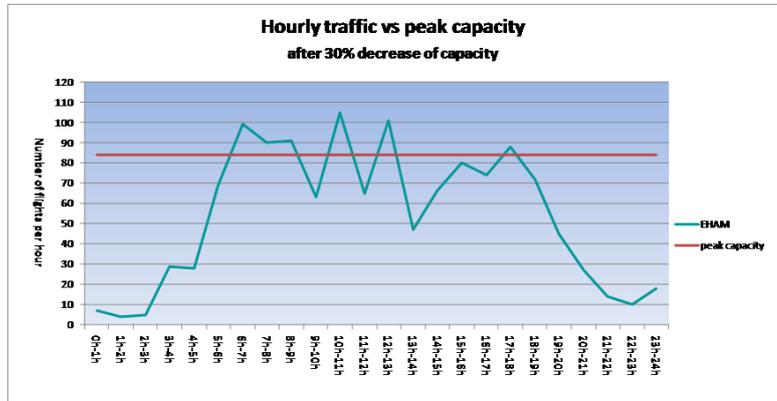


Figure 6 - Hourly distribution of traffic demand at EHAM under disrupted conditions

The scenario of disruption at 5 airports shows a similar pattern as the scenario of one disrupted airport:

- A strong increase of “waiting time” at 5 disrupted airports and not too much impact on other airports due to late arrivals, although still ignoring reactionary delays, but a strong positive effect (reduced load) on airspace sectors by constrained access.
- The ATM system shows the typical behaviour of a saturated system with increase of imposed pre-departure delays at the end of the day. Of course, the disrupted airports had to accept again most of these delays.
- The “waiting time” due to disruption at 5 airports can still be suppressed by a strong increase of imposed pre-departure delays. The imposed delays are similar in total delay and number of impacted flights, as the observed “waiting time” figures due to network congestion.



Figure 7 - Imposed pre-departure delays to mitigate airport/sector congestion for the 5-airport disrupted scenario

Figure 7 shows the imposed pre-departure delays to solve congestion at 5 capacity disrupted airports. Most imposed delays are assigned to flights departing from the disrupted airports.

5.4 Options for enhanced ATFM by prioritisation

Just one option was selected to assess optimisation by prioritisation, i.e. by assignment of priority to departure/arrival flights at disrupted airports. In first instance, prioritisation was attributed to flights of the 5 capacity disrupted airports, but it turned out that a major part of imposed delays moved now to London Heathrow, because the algorithm had no a priori knowledge of the level of saturation of airports in the network. When London Heathrow, EGLL, was added to the group of 5 prioritised airports, the performance improved considerably. However, this first attempt supports the suggestion that further refinement in priority selection and applicability of priority criteria might be even more beneficial to the performance of the network and the operations at disrupted airports.

The selected option yields to prioritise access of flights through designated nodes, which can be either an airport or a sector. Prioritisation is applied whenever there is a choice to prioritise and whenever there is a feasible alternative, often a flight to or from a smaller non-prioritised airport. The prioritisation is implemented by moving the assigned pre-departure delay to the flight to or from the non-prioritised airport.



Figure 8 - Imposed pre-departure delays to mitigate airport/sector congestion for the 5-airport disrupted scenario, applying OPT-ATFM with prioritisation

The most delayed airports in the disrupted scenario were EDDM, EGLL, EDDF, EGKK, EHAM and LFPG, exactly the 5 disrupted airports and, in addition, London Heathrow. In the prioritised scenario the 5 capacity disrupted airports are still part of top-ten of pre-departure delay receiving airports, whilst London Heathrow even falls out of this list. The amount of

imposed pre-departure delays for these most penalised airports drops sharply to roughly 25% of the original amount of imposed delay.

Figure 8 shows that the distribution of imposed pre-departure delays, i.e. the distribution of imposed delays including prioritisation, is more balanced than before as presented in Figure 7. The imposed delays at congested airports strongly decreased and these delays were moved to smaller airports.

The results of both experimental runs, without and with prioritisation, provide insight into the effects of prioritisation on a designated group of flights through the ATM network. It shows how performance of this network can be improved once disruption is understood and congestion anticipated as predicted. The conclusion is that once it is known a priori that one or more nodes of the network are heavily congested, an advantage can be achieved for the performance of the whole network by applying prioritisation on the group of flights through these nodes. Further, this is most obviously beneficial also to the congested hub airport nodes themselves.

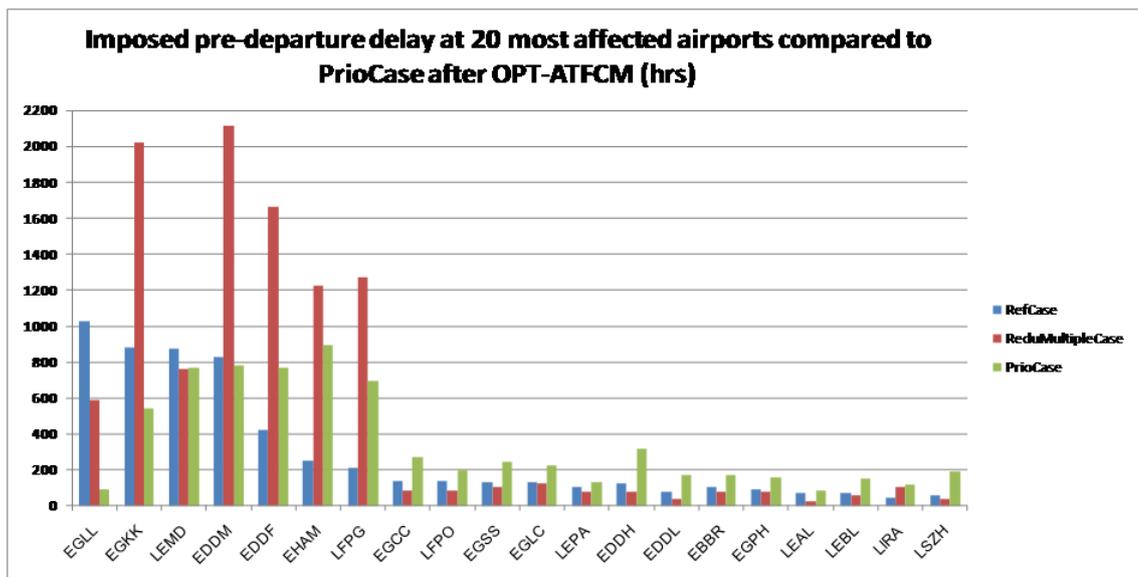


Figure 9 – Chart presenting the differences in imposed pre-departure delays at the 20 most affected airports, comparing Reference Scenario, the 5-airports disrupted scenario and the 5-airports disrupted scenario with prioritisation

Figure 9 shows the redistribution of imposed delays over the most penalised airports: Firstly for the Reference scenario, secondly for the 5-airports-disrupted scenario, and thereafter for the 5-airports-disrupted, 6-airports-prioritised scenario. The benefits are not only a re-distribution of imposed delays but also an improvement of overall performance. The reason is that waste of available capacity is avoided by not penalising flights through already capacity disrupted nodes. Lots of small airports receive imposed pre-departure delays now, in favour of improved throughput for the 5 (6) heavily congested airports, and this has a beneficial effect on overall throughput.

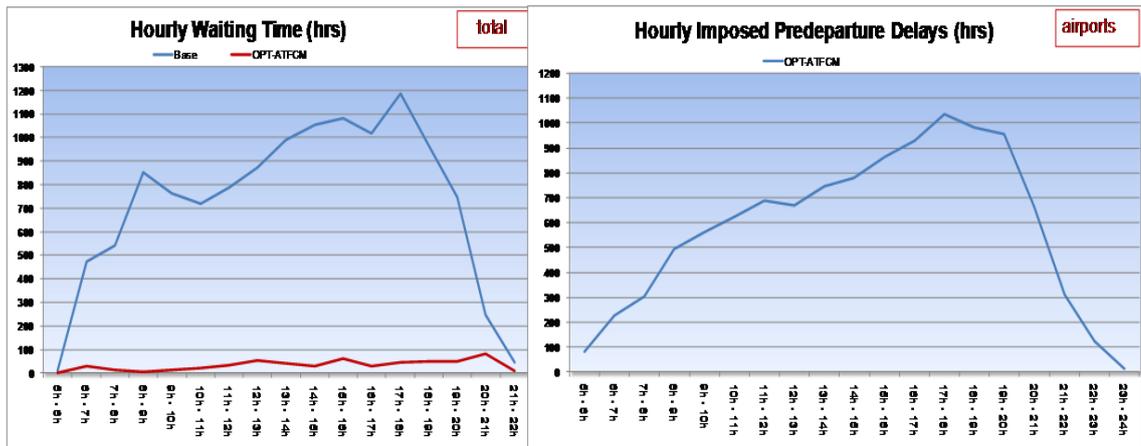


Figure 10 - Hourly distributions of "waiting time" (with and without) imposed pre-departure delays (left) and the distribution of imposed pre-departure delays (right)

The overall performance is illustrated by the graphs of Figure 10. The graphs present an hourly distribution of “waiting time” and imposed pre-departure delays to mitigate “waiting time” within the measured Kernel Network:

- The blue line (left) presents a distribution of “waiting time” for a 5-airports disrupted scenario without imposing any delay. There are indications visible of saturation.
- The blue line (right) presents the imposed pre-departure delays to mitigate the “waiting time” by smoothing air traffic demand, including prioritisation.
- The red line (left) presents the remaining “waiting time”, and this line indicates that most of the experienced “waiting time” problems are solved now.

Comparing these performance figures for different scenarios gives evidence that prioritisation will be effective in reducing “waiting time” as well as limiting the required pre-departure delays to solve the congestion problems.

The following table, Table 2, presents some key figures for the Reference scenario, the 5-airports disrupted scenario (ReduCaseMultiple) and the prioritised scenario (PrioCase). The first part of the table presents the congestion to be solved, the “waiting time”, the second part the solution, the “imposed pre-departure constraints” to mitigate the “waiting time”. Most striking results of applying prioritisation are:

1. The overall observed “**waiting time**” of the prioritised scenario improves with an average of 2 min. per flight, compared to the non-prioritised scenario.
2. The required **imposed pre-departure delay** to solve congestion improves by a more efficient delay attribution mechanism. The net effect is a more balanced distribution of penalties over disrupted airports and all other less critical operating airports:
 - The average imposed pre-departure delay per flight decreases from 35 min. to 32 min. (-8%),
 - The average delay at main airports decreases from 54 min. to 30 min. (-44%)
 - The delay at remaining airports increases from 14 min. to 35 min. (+150%)

Table 2 - Summary of “waiting time” and imposed delays comparing Reference scenario, 5-airport disrupted scenario and 5-airport disrupted scenario + prioritisation

Throughput analysis by measuring “Waiting time”			
	RefCase	ReduCaseMultiple	PrioCase
Total number of flights			
Number of flights with a waiting time in period	4011	4774	5998
Number of flights with a waiting time in period at airports	1368	2838	3493
Number of flights with a waiting time in period at main airports	1239	2694	3351
Number of flights with a waiting time in period at sectors	2465	1795	2338

	RefCase	ReduCaseMultiple	PrioCase
Total waiting time			
Total waiting time in period (hrs)	8576	12003	11246
Waiting time in period at airports (hrs)	3330	8380	6205
Waiting time in period at main airports (hrs)	3154	8097	5903
Waiting time in period at sectors (hrs)	5245	3622	5041

	RefCase	ReduCaseMultiple	PrioCase
Average per flight			
Waiting time in period (min)	24,6	34,4	32,2
Waiting time in period at main airports (min)	16,9	43,3	31,6
Waiting time in period at remaining airports (min)	1,1	1,8	1,9
Waiting time in period at all airports (min)	9,6	24,2	17,9
Waiting time in period at sectors (min)	15,0	10,4	14,4

Calculated imposed pre-departure constraints			
	RefCase	ReduCaseMultiple	PrioCase
Total number of flights			
Number of flights with a pre-departure delay in period at airports	4115	5324	6387
Number of flights with a pre-departure delay in period at main airports	2243	3448	3368

	RefCase	ReduCaseMultiple	PrioCase
Total pre-departure delay after each run			
Total pre-departure delay in period at airports (hrs)	8018	12199	11076
Pre-departure delay in period at main airports (hrs)	5021	10010	5589

	RefCase	ReduCaseMultiple	PrioCase
Average per flight after each run			
Pre-departure delay in period (min)	23,0	34,9	31,7
Pre-departure in period at main airports (min)	26,8	53,5	29,9
Pre-departure in period at remaining airports (min)	18,8	13,7	34,4

6 Conclusions and Recommendations

The research presented in this paper aimed to answer some questions on city-pair connectivity. The approach was to investigate the ATM Network on sensitivity for disruption and to find beneficial mitigation strategies for dealing with disruptive events. A new approach is proposed here to mitigate loss of capacity by smoothing air traffic demand by application of an advanced algorithm for calculating ATFM imposed pre-departure delays. This new ATFM strategy applies optimisation and prioritisation for calculating imposed pre-departure delays, and for one specific case, i.e. capacity disruption at 5 airports, it was validated that such a strategy could lead to a reduction of at least 40% of total amount of imposed pre-departure delay for those disrupted airports. In addition, all major and hub airports could benefit from the applicable disruption-mitigation strategy due to enhanced throughput through the most congested parts of the ATM network.

Sensitivity analysis:

The experiment demonstrated that the applicable ATM network and the air traffic demand was representative and was not excessively congested. Nevertheless, there is capacity available that can be deployed in a more effective way by better balancing the regulation procedures.

The sensitivity experiment demonstrated further how incidental disruption at one or more airports, leading to reduced capacity of those airports, would impact the performance of the ATM network. Local disruption is causing loss of performance by invoking large amounts of “waiting time”, whilst the disrupted airports are penalised again by imposed pre-departure delays to solve the experienced disruption.

Prioritisation:

The results of just one case to improve ATFM suggests that selective optimisation and/or prioritisation can become very beneficial by making more efficient use of available capacity of an ATFM network. This is valid in particular in case of high density traffic flows and when part of the network is fed by saturated airports.

Several other options are possible to improve performance results. For example, prioritisation can be assigned only to traffic flows to and from hub airports during periods of overload of declared/operational capacity. Another option is to prioritise flights with “a critical role” in the deployment scheme of an Airline. The first example will benefit time-efficiency and throughput, the second example cost-efficiency and economic deployment of Airline’s network operations. Anyhow, it must be possible to keep better balance in benefits and penalties by fine-tuning throughput analysis and fine-tuning the issuing of imposed pre-departure delays. A balancing

mechanism will be able to benefit from accurate planning information available and from a delay assignment strategy operating in a local context of space and time.

The results of the presented experiment showed that overall “waiting time” can be reduced whilst even decreasing the total amount of imposed pre-departure delays. The throughput of hub airports showed major improvements and decreased imposed delays, whilst remaining airports had to accept more “waiting time” and more imposed pre-departure delays, but never an excessively large amount of delay per airport. The overall chart of distribution of waiting time and delays looks significantly improved, compared to the non-prioritised case (see Figure 9).

Recommendations:

Enhanced ATFM by optimisation and prioritisation is a concept to make better use of available capacity by a complete and refined process, based on assumed availability of accurate planning data. However, the achievable throughput and efficiency in performance of operations depends strongly on the capacity figures as well. In this experiment, demand and capacity figures, were both representative figures but no verified figures. All outcomes are indicative for that reason, and precise benefits are dependent therefore on experimentally verified capacity figures, in particular on verified airport capacity figures.

It is recommended to perform the described assessment experiment again on a full ECAC-wide ATM network scenario, using carefully verified capacity figures. In particular, the airport capacity figures have to match the “real-life” peak-period operational capacity figures. The outcome of network performance data has to be validated also by a “real-life” operational validation experiment, which can be achieved by ECAC-wide fast-time simulation. The outcome of this fast-time simulation experiment will give the required confidence in realism and will allow quantifying “real” benefits achievable under operational conditions.

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