



# Optimising Air Traffic Flow Management

Improving the assignment of pre-departure delays using optimisation on the assignment of slots

Customer

National Aerospace Laboratory NLR

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## EXECUTIVE SUMMARY

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		Time	Time	Remarks
420	Eindhoven	11:50	12:29	
321	Paris ORY	12:25	12:36	Delayed
4923	Dortmund	12:40	12:39	
853	Copenhagen	12:45	13:07	Delayed
4853	Copenhagen	12:45	13:07	Delayed
1554	Oslo	13:15	12:56	
5443	London LGW	16:30		
224	Paris BVA	17:10		

## 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.

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.

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Improving the assignment of pre-departure delays using optimisation on the assignment of slots

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

Local imbalances between demand and capacity in advanced ATFM are solved by assigning pre-departure delays. Besides the possibility to apply conventional First Come First Serve slot assignment, categories of flights can be prioritised. The rigid application of prioritisation ensures that flights with a prioritised status receive absolute precedence over non-prioritised flights at an overloaded sector or airport. As a result, non-prioritised flights have a risk of getting assigned excessive pre-departure delays. To achieve a more balanced assignment of pre-departure delays, the existing tool is enhanced by including a weighted optimisation between prioritised flights and non-prioritised flights.

### 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.

### 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.

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# Content

Summary	5
Nomenclature	5
Abbreviations	6
I. Introduction	6
II. Background and context	6
II.A. Network Management Operations Centre	7
II.B. Challenges in ATFM	7
III. Preliminary NLR research: Prototype flow management tool	7
III.A. The core algorithm	7
III.B. Modelling air traffic using a Petri-net algorithm	8
III.C. Prioritising disrupted airport flights	8
III.D. Applying reservations	9
III.E. Assigning delays	9
III.F. Limitations	10
IV. Design of the optimisation module	10
IV.A. Variables	10
IV.B. Constraints	11
IV.C. Iterative optimisation	11
IV.D. Objective function	11
V. Experimental set-up and scenario	13
V.A. Slot assignment principles	13
V.B. Network scenarios	14
V.C. Sensitivity analysis weighting factors objective function	14
VI. Experimental results	14
VI.A. Costs of delay	16
VII. Recommendations for future research	17

VIII. Conclusions	18
References	18



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This paper presents the results of a study that has been conducted as part of a larger research programme that explores the use of innovative slot assignment principles in Air Traffic Flow Management. The present work builds on a prototype flow management tool which has been developed during a previous study. In this tool local imbalances between demand and capacity are solved by assigning pre-departure delays. Besides the possibility to apply conventional First Come First Serve slot assignment, categories of flights can be prioritised. The rigid application of prioritisation ensures that flights with a prioritised status receive absolute precedence over non-prioritised flights at an overloaded sector or airport. As a result, non-prioritised flights have a risk of getting assigned excessive pre-departure delays. To achieve a more balanced assignment of pre-departure delays, the existing tool is enhanced by including a weighted optimisation between prioritised flights and non-prioritised flights. The enhanced flow management tool is evaluated in this study by processing a set of flights that represents a day of air traffic in 2008 in the core area of Europe. In addition, network-disruption is simulated by reducing the capacity of some major hub airports. The results show that using optimised prioritisation results in a reduction of required pre-departure delays and costs of delay compared to using a First Come First Serve slot assignment. Moreover, a better control over the spread of delays is achieved by using optimised prioritisation instead of absolute prioritisation.

## Nomenclature

$AT_j$	Planned arrival time of flight $j$	[min]
$C$	Capacity of a node	[flights/hour]
$J$	Set of flights	[-]
$O$	The time a flight takes up capacity in a node	[min]
$P_i$	Weighting factor corresponding to priority level $i$	[-]
$P_j$	Priority level of flight $j$	[-]
$P_{MM}$	Weighting factor corresponding to minimax objective	[-]
$P_{WT}$	Weighting factor corresponding to minimising total waiting time	[-]
$t$	Discrete time instance	[min]
$t_{end}$	Last time instance in the optimisation	[min]
$t_{start}$	First time instance in the optimisation	[min]
$T$	Set of discrete time instances	[-]
$WT_j$	Waiting time of flight $j$	[min]
$X_{j,t}$	Binary variable for flight $j$ at time $t$	[-]
$Z$	Maximum waiting time	[min]
$Z_i$	Maximum waiting time of flights with priority level $i$	[min]

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### **Abbreviations**

ATFM	Air Traffic Flow Management
CASA	Computer Assisted Slot Allocation
FCFS	First Come First Serve
FPPR	First Plan Penalising Regulation
NLR	<i>Nationaal Lucht- en Ruimtevaartlaboratorium</i> , National Aerospace Laboratory
NMOC	Network Management Operations Centre

## **I. Introduction**

The goal of Air Traffic Flow Management (ATFM) is to prevent local demand-capacity imbalances by adjusting flows of aircraft.<sup>1</sup> In other words: ATFM matches the demand of the network with its capacity by initiating flow management measures.

The *National Aerospace Laboratory* (NLR) has initiated a research program on ATFM to investigate innovative slot assignment methods. The research conducted at NLR has resulted in a prototype flow management tool that is able to perform flow management on a large scale European scenario by solving local imbalances between demand and capacity using assignment of pre-departure delays. To permit deviations from the First Come First Serve principle that is currently used to perform flow management in Europe, specific flights can be prioritised in the local context of an overloaded airport or sector.

Prioritisation is executed such that flights with a prioritised status have absolute precedence over non-prioritised flights at a congested airport or sector. Although prioritisation may lead to operational benefits in terms of cost-efficiency and throughput at congested airports or sectors, the rigid application of prioritisation also has disadvantages: if a sector or airport is heavily congested and there are many priority flights, non-prioritised flight may receive additionally delayed slots. Consequently, flights with a non-prioritised status have a risk at getting assigned excessive delays. Moreover, this may result in a high spread of delay.

The current study explores the effects of using a weighted slot assignment between prioritised flights and non-prioritised flights instead of using an absolute prioritised assignment. To enable a weighted slot assignment, an optimisation module is developed and designed that optimises the assignment of slots within the local context of an overloaded node.

This paper first describes the background and context of the research. Subsequently, a detailed introduction is given on the existing prototype flow management tool. Next, the design of the optimisation module is explained. Thereafter, a brief outline is given of the set-up of the experiment, followed by a discussion of the results. The paper is concluded with some recommendations for future research and the corresponding conclusions.

## **II. Background and context**

In Europe, a large number of airports is fully coordinated. This implies that flights are planned such that the traffic load at airports will not exceed the declared capacity. As a result, demand does not exceed capacity at these airports under normal operations,<sup>2</sup> though small weather disturbances may cause a reduction in capacity and may require additional flow management measures. In addition, en-route sectors may create congestion problems. According to Lulli & Odoni<sup>2</sup> *“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”*. ATFM aims to prevent such demand-capacity imbalances by adjusting flows of aircraft on a national or regional basis.<sup>1</sup>

The focus of this research is on tactical ATFM, which is executed on the day of flight operations. During tactical flow management, the air traffic flow is managed by regulating individual flights. Due to the congested character of the European air space, delaying departure times of aircraft is the method that is used most frequently in Europe.<sup>3</sup>

## II.A. Network Management Operations Centre

In Europe, the Network Management Operations Centre (NMOC) performs tactical flow management and assigns departure slots and required pre-departure delays to flights in case of overloads. The Computer Assisted Slot Allocation (CASA) system is the core system and calculates the take-off time for those aircraft which are subjected to ATFM measures.<sup>4</sup> The CASA algorithm works according to a First Come, First Serve (FCFS) principle. This means that flights are allocated to slots in the order in which they are planned in the original schedule.

## II.B. Challenges in ATFM

Because of the continuous growth of air traffic and the congested character of the European ATM network, it is a challenge to continue performing ATFM in a fair and cost-efficient way.

The challenge within ATFM is to strive for equity or fairness. Equity means that a systematic bias against certain flights, airlines or origin-destination pairs is absent.<sup>2</sup> As explained above, the NMOC uses a slot assignment mechanism that is derived from a FCFS principle. This is considered to be a fair method of imposing pre-departure delays because the original scheduled order of flights is maintained.

However, using a fair method does not necessarily mean that it is the most cost-efficient method. Indeed, a FCFS slot assignment principle does not necessarily result in the most cost-efficient assignment of pre-departure delays because larger network effects are not taken into account and the minimisation of the total delay or total costs of delay is not a pre-requisite.

Therefore, to optimise the European ATFM situation, a balance must be found between efficiency (based on minimising some function of total delay cost) and equity.<sup>2</sup> To achieve this, it is important to investigate slot assignment methods that differ from the current FCFS-based slot assignment principle.

## III. Preliminary NLR research: Prototype flow management tool

To examine the impact of innovative slot assignment procedures in ATFM, a prototype flow management tool has been developed at NLR. The tool enables to perform flow management on a day of traffic in the core area of Europe and to avoid overloads in the network of airports and sectors by assigning pre-departure delays to flights. The main principles of the existing prototype flow management tool are discussed in detail in this section.

### III.A. The core algorithm

The core algorithm of the prototype flow management tool consists of three phases that are executed iteratively. The three phases are defined as:

1. Applying reservations in a look-ahead period (Section III.D)
2. Assigning delays (Section III.E)
3. Processing flights using a Petri-net algorithm (Section III.B)

First, for all network nodes (each airport and sector) reservations are made for the flights that are planned to enter these nodes in a look-ahead period of four hours. The flights that are planned to enter a node in the look-ahead period are scheduled using an absolute prioritisation process. This means that flights with priority are planned with precedence over non-prioritised flights. When all capacity of a node is currently taken and a flight cannot directly enter the node at its planned arrival time, it sustains waiting time and receives a future reservation. Waiting time is an artificial parameter that indicates how long a flight is expected to be waiting, either on the ground or in-air, at a certain node. When the four hour look-ahead period is completely covered, all reservations are copied to the original model.

From the reservations that are planned in the look-ahead period, it is determined which flights require pre-departure delay. The amount of pre-departure delay that is assigned equals the maximum waiting time that a flight encounters along its route.

When the required delays are assigned, part of the enhanced schedule is processed to include the effects of the assigned pre-departure delays. This is done for a flight progress time interval of ten minutes

and a Petri-net algorithm is used to simulate the replanned flight movements.

When the ten minutes of flight processing is completed, the model enters the following look-ahead period. This process repeats iteratively until all flights of the 24-hours flight schedule have been processed and an enhanced schedule is determined that will eliminate overloads in the network. Figure 1 visualises the subsequent phases of the prototype flow management tool in a time line.

The continual iterative process of applying reservations in a look-ahead period and subsequently processing actual flights in the Petri-net, has a positive influence on second-order network effects. Due to the assignment of pre-departure delays, flights will arrive at a node later than the initially planned arrival time. This may result in previously used capacity coming available again. This available capacity may be filled up in a following look-ahead period by rescheduling flights. As a result, the amount of required delay for other flights may decrease and second order network effects are suppressed.

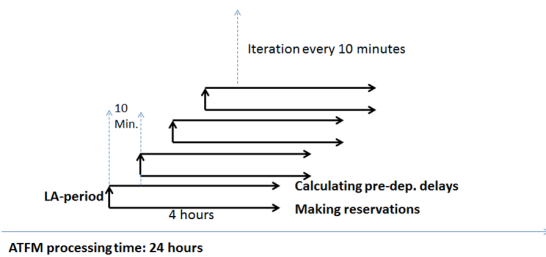


Figure 1. Time line showing the subsequent phases in the core algorithm<sup>6</sup>

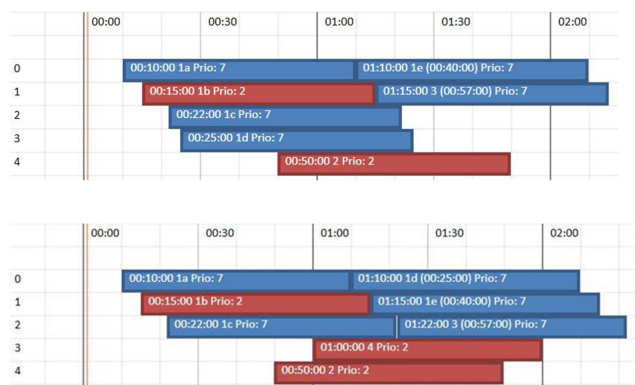


Figure 2. Creating reservations based on arrival time and priority<sup>5</sup>

### III.B. Modelling air traffic using a Petri-net algorithm

In the existing flow management tool, a Petri-net algorithm is used to model the flow of air traffic through the ATM network. To simulate the flights in the network, a Petri-net is constructed consisting of places, tokens and transitions. The Petri-net enables a token to be moved from one place to the other by firing several transitions. In this case, the token represents the flight and the places are the nodes in the network. Detailed information on the implemented Petri-net system can be found in.<sup>6</sup>

### III.C. Prioritising disrupted airport flights

In conventional FCFS flow management, no distinction is made between flights flying to or from main hub airports and flights flying to or from secondary point-to-point airports. However, in<sup>10</sup> it is stated that “*hub-and spoke operations show the largest reactionary delays, whereas point-to-point operations show only a small share of reactionary delay because they often operate independent services without the need to wait for connecting passengers or load*”. Due to the interdependencies between aircraft, crew, cargo and passengers of flights operating at hub airports, the total costs of delay of such flights may increase rapidly in case of disruption. Therefore, it may be beneficial for the overall network to prioritise flights operating at disrupted hub airports and to let them fly their planned schedule as close as possible.

To achieve optimal operational efficiency, flow management cannot be performed by looking at the air transportation network as a set of individual aircraft only required to fly from *a* to *b*. On the contrary, all flights are part of an operating schedule and all decisions that are made should take into account effects on the overall network. According to<sup>11</sup> “*it is important to note that, for an airline, the value of delay is not just its effect on an individual airframe but its effect on the operating schedule*”.

To improve the use of resources and enhance the network operations compared to a FCFS slot assignment principle, disrupted airport flights are assigned a higher priority level than flights from non-disrupted

airports in the existing prototype flow management tool. By prioritising flights flying from or towards disrupted main hub airports, the prototype flow management tool is able to reduce the delays that are assigned at these airports. As a result, disrupted hub airports are alleviated and the total required pre-departure delays are redistributed better between non-disrupted main airports and secondary airports.

To use prioritisation in the flow management tool each flight receives a priority level. This priority level determines whether a flight has precedence over another flight in times of congestion. The highest priority level (level 2) is assigned to flights coming from an out-node. These flights depart from an airport outside the core area of Europe, and therefore cannot be assigned pre-departure delay and receive high priority. The next, lower, priority level (level 3) is assigned to flights that departed and are currently in-air. The lowest priority levels (levels 6 and 7) are for increased priority and standard priority flights, respectively. These two priority levels are currently used to distinguish between disrupted airport flights and non-disrupted airport flights. Note that the priority levels 4 and 5 are assigned internally in the delay assignment process.<sup>5</sup> Priority level 1 is currently not used.

This classification in priority levels can be used in different ways. Therefore, two settings exist in the tool that determine the applicable priority levels:

- *OutOnly*: In this setting, flights coming from an out-node receive priority level 2. All other flights receive priority level 7. This prioritisation setting comes close to the FCFS slot assignment principle that is used in operational ATFM.
- *MainHigher*: In this setting, flights coming from an out-node receive priority level 2. On top of that, flights coming from or going to a disrupted airport node (disrupted airport flights) receive a priority level 6. All other flights receive priority level 7.

### III.D. Applying reservations

Each airport and air sector in the network has an hourly capacity on which future traffic is scheduled: during a look-ahead period the reservations for flight segments planned to arrive at a node up to four hours ahead in time are created.

A reservation is made based on the arrival time of the flight at the node and the priority level of the flight. Flights with a higher priority level always have precedence over flights with a lower priority level. For flights with the same priority level, those with an earlier planned arrival time are planned first.

In Figure 2, the process of assigning reservations is visualised. In this figure, the capacity of the node is represented on the vertical axis. Each row, with a number ranging from 0 to 4, represents a unit of capacity holding a list with reservations. The node visualised in this figure has an hourly capacity of 5 flights. The reservations for the flights planned to enter this node are visualised by the coloured bars. Each reservation is made for one hour. The information on the bars is as follows: first, the expected entry time is given, this is followed by the call sign of the flight. In this example, a short notation call sign (1a, 1b etc.) is used. If the flight cannot directly enter the node, it will get a future reservation. If this is the case, the original planned arrival time is given between brackets. Finally, the priority level of this flight is presented.

In this figure it can be observed that the allocation of reservations is done in an absolute manner. Flights with a higher priority level always have precedence. Low-priority level flights need to make space for the higher-priority level flights. Due to this absolute allocation, situations may occur in which high-priority flights push low-priority flights to the end of the look-ahead period. As a result of this, low-priority flights may receive a large amount of waiting time, just to prevent a small amount of waiting time for high-priority flights.

### III.E. Assigning delays

At the end of processing each look-ahead period the required pre-departure delays are calculated and assigned. First, it is checked whether a flight is eligible to receive a pre-departure delay. Flights that come from an out-node or flights that are already in-air cannot receive a delay. For flights that can receive pre-departure delays there is another requirement: the complete flight must be captured in the preceding look-ahead period to be able to determine the required delay.

Once a reservation has been made for all the flight segments of a flight, the maximum assigned waiting-time along this flight route can be determined. Subsequently, this maximum amount of waiting time is assigned as pre-departure delay.

### III.F. Limitations

To improve the performance of ATFM with respect to fairness and cost-efficiency the effects of enhanced slot assignment methods need to be explored. The prototype flow management tool that has been described in this chapter is able to determine the effects of prioritisation of specific flights on delay assignment and it showed promising operational benefits.

However, according to<sup>5</sup> applying reservations in an absolute prioritising way can be improved. As explained above, using absolute prioritisation may result in an unfair assignment of waiting time to lower-priority flights. As a result, these flights receive excessive pre-departure delays. Furthermore, absolute prioritisation may lead to the formation of gaps of unused capacity between high priority flights. Besides this, there is a high spread in assigned delays: when nodes are saturated, flights with no priority may receive excessive pre-departure delays and as a result there is no control on the standard deviation of assigned pre-departure delays.

Therefore, the current study explores the effects of a weighted slot assignment between prioritised flights and non-prioritised flights instead of using an absolute prioritised assignment. To do so, an optimisation module is developed and integrated into the existing prototype flow management tool to enable weighted optimisation on the application of reservations.

## IV. Design of the optimisation module

Creating reservations using absolute prioritisation may result in an unfair assignment of waiting time to low-priority flights. To reduce the impact of this unconditional absolute assignment, an optimisation module is designed. This module is included in the existing prototype flow management tool and is called after each look-ahead period. It enables a weighted optimisation of the allocation of reservations and the corresponding assignment of waiting times to flights. Binary programming is used to perform the weighted optimisation of the allocation of reservations for each airport and sector. The design of the optimisation module is clarified by introducing the variables, constraints, and objective function of the optimisation.

### IV.A. Variables

The variables of the binary programming formulation are defined to be:

$$X_{j,t} = \begin{cases} 1 & \text{if flight } j \text{ is planned to enter the node at time } t \\ 0 & \text{else} \end{cases} \quad (1)$$

The binary variable  $X_{j,t}$  is assigned the value one if flight  $j$  from the set of flights  $J$  is planned to enter the node at discrete time  $t$  in time set  $T$ .

Flights with priority 2 or 3 ( $P_j = 2$  or  $3$ ) cannot receive a pre-departure delay. Consequently, these flights should enter the node at the same time as they are planned to enter the node. As a result, the variables that belong to these super priority flights can be set in advance. For the time of arrival at the node ( $AT_j$ ), the binary variable equals one. For all other time instances it equals zero:

$$\forall j \in J; P_j = 2 \vee 3: \quad X_{j,t} = \begin{cases} 1 & \text{if } t = AT_j \\ 0 & \text{else} \end{cases} \quad (2)$$

In rare cases it may happen that a node is so congested that even a priority 2 or 3 flight requires waiting time. In such cases, such a flight should enter the node at the calculated entry time as determined in the absolute prioritisation process.

Besides having restrictions on the super-priority flights, a flight cannot enter the node before its planned arrival time. Therefore, for each flight all binary variables belonging to the time instances before the planned

arrival time of the flight are set to zero:

$$\forall j \in J; t < AT_j: \quad X_{j,t} = 0 \quad (3)$$

#### IV.B. Constraints

To ensure a correct planning of all the flights of the set  $J$  in the time interval  $T$ , several constraints are required. The first set of constraints (Equation 4) ensures that each flight is planned exactly once:

$$\sum_{t \in T} X_{j,t} = 1 \quad \forall j \in J \quad (4)$$

The second set of constraints (Equation 5) ensures that the planned entry time of each flight is greater or equal to its arrival time at the node:

$$\sum_{t \in T} t \cdot X_{j,t} \geq AT_j \quad \forall j \in J \quad (5)$$

The next set with constraints are the capacity constraints. These constraints ensure that at each discrete time instance the number of flights in the node does not exceed its capacity. In Equation 6 the capacity constraints are defined.

In this equation,  $O$  is the time that a flight occupies capacity in a node. This value equals 60 minutes. Furthermore,  $C$  equals the capacity of the node. The capacity constraint describes that at each discrete time instance  $t$ , the sum of the number of flights that start in an hour interval around time  $t$  should be less or equal to the capacity of the node. For each time  $t$ , the constraint ensures that during the time interval  $s$ , ranging from  $t - 30$  to  $t + 29$ , the sum of the binary variables  $X_{j,s}$  does not exceed the capacity of the node.

$$\sum_{j \in J} \sum_{s=\max(t_{start,t}-0.5 \cdot O)}^{\min(t_{end,t}+0.5 \cdot O-1)} X_{j,s} \leq C \quad \forall t \in T \quad (6)$$

The *max* statement in the lower limit of the summation over  $s$  ensures that the starting point of the summation interval is not before the start time of the discrete time interval ( $t_{start}$ ). Furthermore, the *min* statement in the upper limit ensures that the end point of the summation does not go beyond the last time step of the discrete time interval ( $t_{end}$ ).

#### IV.C. Iterative optimisation

Iterative optimisation is used in the optimisation module to improve the performance of the discrete optimisation. This concept is based on<sup>7,8</sup>

To use iterative optimisation in the binary problem formulation, all capacity constraints are relaxed. Next, an optimal solution is obtained using these relaxed conditions. The optimal solution for the relaxed conditions is checked for capacity conflicts. If capacity conflicts exist at certain discrete time instances, the corresponding constraints are added. Again, an optimal solution is determined and checked for capacity conflicts. This is repeated iteratively until no capacity conflicts exist anymore and the overall optimal solution is found.

Adding iterative optimisation to the initial discrete model decreases the computation time of optimising the example node. Because not all capacity constraints are added in one go, iterative optimisation helps in preventing over-constraining of the optimisation problem.

#### IV.D. Objective function

The optimisation shall minimise the total waiting time in a node and shall be able to suppress excessive amounts of waiting time. Consequently, the objective function consists of two parts, viz.: minimisation of total waiting time and minimisation of the maximum waiting time. Besides this, the optimisation shall be able to distinguish between different priority levels. Therefore, priority weighting factors are added to the objective function.

##### Minimise total waiting time

The first part of the objective function minimises total waiting time. Minimising total waiting time is equal to

minimising the calculated entry times of all flight reservations. The entry time of a flight is represented by the sum of all binary variables corresponding to that flight ( $X_{j,t}$ ) multiplied with the corresponding integer time instances ( $t$ ). Therefore, minimisation of the total waiting time in a node is formulated as:

$$\text{Minimise : } \sum_{j \in J} \sum_{t \in T} t \cdot X_{j,t} \quad (7)$$

### Minimax function

Besides minimising total waiting time in a node, the goal of the objective function is to prevent the assignment of excessive waiting times. This can be achieved by using a minimax objective. A minimax objective requires a maximum to be minimised.

The main idea of a minimax objective is shown in Figure 3. The amount of waiting time is shown for five flights. The variable  $Z$  equals the maximum value of the waiting times that are assigned to the five flights. The minimax objective requires to minimise this value  $Z$ . In the figure,  $Z$  is an imaginary bar that minimises the maximum and spreads the waiting time over multiple flights.

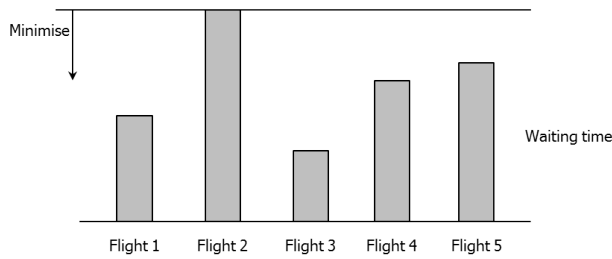


Figure 3. Minimax objective

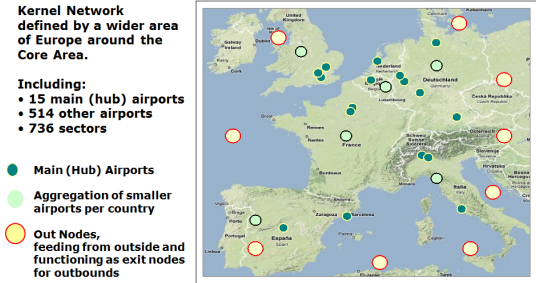


Figure 4. Experimental scenario<sup>6</sup>

To make use of a minimax function in the binary programming formulation, an additional decision variable must be added. This variable is called  $Z$  and must represent the maximum waiting time of all flights in the node. The waiting time of a flight is determined by subtracting the planned arrival time of the calculated entry time. The waiting time of flight  $j$  ( $WT_j$ ) in the look-ahead period with a set of discrete time steps  $T$  is determined by the following equation:

$$WT_j = \sum_{t \in T} (t - AT_j) X_{j,t} \quad (8)$$

$Z$  is forced to represent the maximum waiting time by including the following set of constraints for all flights in the look-ahead period:

$$\sum_{t \in T} (t - AT_j) X_{j,t} \leq Z \quad \forall j \in J \quad (9)$$

To ensure that the maximum waiting time is minimised, the term  $Z$  must be added to the objective function:

$$\text{Minimise : } Z \quad (10)$$

### Priority weighting factors

To enable a balanced allocation of reservations between different priority flights, weighting factors are used in the objective function of the optimisation.

Flights with priority level 2 and 3 are not allowed to receive any pre-departure delay and will therefore not be included in the optimisation. Priority levels 4 and 5 are assigned to those flight parts that are planned internally. It is preferred to prevent these flights from receiving large amounts of waiting time. Finally, flights with priority level 6 and 7 are the lowest priority flights and will sustain most of the waiting time.

The flights with priority level 4, 5, 6 and 7 are allowed to receive waiting time in a node. For these priority levels a corresponding weighting parameter is introduced. These parameters are defined as  $P_4$ ,  $P_5$ ,  $P_6$  and  $P_7$  and represent the weighing of a specific priority flight in the objective function.

First, the part of the objective function that represents minimisation of the total waiting time is multiplied with the priority weighting factors. This is done by multiplying the total waiting time of a set of flights of the same priority level ( $P_j = i$ ) with the corresponding weighting factor ( $P_i$ ):

$$\text{Minimise : } \sum_{i=4}^7 (P_i \cdot \sum_{j \in J: P_j=i} \sum_{t \in T} t \cdot X_{j,t}) \quad (11)$$



Subsequently, a minimax function is defined for the four different priority classes. These are also multiplied with corresponding priority parameter:

$$\text{Minimise : } \sum_{i=4}^7 (P_i \cdot Z_i) \quad (12)$$

The end-user of the prototype flow management tool can specify realistic values for these weighting factors and feed these into the tool. This way, the user is able to control the importance of the different priority flights. In the scope of the current research a sensitivity analysis has been conducted to determine meaningful values for the weighting factors. The results of this sensitivity analysis are discussed in Section V.C.

### Overview

Since the objective function consists of two main parts, corresponding weighting factors are created to determine the balance between these parts. The weighting factor for minimising total waiting time is  $P_{WT}$ . The weighting factor of the minimax criterion is  $P_{MM}$ . The values of these factors can also be specified by the end-user of the prototype flow management tool.

Combining all the elements that were introduced above results in the following overall objective function:

$$\begin{aligned} \text{Minimise : } & P_{WT} \cdot (P_4 \cdot \sum_{j \in J: P_j=4} \sum_{t \in T} t \cdot X_{j,t} + P_5 \cdot \sum_{j \in J: P_j=5} \sum_{t \in T} t \cdot X_{j,t} + P_6 \cdot \sum_{j \in J: P_j=6} \sum_{t \in T} t \cdot X_{j,t} + \\ & P_7 \cdot \sum_{j \in J: P_j=7} \sum_{t \in T} t \cdot X_{j,t}) + P_{MM} \cdot (P_4 \cdot Z_4 + P_5 \cdot Z_5 + P_6 \cdot Z_6 + P_7 \cdot Z_7) \end{aligned} \quad (13)$$

## V. Experimental set-up and scenario

Figure 4 visualises the main airports in the geographical area that is covered by the scenario used to assess the prototype flow management tool. Besides this, an aggregation of all the smaller airports per country is shown. Finally, the out-nodes show the borders of the ATM network that is used in the tool. This network is created and used in the previous research projects on ATFM at NLR and will therefore also be used in the current research. To limit computational effort, a part of the complete ECAC area, represented as an enlarged area around the core area of Europe, is simulated. In this network, there are 15 main airports and 499 secondary airports. Furthermore, 736 nodes represent the en-route sectors and Terminal Manoeuvring Areas (TMA).

Although the actual capacities of airports and sectors may vary over the day, the capacities in the model are set to a constant integer value. The capacities of airspace sectors range between 20 to 50 flights per hour. The typical capacity for a main airport is between 80 and 125 flights per hour and the typical capacity for a secondary airport is set to be between 25-50 aircraft per hour.<sup>5</sup>

The flight scenario that is used in the flow management tool originally represents a day without severe disruption or bad weather in July 2005. The flight scenario has been upgraded with flights to represent a similar day in 2008. The original ECAC wide scenario consisted of approximately 32000 flights. To represent the scenario in the network visualised in Figure 4, the amount of flights has been reduced to 24492 flights.<sup>6</sup>

### V.A. Slot assignment principles

The optimising prototype flow management tool is tested using three slot assignment principles. For each scenario, flow management is performed using OutOnly prioritisation, MainHigher prioritisation and optimised prioritisation:

- **OutOnly prioritisation** closely resembles a FCFS slot assignment principle. In this setting, only flights coming from outside the core ECAC area are prioritised and these are not allowed to receive pre-departure delays.
- **MainHigher prioritisation** aims at enhanced throughput at disrupted airports and assigns absolute priority to flights coming from and going to these disrupted airports.
- **Optimised prioritisation** includes the optimisation module that is developed in the current study and assigns reservations using a weighted optimisation between prioritised and non-prioritised flights.

### V.B. Network scenarios

Flow management measures are taken when the capacity of either an airport or an en-route sector is expected to drop below demand or when demand is expected to exceed capacity. Capacity of airports may decrease during periods of disruption. Examples of disruption are strikes, de-icing, ICT failures, poor weather or airport construction work. To simulate such disruptions in the network, the nominal capacities of a set of main airports are reduced.

The scenario (**reduced+ scenario**) that is discussed here comprises disruption at seven main airports. The capacity of both Amsterdam Airport Schiphol (EHAM) and Paris Charles de Gaulle Airport (LFPG) is reduced with 30%. In addition, the capacities of Frankfurt Airport (EDDF), Munich Airport (EDDM) and London Gatwick Airport (EGKK) are reduced with 20%. Two additional airports in the congested London area and Paris area are added as disrupted airports. These airports are London Heathrow Airport (EGLL) and Paris Orly Airport (LFPO) and their capacities are reduced with 15% and 45%, respectively.

To assess the effectiveness of optimised prioritisation in ATFM, the distribution of required pre-departure delays is assessed for this scenario using the different prioritisation methods. In addition, parameters such as average delay and spread of delay are also assessed.

### V.C. Sensitivity analysis weighting factors objective function

A sensitivity analysis has been performed to determine the effects of the weighting factor values in the objective function on the assigned pre-departure delays and the remaining waiting time in the system. Different configurations were tested while running the tool using optimised prioritisation. The scenario is processed until 10:00 AM and the corresponding outputs are analysed.

From the sensitivity analysis it follows that the best overall operational performance is found using the weighting factor values presented in Table 1. These settings have been used in all validation runs.

In this sensitivity analysis a small part of the complete spectrum of parameter settings was analysed

Table 1. Parameter settings for the objective function

	$P_{WT}$	$P_{MM}$	$P_4$	$P_5$	$P_6$	$P_7$
Parameter value	1	1	3	3	1.5	1

for the current scenario. This shows that the values of the objective function parameters allow control over important performance parameters such as total assigned pre-departure delay, remaining waiting time and average and standard deviation of the assigned pre-departure delays. Detailed information on the complete sensitivity analysis is presented in.<sup>12</sup>

## VI. Experimental results

The effects of including optimisation in the prototype flow management tool are assessed for the reduced+ scenario. The reduced+ scenario consists of a network in which 7 airports are affected by disruption. In this section the results of the OutOnly, MainHigher and optimised priority runs are discussed. The pre-departure delays that are required for flow management are shown in Table 2.

Using OutOnly prioritisation requires in total 1761.28 hours of pre-departure delay. Of this, approxi-

Table 2. Results of flow management for the reduced+ scenario, using OutOnly, MainHigher and Optimised prioritisation

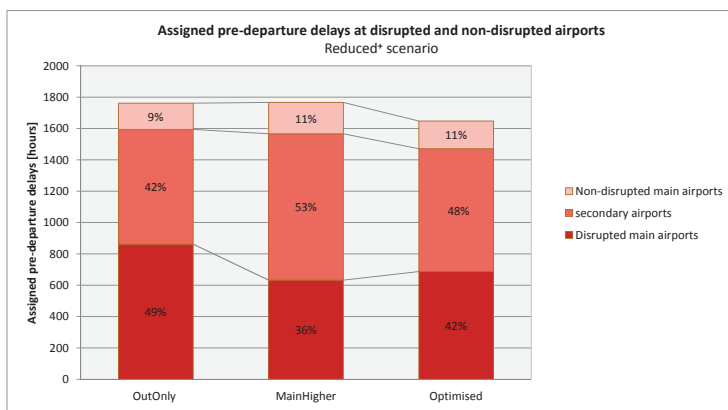
<i>Reduced+ scenario</i>		At all airports	Main airports	Disrupted airports	Secondary airports
<b>OutOnly</b>	Pre-departure delays [hr]	1761.28	1029.00	861.87	732.28
	Nr. of flights [-]	6357	3679	2964	2678
<b>MainHigher</b>	Pre-departure delays [hr]	1766.45	832.92	632.63	933.53
	Nr. of flights [-]	6317	3511	2784	2806
<b>Optimised</b>	Pre-departure delays [hr]	1647.43	864.03	687.27	783.40
	Nr. of flights [-]	6274	3606	2911	2668

**Table 3. Remaining waiting time after flow management using OutOnly, MainHigher and Optimised prioritisation, for the reduced+ scenario**

<i>Reduced+ scenario</i>		Total	At airports	At sectors
<b>OutOnly</b>	Remaining waiting time [hr]	16.28	11.02	5.27
	% of original waiting time [-]	1.17	1.23	1.06
<b>MainHigher</b>	Remaining waiting time [hr]	9.57	5.58	3.98
	% of original waiting time [-]	0.59	0.59	0.59
<b>Optimised</b>	Remaining waiting time [hr]	19.92	10.02	9.90
	% of original waiting time [-]	1.24	1.06	1.47

mately 860 hours are assigned to the seven disrupted airports which are therefore heavily affected. Prioritising the flights to and from these airports, results in a slight increase of total required pre-departure delays of approximately five hours. However, the required delays at the disrupted airports are suppressed by more than 200 hours. Consequently, the secondary airports have to deal with an increase of assigned delays. When optimisation is used, a reduction of overall assigned delays of around 120 hours is achieved. This is confirmed in the bar-chart that is presented in Figure 5.

Figure 5 shows that optimisation results in a more balanced distribution of delays between disrupted



**Figure 5. Assigned pre-departure delays at disrupted and non-disrupted airports, for the reduced+ scenario**



**Figure 6. Geographical distribution of differences in assigned pre-departure delays at airports between OutOnly prioritisation and optimised prioritisation for the reduced+ scenario**

airports and secondary airports. Whereas in the MainHigher situation 36% of delay is assigned at the disrupted airports, this increases to 42% in the optimised situation. Moreover, the share of delays at the secondary airports decreases from 53% tot 48%.

The remaining waiting times in the system after performing flow management are presented in Table 3. It is determined that the assignment of pre-departure delays suppresses more than 98% of the waiting time in the system for the three slot assignment principles.

As explained before, using optimisation results in advantages for the disrupted airports compared to using OutOnly prioritisation. This is confirmed and visualised in Figure 6. In this figure, a large decrease in required delays is noticed at the 7 disrupted main airports. Besides this, some other secondary airports in the UK, France and Italy benefit from the optimisation. To create these benefits, the delays at the other secondary airports have increased. The delays are spread evenly between these airports and there are no noticeable outliers.

The assigned pre-departure delays at the airports that are mostly affected are shown in Figure 7. The most left bar represents the pre-departure delay at London Heathrow airport (EGLL). Since this airport suffers from disruption in the current scenario, substantial delay is required at this airport in the OutOnly setting. Using MainHigher prioritisation allows to suppress the amount of delay significantly. Finally, optimisation results in a slight increase in delays at EGLL and the other disrupted airports. However, the secondary airports are alleviated and a more balanced distribution of imposed pre-departure delays over

the airports of the ATM network is achieved.

Table 4 shows that the maximum assigned delay, using optimisation, is almost an hour lower compared

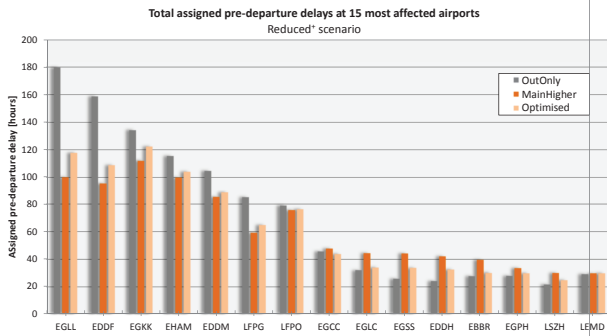


Figure 7. Total assigned pre-departure delay at 15 most affected airports for the reduced+ scenario

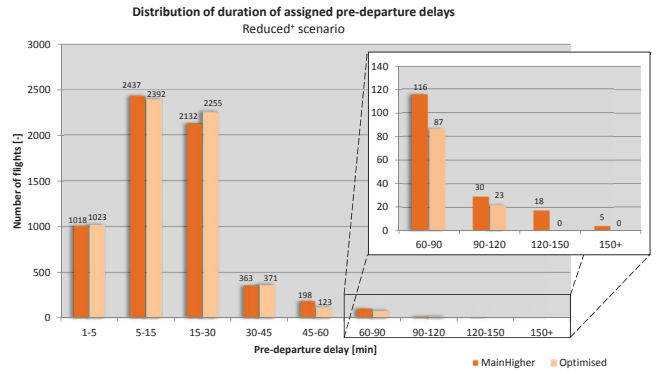


Figure 8. Distribution of the duration of assigned pre-departure delays for the reduced+ scenario using MainHigher prioritisation and optimised prioritisation

to the situation in which OutOnly and MainHigher priority is used. In addition, optimisation is able to suppress part of the average assigned delay, compared to using OutOnly and MainHigher priority. Compared to the OutOnly settings, the spread of delay did not decrease. This is ascribed to the fact that in OutOnly prioritisation there are not as many priority classes and the creation of gaps of unused capacity is limited. Moreover, the spread of delay using optimisation has decreased with one and a half minute compared to MainHigher prioritisation. This reduction in spread is also confirmed in Figure 8.

According to Figure 8 there are 5670 flights with a pre-departure delay lower than 30 minutes in the

Table 4. Maximum assigned delay, average assigned delay and spread of delay for the reduced+ scenario, using OutOnly, MainHigher and optimised prioritisation

Reduced+ scenario	OutOnly	MainHigher	Optimised
Maximum assigned pre-dep. delay [hh:mm:ss]	02:47:00	02:47:00	01:54:00
Avg. pre-dep. delay over all flights [mm:ss]	04:19	04:20	04:02
Std. dev. pre-dep. delay over all flights [mm:ss]	09:32	11:07	09:36

optimised situation. If MainHigher priority is used, there are 5587 flights with a delay less than 30 minutes. On top of that, it is seen that the number of flights with delays higher than an hour has decreased significantly while going from MainHigher to optimised prioritisation (from 169 to 110). Using optimisation does not require any flight to have a delay in excess of two hours, whereas in the MainHigher situation over 20 flights have a delay exceeding two hours.

### VI.A. Costs of delay

In this section a simplified analysis on the estimated costs of delay is presented. The cost-function that has been adopted in this study was originally defined in,<sup>5</sup> based on.<sup>9</sup>

In<sup>9</sup> it is concluded that there exists a relation between aircraft take-off weight and the corresponding cost of delay. In addition, the at-the-gate delay cost estimates are given for a B737-800 and B747-400. The costs of 15 minutes of delay for these aircraft are estimated at €440 and €1230, respectively, and include the passenger costs of airlines.<sup>9</sup> In<sup>5</sup> these cost values are combined with the aircraft take off weight, resulting in a linear relation for the cost of a minute of delay.

A non-linear cost function is used to express that two 15 minutes delay costs are less than one delay of 30 minutes.<sup>9</sup> Delays lower than 5 minutes are not counted at all in the cost of delay. Moreover, for a delay between 5 and 15 minutes, a linear cost relationship is used. For delays in excess of 15 minutes, the corresponding cost increases exponentially with the extent of the delay. The resulting relations are presented in.<sup>5</sup>

To determine the total cost of delay for each scenario, the cost of delay for general aviation jets and business jets are not included. In addition, only the flights in the flight plan for which the aircraft type is known can be

included in the analysis. The resulting costs of delay, using OutOnly, MainHigher or optimised prioritisation, are shown in Table 5. In addition, the relative changes in delay with respect to OutOnly prioritisation are shown for the MainHigher and optimised case.

It is concluded that optimised prioritisation results in significant cost reductions with respect to the FCFS,

**Table 5. Total cost of delay and the relative change in cost of delay compared to OutOnly prioritisation**

	<b>OutOnly</b>	<b>MainHigher</b>		<b>Optimised</b>	
Reduced <sup>+</sup>	2.5 M€	2.3 M€	-9.50%	2.2 M€	-11.42%

OutOnly prioritisation. For the reduced<sup>+</sup> scenario, a reduction of around €300.000,-, which is more than 11%, is achieved.

When shifting from MainHigher prioritisation to optimised prioritisation, the total amount of delays at disrupted airports increases. On average, the cost of delays at disrupted main airports are higher than the cost of delays at secondary non-disrupted airports due to the large share of wide-body aircraft flights at these disrupted main airports. Therefore, optimisation may contribute to a small increase in costs of delay. Though, it is noted that for the reduced<sup>+</sup> scenario, the total costs of delay using optimisation is decreased, compared to using MainHigher prioritisation. From this it follows that there is enough room in this scenario to redistribute the delays between disrupted main airports and non-disrupted secondary airports in a more optimal way, compared to using MainHigher prioritisation.

In summary, these results show that the optimised system makes the process of flow management more cost-efficient, but also more robust in dealing with disruption and loss of capacity.

## VII. Recommendations for future research

The optimising prototype flow management tool is validated using different prioritisation and optimisation methods for a specific flight plan and a network with disruption in.<sup>12</sup> To further improve the tool and its operational applicability, some recommendations are made for future research:

- The flight plan that is currently used in the tool dates from 2005 and is updated to represent a scenario in 2008. This scenario is limited and outdated. Therefore, a more up-to-date scenario is required.
- The network that is currently used represents a core area of the total ECAC area. To improve the operational applicability of the tool it is valuable to include the complete European-wide scenario.
- In the current scenario, all capacities are assumed constant over the day. It is operationally more realistic if part of the capacities are specified as hourly capacities. For example, airport capacity depends on the applicable runway configuration, which may change over the day. In addition, this enables the simulation of more realistic disruptions of, for example, a few hours.
- Currently, reactionary delays are not taken into account. To include true network operations more research must be done on the effects of connecting flights and reactionary delays. Therefore, it is required to have a flight plan in which connection information is available.
- To contribute to collaborative decision making, airlines should be involved in the ATFM process to a greater extent. The prototype flow management tool includes an option to prioritise specific flights. This option may be further developed such that airlines can increase the priority of specific flights at a certain cost.
- In the assessment of the different scenarios, constant values are used for the weighting factors in the objective functions. Therefore, a constant weighting between different priority flights is considered. Determining the weighting factors for each node individually may result in a better assignment of delay. For example, it may be beneficial in heavy congested nodes to assign a very high weighting factor to low-priority flights to ensure that these flights do not receive high amounts of weighting time. In addition, a Monte-Carlo simulation could be executed to find an optimal set of weighting factors for a complete day of operations.

- To be able to use the prototype tool in tactical operational ATFM, the computation time should be improved. At the moment, it takes the optimised prototype flow management tool slightly under 12 hours to process and optimise a day of flight operations. This may be reduced by improving the flow management algorithm or to use higher-performance computational software and hardware.
- Fast time simulations should be performed to verify whether the operational performance benefits that are found using the prototype flow management tool are indeed realised under real life operational conditions.

## VIII. Conclusions

The resulting optimising prototype flow management tool is used to perform flow management, using Out-Only, MainHigher and optimised prioritisation.

Optimised prioritisation reduces the total amount of assigned pre-departure delays with respect to the OutOnly and MainHigher prioritisation. A reduction in delay of 6.5% is achieved when optimised prioritisation is used instead of OutOnly prioritisation. This reduction is a result of redistributing the required delays over disrupted and non-disrupted airports in a more optimal way.

Compared to using MainHigher prioritisation, using optimised prioritisation results in a slight increase in pre-departure delays at the disrupted airports. This is a result of loosening the absolute prioritisation of flights coming from and going to these airports during optimisation. Although the delays at the disrupted airports increased, the assigned pre-departure delays at the non-disrupted secondary airports decrease significantly.

Using optimised prioritisation results in a better control over the standard deviation of the assigned delays, compared to using the absolute MainHigher prioritisation. Using a simplified model to estimate global cost impact shows that the total costs of delay with respect to OutOnly prioritisation are estimated to be reduced by -11%. Finally, it is shown that the tool is able to maximise the throughput by suppressing the original waiting time in the system by almost 99%. The optimising prototype flow management tool is able to process a day of flights in a large part of the ECAC airspace within 12 hours, using a fairly powerful pc-system.

Including the optimisation module in the existing tool results in a robust prototype flow management tool that is able to perform flow management in a more balanced way for different disrupted scenarios. Using optimisation reduces the total amount of assigned delays and the costs of delay compared to the OutOnly priority setting. In addition, it is shown that the throughput is nearly optimal and that the tool has a better control on the spread of pre-departure delays, compared to the absolute prioritisation that is used in MainHigher prioritisation.

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## WHAT IS NLR?

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