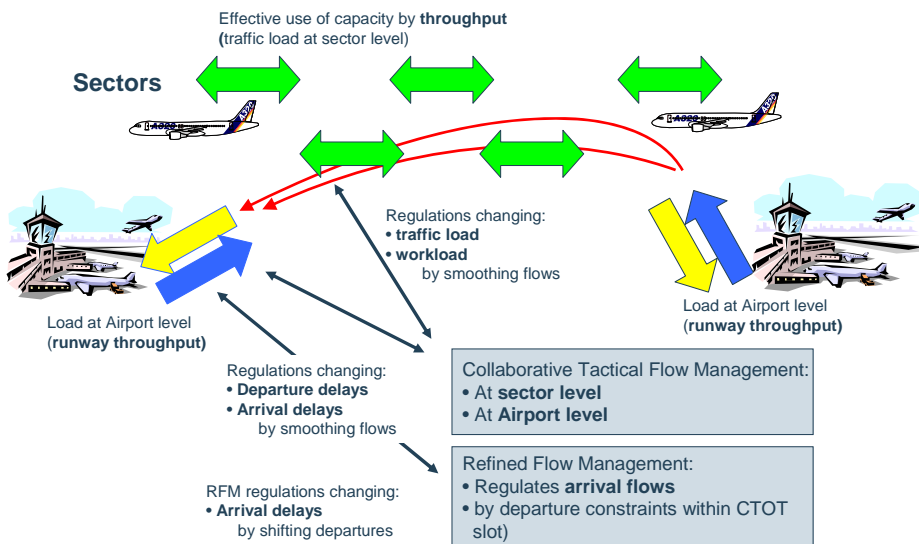## Executive summary

# Flow Management on the ATM Network in Europe



**Problem area**

This technical Paper addresses European wide Demand and Capacity Balancing by Collaborative Air Traffic Flow Management (CTFM) and Refined Flow Management (RFM), zooming in at part of the core area to analyse critical aspects of this sub-network of operations.

The challenge of future developments in Air Transport is to find an optimal balance between Demand and Capacity:

▪ Following STATFOR predictions and User expectations, the Demand will increase steeply. STATFOR predicts around +50% air traffic demand in Europe for 2020; the Users require Air Traffic Management (ATM) to be able to accommodate at least twice the present-day demand (+100%),

▪ The Capacity provided is determined by Airport capacity, restricting the need to provide enough ATM capacity to meet Airport demand.

▪ The ATM Capacity required is determined by the way Users want to make use of Airport capacity, but the ATM Capacity provided is determined by the route network, the sectorisation, the organisation of ATM and the workload imposed by ATM service provision.

The most critical elements in the ATM network, the bottlenecks, are determining the optimal

This report is based on a paper presented at the 7th AIAA Technology Integration, and Operations (ATIO), Belfast (Northern Ireland), 18-20 September 2007.

performance of the ATM network. Because Europe offers a natural and coherent scope of operations, performance has to be studied at the level of the European network. Delays and disruption in even remote European areas are directly impacting the operations at congested airports and in congested areas, and measures have to be taken therefore at a European level to minimise a negative impact.

## Description of work

Part of the SESAR Definition Programme was to conduct performance assessment experiments in workpackage 2.3.1 of that project. This paper reports on results of NLR's experiment in that workpackage.

The experiment of NLR addressed the following conceptual elements.

- The Network Operational Plan (NOP) and Demand and Capacity Balancing (D&CB)
- Collaborative Traffic Flow Management (CTFM)
- 4D trajectory planning
- Airport-to-Airport regulations by Refined Flow Management (RFM)

NLR conducted their experiment by performing sets of fast-time simulations using TAAM®, and by performing throughput analysis using a Network Analysis Model (NAM).

## Results and conclusions

An overview of the outcome of the analysis of simulation results of the experiments of NLR is described in this paper.

The questions addressed in the experiment, were to investigate first the forecast scenarios and their consequences and secondly how operational enhancements could improve operations. The first question leads to the conclusion that even modest forecasts of demand were showing structural deficiencies of capacity both at airport and sector level.

The second question was how successful the enhanced concept elements were to mitigate the congestion problems?

In the experiment there was only one way to solve unbalances and that was by imposed delays. The results yield sometimes very large constraining delays, which can be interpreted partly as strategic constraints and partly as tactical constraints/delays. Moreover, significant parts of these delays are bound to a small number of specific airports and sectors. The trade-off was a reduction of in-flight delays and sector overloads.

The applied full network CTFM model was effective in reducing delays but at a high price. What was missing, was a clear optimisation strategy. The RFM model was ineffective, because delays were already suppressed by CTFM. However, the mechanism of RFM is more subtle and provides its benefits at the price of fewer constraining delays than CTFM.

Therefore further study is recommended on:

- Optimisation of the applicable network in terms of an optimal routing and a proper balance of capacities as an essential part of development of the SESAR operational concept.
- An optimisation strategy for flow management (CTFM) to determine pre-departure constraints with minimal delaying effects.
- An optimisation strategy to smooth arrival flows to congested destinations which is both in balance with CTFM and ensures minimal delays.

## Applicability

The work reported contributes to reach performance assessment capability for an advanced operational concept at an ECAC-wide level.

The scenarios of 2005, 2012 and 2020 are offering a view on bottlenecks and constraining conditions in ATM, now and in the future. There is no way to profit from conceptual benefits if not the whole network is in balance, offering sufficient capacity to ensure an undisturbed throughput of demand over a representative day of operations in Europe. This study, therefore, shows how to identify the bottlenecks and how to analyse possible ways to mitigate the problems.

NLR-TP-2007-650

# Flow Management on the ATM Network in Europe
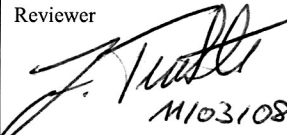
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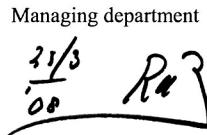
| | |
|---|---|
| Customer | National Aerospace Laboratory NLR |
| Contract number | ---- |
| Owner | National Aerospace Laboratory NLR |
| Division | Air Transport |
| Distribution | Unlimited |
| Classification of title | Unclassified |
| | December 2007 |

Approved by:

| Author | Reviewer | Managing department |
|---|---|---|
| 11/3/08 | M/03/08 | 21/3 08 |

## Summary

Last years' steady increase of air traffic demand forces Air Traffic Management in Europe to anticipate on how to provide the capacity needed. A programme like SESAR aims to address capacity but, at the same time, aims to improve ATM by reducing costs and increasing efficiency of flights. In this context there is a need to be able to assess the performance of ATM service provision at an ECAC-wide scale, and to investigate the trade-offs. This paper addresses one essential part of this assessment, namely how well the ATM system is able to maintain an acceptable balance between demand and capacity for future operations under certain assumed conditions in the applicable scenarios. These conditions are reflected in particular by forecast figures for traffic demand and by assumptions regarding available capacity. Improvements of operations can be part of these scenarios as well. Fast-time simulations and model-based processing provide the means to assess achievability of performance targets. The result is a first estimate of accommodated demand, achievable operational performance benefits and potential improvement of operations by the addressed operational concept elements. The results of the work presented in this paper were obtained by conducting an initial operational performance assessment experiment, being part of the Definition Phase of the SESAR Programme.

# Contents

# 1 Introduction

All air traffic forecast indications are pointing towards a sustained air traffic growth over the coming years in Europe. Trends in growth rates have been identified and tend to yield values between 2% and 4% even in the long term. Less evident is how to cope with this growth. SESAR, as the major European ATM improvement programme, aims to provide the required growth in capacity. At the same time, the programme aims to improve efficiency, to improve safety and to reduce environmental load. In addition, the ATM system has to become more cost-effective [Ref. 1, 2, and 3].

The questions raised are if it is anyhow possible to provide sufficient capacity to cope with the expected increased traffic levels in a flight-efficient and cost-efficient way and where the capacity comes from? Is it from the advanced operational concept, the expansion of infra-structure, or the political drivers that stimulate a more efficient organization of ATM in Europe? Part of the Definition Phase of SESAR was to perform operational assessment on SESAR Operational Concept [Ref. 4]. This paper presents conducted simulation experiments and their results to address Demand and Capacity Balancing (D&CB) by ATM in Europe. The experiments were based on STATFOR predictions on trends in air traffic growth figures [Ref. 6, 7, 8, 9, and 10] and on estimates of capacity growth figures of Airports and airspace sectors. EUROCONTROL provided the relevant data, based partly on known growth indicators and partly on expert judgment [Ref. 11 and 12]. It became evident during the experiments, that the achieved operational performance results are heavily dependent on the quality of scheduling as well as on the balance in the network as a whole. The bottlenecks in the network easily become dominant in determining the performance of the network.

It is fairly impossible in that respect to meet the quality of real-life conditions in balancing the network, and it is also difficult to define and assess the proper airspace organization to accommodate the increased demand. The results are therefore indicative in the first place and can be used to assess the major constraining conditions in future operations in Europe. The overview of simulation experiment and results is based on the work reported as part of the SESAR Definition Phase [Ref. 5].

# 2 Demand and Capacity Balancing

Demand is considered here from the point of view of civil commercial air traffic demand operated by Airlines. Demand is characterized by variations in traffic density and peak periods over the day. The received forecast demand figures were taking into account a certain smoothing over available capacity, and this could relate to overloaded airports as well as sectors

[Ref. 11 and 12]. Further, the forecast figures are such that mainly hub airports are systematically overloaded and that part of the airport capacity is not fully deployed. Therefore, for the purpose of effectiveness to provide increased capacity to the ATM system, two different aspects of capacity usage might be considered:

- Maximum capacity of an airspace volume or airport component (runway, taxiway, apron, etc.) is determined by maximum achievable throughput during a given period of time.
- Effective capacity of an airspace volume or airport component (runway, taxiway, apron etc.) is determined by the effectively achievable throughput during a given period of time, which is below maximum throughput and which is characterized by average and spread of delay.

During periods that the maximum throughput is not achieved, this quantity cannot be measured directly and only an effective deployment of available capacity is assessed. This is also what is economically relevant, and it is a main driver, therefore, to perform ECAC-wide performance assessment experiments, allowing assessment of effectively achievable performance benefits, given specific demand and network capacity characteristics.

Demand and Capacity balancing has to address runway and airport related capacity constraints as being principally the most constraining elements of the ATM process. However, each sector as part of an organized airspace structure may become a constraining element as well. Therefore the ATM network as a whole has to be considered, comprising a network of airspace and airport nodes:

- Airspace sectors with a capacity determined by number of flights to pass per unit of time and characterized by certain dynamics determining the acceptable level of variation of demand.
- Airports with a capacity determined amongst others by runway throughput and characterized by very low dynamics in accepting variations of throughput. Apart from runway configurations and weather conditions, the capacity may vary also by variations in traffic mixes such as weight categories and distributions of departure and arrival traffic.

Both, airspace sectors as well as airports will have the potential to enhance throughput, being beneficial as long as applicable to high density traffic conditions. Airspace related capacity gains find their origin to a considerable extent in organizational and efficiency increasing improvements, and therefore Airspace Management (ASM) is an important area of supportive concepts also.
Additional benefits may come amongst others from the concept elements related to Flow Management focusing on more efficient use of available capacity. The potential of Collaborative Traffic Flow management (CTFM) to improve throughput and to reduce average

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delays, was very significant in the past, and there might be still significant benefits to achieve. Therefore, CTFM was subject of performance assessment experiments, as one of the few means to keep control on balancing demand and capacity.

At airport level, capacity gains come from infrastructure in the first place; conceptual improvements can be considered as refinement, maximizing beneficial deployment of available resources. Because runway-related concept elements are critical regarding capacity, also small benefits are expected to be effective, and possibly to have a large impact indeed.

It should be noted, in this respect, that it is impossible in case of performance assessment for future scenarios to balance the schedules against available capacity as carefully as under real life operational conditions. Therefore, imposed CTFM delays have to be interpreted on the one hand as representing the constraints imposed by a strategic collaborative scheduling process performed at least half a year before the day of operation and on the other hand representing the delays imposed to keep the load on the ATM system manageable at a tactical level, reducing sector and runway load as required.

## 3    Advanced Concepts

Some of the concept elements of the Operational Concept of SESAR were addressed in the performance assessment experiments, but the level of assessment was constrained by the level of detail of descriptions available and by limitations to adapt available simulation tools and to prepare scenarios [Ref. 4 and 5]. The advanced operational concepts addressed were:

- **Demand and Capacity Balancing (D&CB)**: A dynamic D&CB model allows evaluating the operational conditions of air traffic running through an ATM network defined by airspace sectors and airports. Realistic or semi-realistic scheduling and simulated "real-time" demand and capacity balancing was applied in the experiments, whereas running fast-time simulations under present-day modes of operations were used to assess the effectiveness of assumed pre-departure CTFM measures on flight operations.

- **Information management and Collaborative planning**: Throughput is improved by collaborative planning, reflected in the Network Operations Plan (NOP). Enhanced pre-departure planning is based on early availability of 4D-planning data. Accurate 4D flight plans were generated in the experiments, although neither the capacity was ensured to execute the flight plans, nor the flight plans were planned conflict free. The fast-time simulations had to evaluate how efficient flight operations could be accomplished for different scenarios.

- **Trajectory management and Departure management**: The ATM network is operating in the nominal case to execute a 4D flight plan and to realize the Target Time of Arrival

(TTA). However, in case there are constraining conditions imposed to the TTA due to arrival congestion at destination, Airport-to-Airport regulations supported by a Refined Flow Management process (RFM), making use of the 4D planning accuracy, provide pre-departure traffic flow regulations to regulate arrival flows to congested destinations. The fast-time simulations had to evaluate if this would be beneficial to efficiency [see also Ref. 13 and 14].

## 4 Approach of performance assessment of ATM in a European scenario

Experiments were set-up to assess firstly the effect of changes in the scenario from 2005 to 2012 and 2020, secondly, to assess the effect of changes in the scheduling of flight executive operations. The effect of pre-departure conceptual changes was reflected in an adapted scheduling. However, if any in-flight operational improvement had been applied, this should have been expressed implicitly in the applicable airport and sector capacity figures. In the flight executive process no changes were made, except for some changes for a few airports to ensure that they would be able to realize their forecast capacity figures. Related to throughput, these simulations provided results mainly in terms of ground delays, traffic loads and sector workload (see Figure 1).
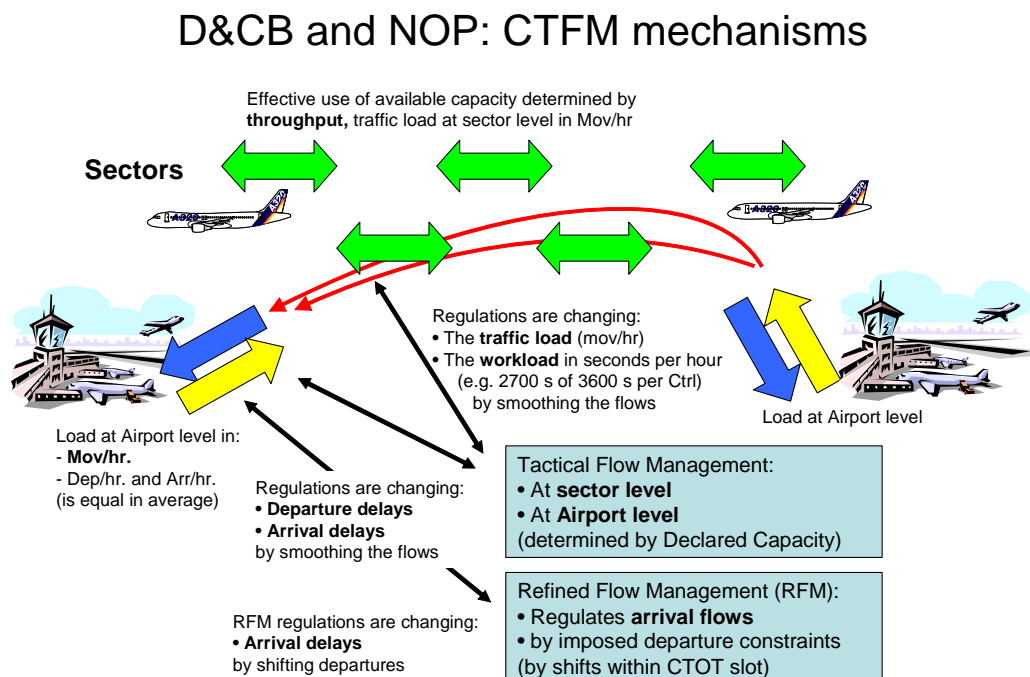
## D&CB and NOP: CTFM mechanisms



*Figure 1 Performance assessment, air traffic regulations and their impact on the network*

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The simulation set-up, simulated with support of TAAM®, reflects operations in real-life as close as possible, but unfortunately this set-up is not very transparent with respect to bottleneck analysis. For example, runway throughput delays may unexpectedly change the actual perceived load in sectors. In addition, traffic load and/or workload are difficult to be compared with ground delays, whereas the simulations tend to increase in size and duration due to the complexity of accurate modeling.

Operational performance assessment was addressed therefore in two ways: by **Network modeling** to assess throughput and network critical aspects, and by **Fast-time simulation** to assess operational performance characteristics.

### 4.1    Network modeling

Network modeling was applied by running a scenario through a simple Petri-net model of the ATM network. The aim of this model is to be able to simulate flights through the network in such a generic way that airports and sectors could be identified in an equivalent way as "hotspot" bottlenecks. Flights are processed as scheduled and following their flightplan.

Whenever there is no capacity left at an airport or sector node the approaching flights have to wait and they accumulate delay individually and for the node that causes the delay. Performance assessment is focused on throughput behavior of the ATM network only and the model allows to measure critical hotspots in an unambiguous way.
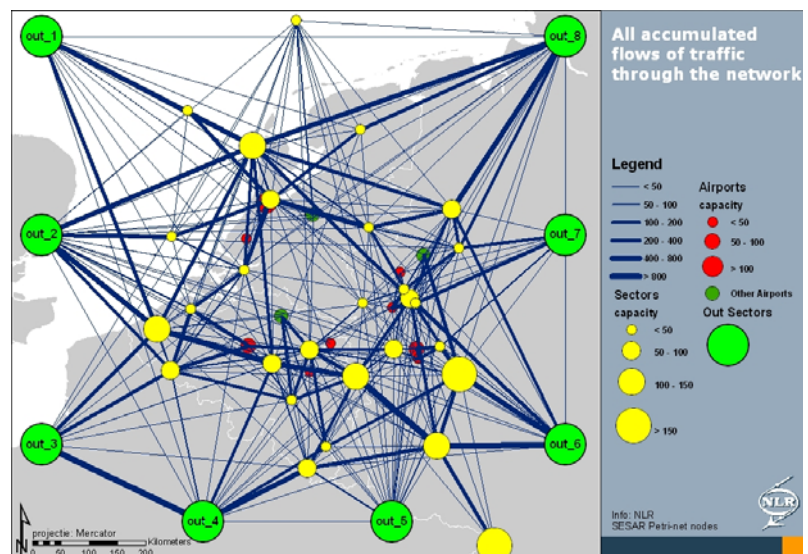


*Figure 2 Representation of Network Analysis Model of part of the core area of Europe and the applicable 2005 traffic flow scenario*

The measured results in terms of delays are not directly linked to daily operational practice and shall have a relative notion only.

The model was applied on part of Europe only, an (aggregated) area of the BENELUX and the environment of Düsseldorf, and the model was processed for 2005, 2012 and 2020 scenarios, varying traffic flows and traffic density as well as airport and (aggregated) sector capacity (see Figure 2).

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### 4.2 Fast-time Simulation

An ECAC-wide fast-time simulation environment was set up, capable to run fast-time simulations over 24 hours. The environment was determined by around 1000 sectors and 1000 airports (133 major airports). The scenarios were received from EUROCONTROL, processed by their FAP tools [Ref. 12] and an initial step was accomplished in balancing demand and capacity at a static level for each year. Basically, there were three scenarios:

1. **Present-day scenario, 2005**, simulating around 32.000 flights, using present-day airport and airspace sector capacity and using a present-day route network.

2. **Short-term future scenario, 2012**, simulating 17% more traffic following STATFOR predictions, using an ARNV-5 shortest route network, and assuming an estimated increase of capacity available for airports (+58%, but unequally distributed) and sectors (+11%).

3. **Long-term forecast scenario, 2020**, simulating 50% more traffic and assuming a further increase of capacity available for airports (+67%, again unequally distributed) and sectors (+19%).
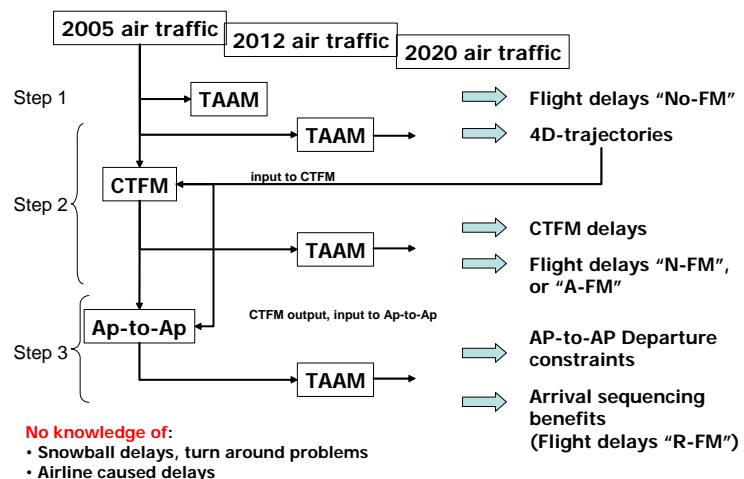


*Figure 3 Performance assessment by fast-time simulation with TAAM®*

Each fast-time experimental run consisted of simulating the flights according to flightplans and schedules of one of the three scenarios using TAAM® as fast-time simulation facility, simulating flights from runway to runway. One extra run was required to create unconstrained "ideal" 4D trajectories. Further, it was optional to perform Flow Management or Refined Flow Management by stand-alone pre-processing. The result of pre-processing was a modified scheduling and the aim was to assess differences in performance by execution of the flight under the operational conditions defined by the applicable scenario and the selected pre-processing option(s) (See Figure 3).

The conduct of the experiment addressed several aims to assess performance benefits:

- To assess similar flow management performance levels as today (2005) using the simulation models with the objective to confirm validity of use of these models for performance assessment.

- To assess benefits by assumed application of advanced concepts for flow management under today's traffic conditions (2005), answering the question if these advanced concepts could be considered to operate beneficially under present-day operational conditions.
- To assess benefits by assumed application of advanced concept elements under future operational conditions (2012 and 2020). Two questions had to be answered now: Firstly, the question if an appropriate balance could be ensured between expected demand and assumed available capacity, secondly, the question if under these operational conditions the benefits of advanced concepts are still applicable and achievable.

## 5 Metrics and Key Performance Indicators

The performance assessment experiment addressed the Key Performance Areas (KPAs) of Capacity and Efficiency. Several Key Performance Indicators (KPIs) were considered:

- The throughput at airport level was measured indicating achievable future traffic load with today's infrastructure. However, some airports were modeled such as to realize their forecasted capacity performance levels, rather than the levels they can realize today, using the existing runway configurations.
- The throughput at sector level was measured by fast-time simulation to assess potential overload and by Petri-net modeling to assess overload by generating delays whenever exceeding the declared capacity.
- Imposed delays were determined by processing Flow Management and Refined Flow Management processes, and the effects of these delays were assessed on departure and in-flight delays by fast-time simulation, as well as potential benefits by reduction of departure and arrival sequencing delays.
- Delays were measured with the Network Analysis Model as direct indicators for constraining bottlenecks in the ATM network.
- Workload at sector level is an indicator of the effectiveness of CTFM to control the load on the ATM system. The average workload per sector per hour is a stable KPI allowing measuring overall success of CTFM. However, CTFM should be able to reduce peak load demand in the first place and therefore the capability to reduce maximum workload per sector per hourly period was assessed as well.
- The calculated RFM mini-slot departure constraints were indicators for inefficiencies of simulated operations to make effective use of available arrival capacity at congested destinations. The obtained reduction of arrival sequencing delays is an indicator of potential gain in flight duration and the imposed RFM constraints are indicators for the penalties required to achieve optimization of congested arrival flows by smoothing traffic load.
- Finally, the margins in distance flown and fuel consumption were measured to assess the direct benefits achieved by increased efficiency of flight operations.

It should be noted that all delay measurements were restricted to pre-departure and in-flight ATM delays and that turn-around and reactionary delays caused by Airline and Airport operations were excluded from the simulation and modeling processes and could not be assessed.

## 6 Throughput Assessment by the Network Analysis Model

The three applicable scenarios (2005, 2012 and 2020) were obtained by compressing 2005 air traffic of the fast-time scenario (see Figure 4), and processing the model with adapted (aggregated) airport and sector capacity figures. The most valuable outcomes were:



*Figure 4 Distribution of air traffic over the day (2005, 2012, and 2020), processed through the Network Analysis Model*

- The bottleneck behavior was unambiguous, and was caused by airports as well as sectors.
- The bottleneck behavior confirmed pronounced peak behavior due to queuing on just a small subset of airports and sectors. Results by fast-time simulations are more predictable regarding real-life behavior, but these results might be mistrusted due to the complexity of the modeling. The Petri-net model, based on the modeling of air transport queuing characteristics only, is used therefore to confirm fast-time simulation results.

Comparing the results of 2005, 2012 and 2020, it is observed (see Figure 6) that:

- Delays around the Düsseldorf area are almost disappearing in 2012. This is caused by a sharp increase of the forecasted capacity of the airport.
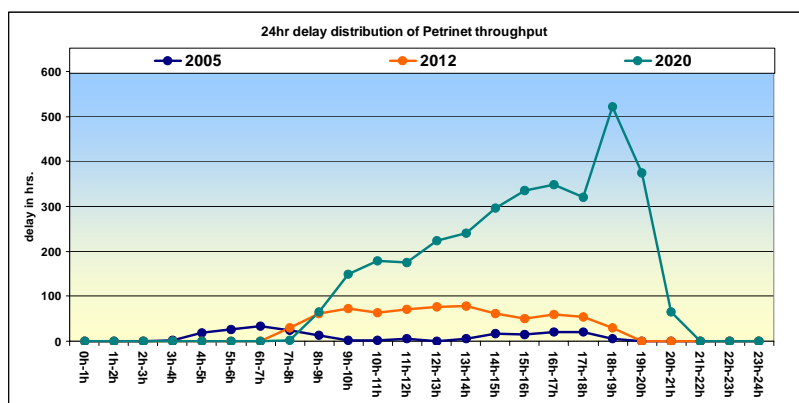


*Figure 5 Distribution of delays of air traffic over the day, showing saturation effects for 2020*

- The number of sectors with delays is steeply increasing in 2020 and the network shows saturation effects (see also Figure 5).
- In particular, the Schiphol area shows a sharp increase of delays, mainly caused by a bottleneck of the feeding and receiving sectors around the airport. The capacity of these sectors was adapted insufficiently to cope with the increase of forecasted airport demand for 2020.
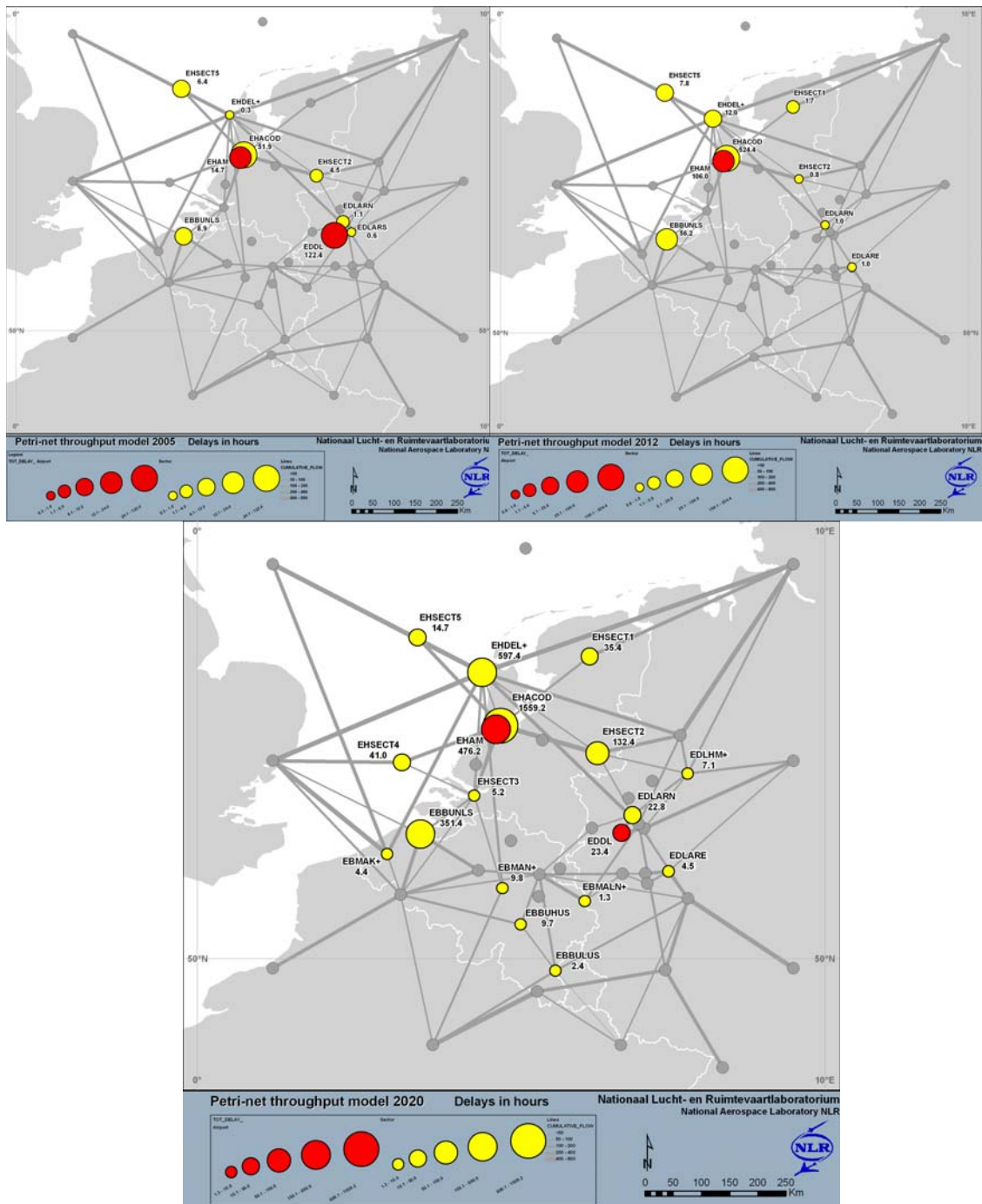


*Figure 6 Selected Petri-net network, applicable to 2005, 2012, and 2020 traffic flows and identification of hotspots (non-proportional scaling applied!)*

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These results are to be considered as indicative. It should be noted that in particular around the airports the sector modeling might have been too generic to reflect accurately the applicable procedures.

# 7 Conduct of the Fast-Time Experiment and results

First an overview of simulation results is given, addressing the assessment objectives at a general level and dealing with delays and workload at sector level, and then results are summarized in a comparative overview.

## 7.1 Fine-tuning and Calibration (2005 scenario)

### 7.1.1 General observations
The performance of CFMU CASA model [Ref. 15, 16, and 17] was compared with the NLR model (N-FM), performing flow management by regulating at an hourly basis without including constraints on airport flows. The N-FM model was processed on the one day sample of non-flow-managed data and compared, fine-tuned, and calibrated with flow-managed CFMU data. The scheduling data was simulated fast-time in the same way for both models. Calibration was accomplished successfully, but the performance of the NLR model has not the aim to be comparable with the performance of an operational model. The CFMU CASA model is performing on a more subtle way, taking into account opening and closing schedules of sectors and operating probably with a finer sliding windowing scheme. The NLR N-FM module was processed straightforward on traffic for 24 hours without iteration and without flightplan updates, but also without any kind of manual intervention.
Some adaptations were required to reach a comparable performance level:
- A few sectors were removed from the Flow Management process because they were causing unnecessary disruption, typically sectors with less than 15 mov/hr.
- Some (generic) procedures around some large airports were not reaching the required performance level and these procedures were adapted to reach a similar performance as the CFMU reference sample.

### 7.1.2 Results
After fine-tuning, the performance level of applied regulations was found to be very similar. The average imposed delay per flight was almost the same (92 s, without applying thresholds), but the NLR model calculated less departure constraints with larger delays (CFMU: 2991 flights, NLR: 2037 flights). This confirms better performance of the operational CASA model.

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The maximum hourly traffic load and the maximum hourly workload were analyzed to get an understanding of the impact of flow regulations on sector load. Figure 7 shows the distribution of maximum hourly traffic load against workload of the most loaded measured sectors of the simulation run, based on CFMU scheduling data.

This view can be considered as a reference. The outliers in traffic load are some non-regulated (low capacity) sectors; the outliers in workload are typically sectors like TMAs for which the generic workload model, based on a one-controller 2520 sec.



**CFMU imposed constraints on a "perfect" day, ... no disruption.**

**Impact: some reduction of workload**
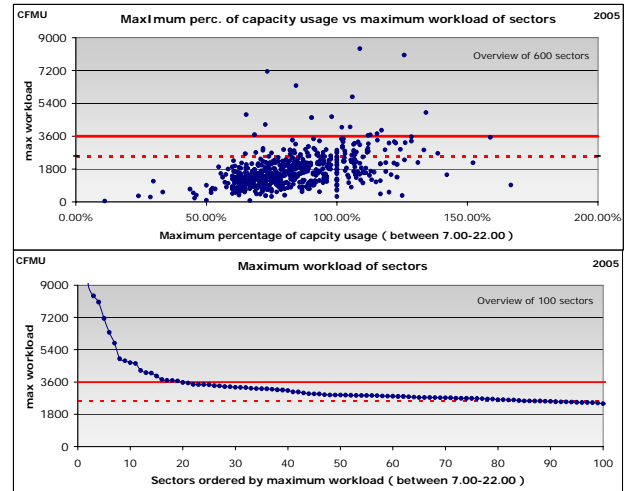


*Figure 7 Reference data of maximum traffic load against workload per sector after CFMU regulations (2005)*

workload availability, does not work appropriately.

Fine-tuning the N-FM model, the sensitivity of CTFM to build up delays was striking. For that reason, it was investigated how tightly focused delays were allocated to specific parts of the network. It turned out that already in 2005, the most frequently imposed planning delays were attributed to a limited selection of 21 airports (~40% of traffic demand), and this division is similar for 2012 and 2020. This suggests in fact that applying CTFM constraints is heavily focused on a limited sub-network in Europe of around 20 airports.

## 7.2 Benefits by advanced concepts (2005 scenario)

### 7.2.1 General observations

Traditional Flow Management is mainly managing the load of overloaded sectors, First-Come First-Served (FC-FS), identified here as the N-FM model. However, if the requirement is to come to CDM based D&CB to manage the total network, a Flow Management model has to be applied that is appropriate to include at least all airports and all sectors. There were some implications for this model (identified as the A-FM model):

- Airports are more sensitive to variations in capacity and load than sectors; therefore a larger tolerance was accepted to apply CTFM on airport demand (+10%).

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- The performance to control sector overload seems sufficient to managet present-day levels of congestion, however, the simple FC-FS mechanism was failing on heavily congested traffic samples, because it failed to reduce sector workload (see also below). The FC-FS mechanism was maintained, but the smoothing enforced to avoid cluttering of delayed flights. This was tested successfully to some extent.

The concept of RFM was also applied. The concept assumes to impose departure constraints within a slot, but for simplicity reasons no early departures but only delays were calculated in the simulations. In real-life, however, front loading will be applicable indeed. Front loading may be applicable for CTFM delays as well, but in that case the delays will easily exceed the benefits by early departures and that is not the case for RFM.

### 7.2.2   Results

To reach results on managing the total network, the number of flights that receive imposed departure constraints have to increase steeply. Applying the full-network A-FM model on the 2005 scenario, however, had virtually no effect on (airport related) departure/arrival delays. RFM, however, had a positive effect because the in-flight arrival delays dropped down to 14 s on average albeit under ideal operational conditions (see the table in Figure 8).
The success of the A-FM model is expressed in its effect on sector load, albeit against a very high increase of delays. This model was able to suppress traffic load and workload which might be a justification to increase declared capacity but for present-day levels of congestion the effect is very small and the price just high (see Figure 8). RFM has no effect anyhow at sector level, because it is outside its scope.

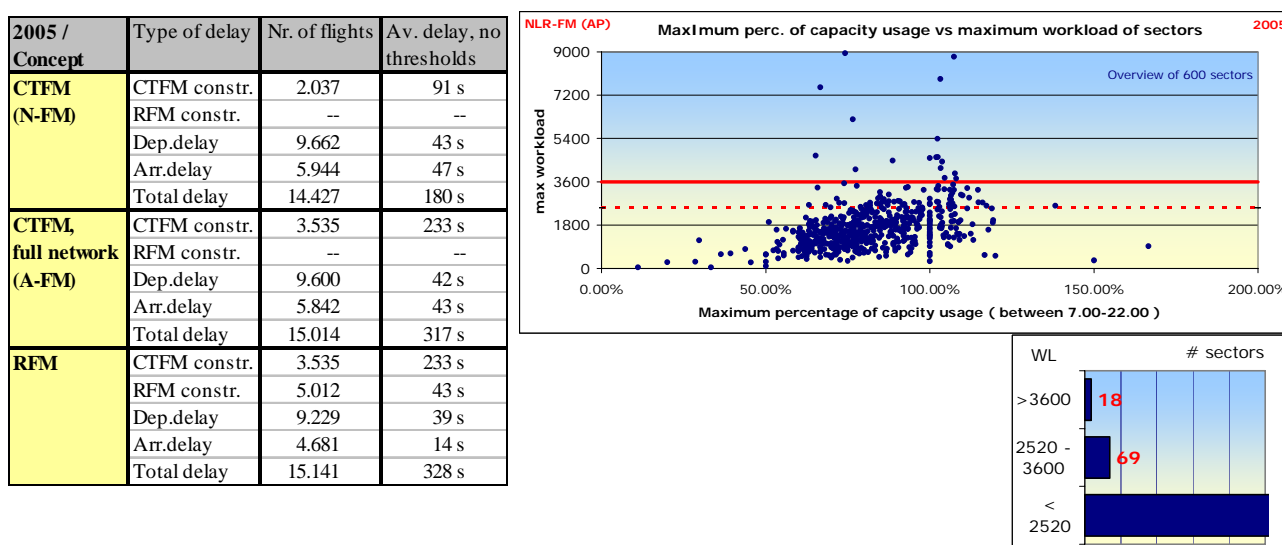| 2005 / Concept | Type of delay | Nr. of flights | Av. delay, no thresholds |
|---|---|---|---|
| **CTFM (N-FM)** | CTFM constr. | 2.037 | 91 s |
| | RFM constr. | -- | -- |
| | Dep.delay | 9.662 | 43 s |
| | Arr.delay | 5.944 | 47 s |
| | Total delay | 14.427 | 180 s |
| **CTFM, full network (A-FM)** | CTFM constr. | 3.535 | 233 s |
| | RFM constr. | -- | -- |
| | Dep.delay | 9.600 | 42 s |
| | Arr.delay | 5.842 | 43 s |
| | Total delay | 15.014 | 317 s |
| **RFM** | CTFM constr. | 3.535 | 233 s |
| | RFM constr. | 5.012 | 43 s |
| | Dep.delay | 9.229 | 39 s |
| | Arr.delay | 4.681 | 14 s |
| | Total delay | 15.141 | 328 s |



*Figure 8 Table with average delays, and figure of maximum traffic load against workload of sectors in Europe (scenario 2005. no thresholds)*

### 7.3 Benefits by advanced concepts (2012 and 2020 scenarios)

#### 7.3.1 General observations

The increase of traffic demand was based on STATFOR forecasts [Ref. 6, 7, and 8] but the increase of capacity was derived from estimates on achievable improvement or on capacity that might become available somehow. Capacity estimates were not necessarily based on performance requirements of the network. The indications to support this view are:

- A more efficient ARNV-5 route network was applicable; however, the sectorization and capacity figures were not necessarily adapted as well. The result was a more efficient performance of flight, but with extra delays. The airspace organization has to be optimized yet.

- Generally, it was the impression that forecasted sectorization and declared capacity figures were not able to keep pace with the required capacity due to increased traffic demand, but some bottleneck areas tended really to become dominating the generation of delays. TMA sectors were typically missing sufficient growth to cope with the expected increase of traffic, and the capacity of 33 sectors was over a connected period of 15 hours in average less than the hourly demand, causing heavy delays.

#### 7.3.2 Results

Due to unbalanced scheduling and saturation effects on the network, the impact of advanced CTFM (A-FM) is much more significant now. Steeply increasing imposed delays could suppress part of the in-flight delays around airports and also sector traffic load and workload. In general, the results of 2012 (+27% demand) are showing a more acceptable result than 2020 (+50% demand). This is clearly the consequence of network saturation and exploding bottleneck behavior, even if throughput of some airports were increased artificially to realize the forecasted capacity.
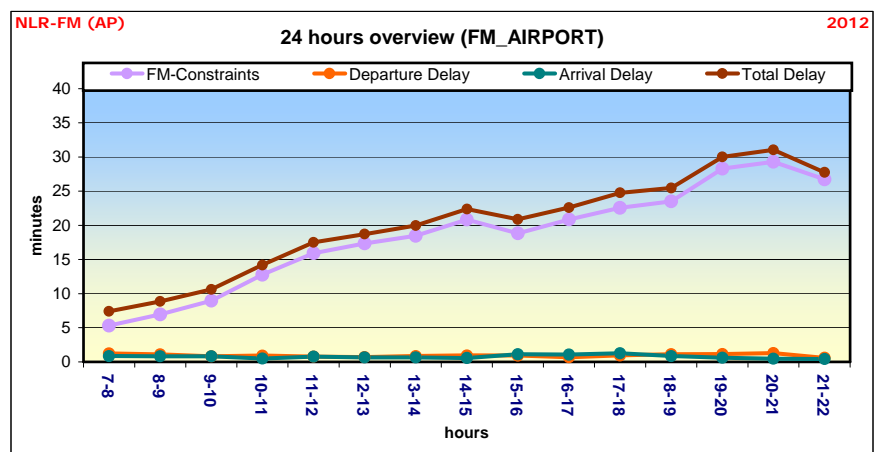


Figure 9 Distribution of delays over the day, saturation effects towards the end-of-the-day (2012)

Saturation becomes visible by propagation of imposed constraining delays towards the end of the day (see Figure 9). The average delays (without applying any thresholds) are tripling in 2012 compared to 2005, and delays are doubling again for 2020. The delays can be justified

only as far as they are able to keep executive and in-flight delays at a level comparable with 2005 (see the tables in Figure 10).

| 2012 / Concept | Type of delay | Nr. of flights | Av. delay, no thresholds |
|---|---|---|---|
| CTFM (N-FM) | CTFM constr. | 9.543 | 766 s |
| | RFM constr. | -- | -- |
| | Dep.delay | 12.550 | 61 s |
| | Arr.delay | 8.785 | 73 s |
| | Total delay | 22.041 | 899 s |
| CTFM, full network (A-FM) | CTFM constr. | 10.182 | 980 s |
| | RFM constr. | -- | -- |
| | Dep.delay | 12.010 | 51 s |
| | Arr.delay | 8.183 | 52 s |
| | Total delay | 22.094 | 1.082 s |
| RFM | CTFM constr. | 10.182 | 980 s |
| | RFM constr. | 4.661 | 36 s |
| | Dep.delay | 11.809 | 48 s |
| | Arr.delay | 8.131 | 48 s |
| | Total delay | 23.076 | 1.112 s |

| 2020 / Concept | Type of delay | Nr. of flights | Av. delay, no thresholds |
|---|---|---|---|
| CTFM (N-FM) | CTFM constr. | 20.627 | 2.220 s |
| | RFM constr. | -- | -- |
| | Dep.delay | 18.097 | 191 s |
| | Arr.delay | 13.881 | 120 s |
| | Total delay | 32.542 | 2.530 s |
| CTFM, full network (A-FM) | CTFM constr. | 21.489 | 2.658 s |
| | RFM constr. | -- | -- |
| | Dep.delay | 16.273 | 116 s |
| | Arr.delay | 12.159 | 81 s |
| | Total delay | 32.581 | 2.854 s |
| RFM | CTFM constr. | 21.489 | 2.658 s |
| | RFM constr. | 4.684 | 28 s |
| | Dep.delay | 16.199 | 114 s |
| | Arr.delay | 12.212 | 79 s |
| | Total delay | 33.218 | 2.879 s |

*Figure 10 Tables with average delays due to CTFM constraints (2012 and 2020)*

To show the effect on traffic load and work-load, the best result (2012) is selected (see Figure 11). A baseline run (no flow management) is compared with the A-FM model because this presents the reduction of load in the best way. The traditional N-FM model was anyhow failing to reduce the load.
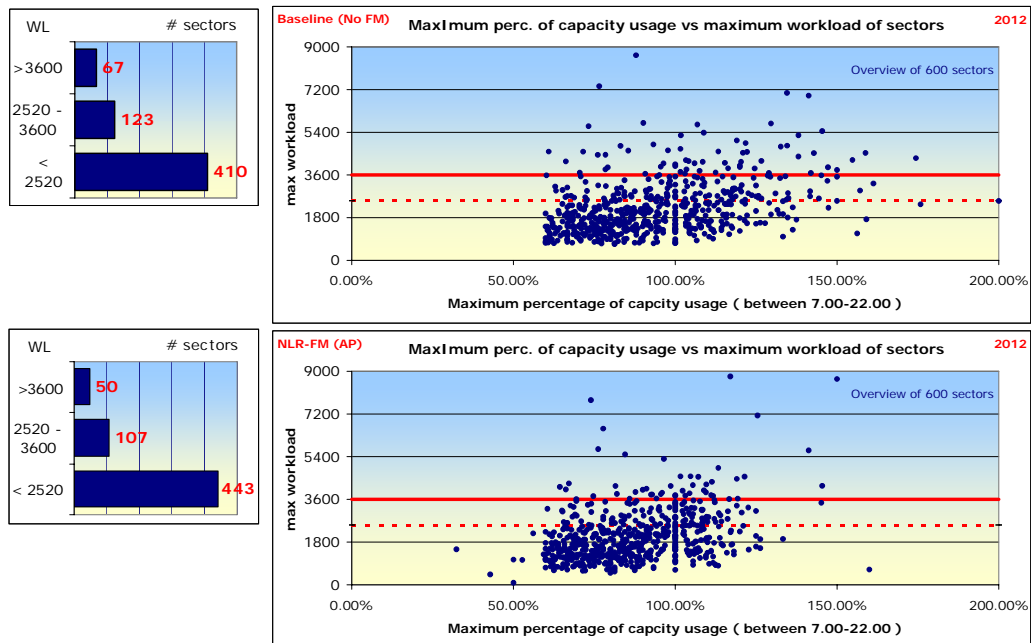


*Figure 11 Advanced CTFM against Baseline, maximum traffic load and workload at sector level (2012)*

# 8 Fast-time simulation results and analysis – Quantitative summary and comparison

## 8.1 Flight efficiency and delays

The summary of results is based on figures that include thresholds because those values can be compared with performance target indicators. It is today's practice to count delays above a 10-minutes threshold, but the objective of SESAR is to achieve increased predictability and to refer to performance targets, based on a 3-minutes threshold [Ref. 2, section 3.4]. This 3-minutes threshold is applied in the tables in this section.

The Baseline scenarios (No-FM) were scenarios, simulated without applying any regulations. These scenarios are unrealistic because sector load problems are measured, but ignored. Nevertheless they provide reference material. The scenarios are showing increasing delays towards 2020. The departure delays are building up over the day in 2020, being an indicator of airport saturation behavior. This occurs in spite of challenging forecast capacity figures for most airports. The saturation effects are caused by the imbalance of airport growth figures. The real problems with the Baseline scenarios, however, are caused by sector overload problems that are the actual drivers currently forcing CTFM regulations. Observed departure and arrival delays (characterizing airport throughput) are presented in Figure 12.

The calculated CTFM constraints were determined firstly as today by a FC-FS model (N-FM model). However, this model fails on heavily overloaded traffic conditions for two reasons:

- The airport flows are at least as sensitive to overloading as flows through sectors. These flows were not regulated and have to be regulated as well,
- The effect of the regulations started to become ineffective due to the amount of demand overload carried over to a subsequent period. This was mitigated by applying "extended smoothing", an ad-hoc mechanism to force distribution of demand.

The enhanced CTFM procedures (A-FM model) were able to suppress departure and arrival delays and were able also to manage sector traffic

| Total delay figures | 2005 | 2012 | 2020 |
|---|---|---|---|
| Percentage delayed flights | 11% | 26% | 44% |
| Average CTFM constraint per flight | 3,9 min. | 16,3 min | 44,3 min |
| Total average delay per flight (applying 3 min. threshold) | 4,9 min. | 17,7 min | 47,4 min |

| Total savings of flight executive delays | 2005 | 2012 | 2020 |
|---|---|---|---|
| Average departure delay per flight | 2 s | 15 s | 111 s |
| Total reduction of departure delay time | 18 hrs/day | 156 hrs/day | 1483 hrs/day |
| Average arrival delay per flight | 7 s | 25 s | 89 s |
| Total reduction of in-flight arrival sequencing time | 62 hrs/day | 261 hrs/day | 1189 hrs/day |

*Figure 12 Table with imposed constraints/total delay figures and a table with total savings of flight executive delays due to imposed constraints (2005, 2012, and 2020)*

load and workload, but at the price of imposing severe flow restrictions. Unfortunately, there is no way at present to force minimal delays. The FC-FS principle gives no optimization principle and works sometimes in an adverse way. If an optimization criterion would be used to control the amount of calculated CTFM regulations, a trade-off has to be determined of imposed CTFM delays against control on acceptable flight operational delays and sector load.

Regarding the results, it should be noted that most of the delays are caused by a limited set of bottlenecks that create excessive peak delay behavior. Forecast figures were applied to determine the balance of demand and capacity in the network for 2012 and 2020 and no modifications were applied. The delays should be considered therefore as "strategic" delays mainly to be solved by improving the Network on the one hand and the optimization strategy on the other hand (see the tables of Figure 12).

### 8.1.1 CTFM constraints and sector load

The impact of CTFM constraints on sector load was considered from the point of view of the hourly period with maximum traffic load and workload of each sector. Unfortunately, the period of maximum sector load is not a very stable quantity and the outcome can be sensitive for traffic and capacity variations. A more stable quantity is the accumulation of all measured hourly sector workload measurements over all sectors in Europe during the 15 busy hours (07:00 to 22:00).
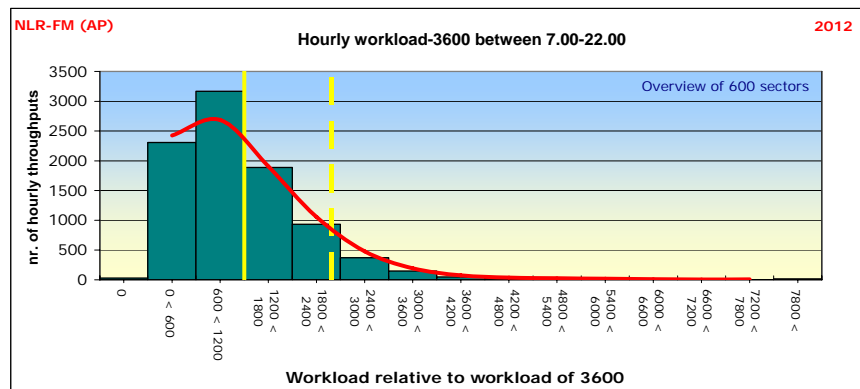


Figure 13 Distribution of measured hourly workload of all sectors over 15 hours, 2012 scenario (A-FM model)

The average workload figures and the spread were used to determine an estimate of the average achievable reduction in load.

Figure 13 presents a histogram of the distribution achieved with the A-FM model for the 2012 scenario, and Figure 14 presents a table summarizing results obtained with the Baseline model (No-FM), the traditional FC-FS model (N-FM), and with the advanced model working on the total network (A-FM).

The results show that it is possible to reach acceptable sector load conditions by applying enhanced CTFM and using forecasted sector capacity figures as long as the operational conditions are not "saturated". It is difficult to materialize the obtained workload reduction figures by increase of declared capacity concretely because:

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- The potential benefits are relative to a non-feasible Baseline scenario.
- The forecasted capacity figures are based on the assumption that control on workload is feasible by managing the traffic load.
- The effect of raising the capacity figures of some sectors is unpredictable.

The benefits of workload reduction can be achieved by analyzing the network, identifying the

| Year | Baseline (No-FM) | Traditional CTFM FC-FS model (N-FM) | CTFM full FC_FS model, including airports (A-FM) | Gain CTFM full FC-FS model compared to Baseline |
|------|------------------|--------------------------------------|--------------------------------------------------|-------------------------------------------------|
| 2005 | Balanced load | No significant effect on overloads | Some effect on limited appearance of overload conditions | Overall ~1% (28% on peak behaviour) |
| 2012 | Unacceptable load | Ineffective to suppress overloads | Able to reduce control and reduce sector workload | Overall ~4% (25% on peak behaviour) |
| 2020 | Unacceptable load | Ineffective to suppress overloads | Able to control overloads, but saturation prohibits a reduction of workload, | Overall ~0% (9% on peak behaviour) |

*Figure 14 Table with summary of results of findings related to workload assessment*

critical bottlenecks, trying to find valid ways to re-balance the demand with the capacity of the sectors and/or the airports, and to re-assess the potential to cope with the sector load. The Network Analysis Model can help to identify the critical bottlenecks and the simulation process can help to assess the load under CTFM constraining procedures. Finally, the effect on CTFM constraints can be evaluated.

### 8.1.2 RFM and reduction of arrival sequencing delays

Refined Flow Management (Airport-to-Airport regulations) provides its benefits by fine-tuning the smoothing of arrival flows to congested destinations. The smoothing of arrival flows has to be determined in minutes precise in order to be effective (mini-slots). This contrasts with the traditional flow regulations of 15 minutes windows for the CTOT (Calculated Take-Off Time). The results of RFM are below expectations. A reduction of arrival sequencing delays with an average of ~10 s per flight was foreseen and only ~2 s per flight was measured [see also Ref. 14]. The explanation comes from a significant reduction of arrival sequencing delays achieved by enhanced CTFM already (see results above), and achieved by a forced re-distribution of traffic. The question is if delay reduction was achieved in the least penalizing way, and the answer is negative. In this respect, RFM should be considered as the preferred mechanism due to its low penalties, although it should be noted that RFM does not affect sector load whereas CTFM does.

The aim was to reduce arrival sequencing delays. Because this was accomplished partly by CTFM, partly by RFM, the reductions are considered when both conceptual improvements were implemented together. The same holds for reduction of departure delays. In addition, CTFM and RFM mainly affect hub operations, whilst also the benefits go to those airports. Around 40% of imposed constraints can be identified with a sub-network of large airports, dominated by the 10 largest airports. The perceived benefits are summarized in the table in Figure 15, making a subdivision in the 10 largest hub-airports, large airports and other airports. Figure 16 presents an example of maps (2012) of those airports that are benefiting reduction of departure and arrival sequencing delays.

The questions that could not be answered, are which CTFM measures are necessary and required to reduce the sector load against minimal constraining delays, and how the CTFM

| Year | 2012 | | | 2020 | | |
|---|---|---|---|---|---|---|
| Benefits by delay reduction | DEP hrs/day | ARR hrs/day | Total hrs/day | DEP hrs/day | ARR hrs/day | Total hrs/day |
| Total 10 hub Airports | 85 | 208 | 292 | 861 | 398 | 1259 |
| Total next 20 Airports | 31 | 34 | 65 | 89 | 118 | 207 |
| Total of all Airports | 136 | 261 | 397 | 1029 | 548 | 1576 |
| Percentage delay reduction of 10 hub Airports relative to all airports | 57% | 72% | 65% | 76% | 69% | 73% |

*Figure 15 Table with summary of results of departure/arrival delay reduction in hours/day due to CTFM/RFM*

regulations could be established in such a way that RFM could be effective to its maximum extent. What is needed is an optimization principle that manages sector load, arrival queuing and departure queuing against minimal constraining conditions. Such a principle would give prioritization to the maximum deployment of the most constraining elements of the ATM system in order to maximize the throughput.
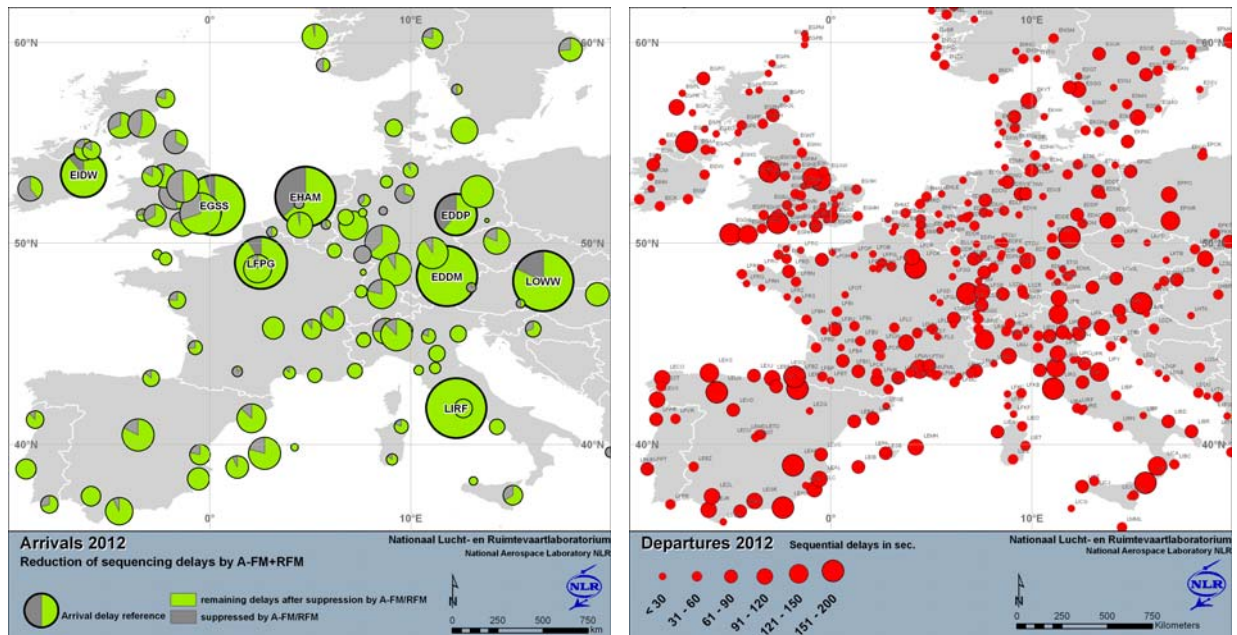
**NLR A-FM + RFM, 2012 results:**
- **Limited number of major airports are benefiting by reduced arrival delays: 111**
- **Most benefits on arrivals for hub-airports**
- **Many airports are benefiting by reduced departure delays: 457**

*Figure 16 Maps with summary of results of reduced arrival and departure delays due to CTFM/RFM (2012)*

### 8.1.3 Flight duration and Fuel efficiency

Flight duration and fuel efficiency was recorded during the experimental runs for all flights. A summarizing table with findings is presented in Figure 17.

The following trends are shown (per flight):

▪ A reduction of time flown (from 2005 to 2012) is observed. Very likely this is caused mainly by direct routing (ARNV-5).

▪ An increase of fuel consumption is observed. This is likely to be caused by a higher percentage heavy aircraft (see average pax. nr. per flight).

| Year | Simulation | fuel | Perc. | pax | Perc. | time_flown | Perc. |
|------|-----------|------|-------|-----|-------|-----------|-------|
|      |           | kg   |       | nr  |       | s         |       |
| 2005 | Baseline  | 9942 | Ref.  | 122.7 | Ref. | 9061      | Ref.  |
| 2005 | CFMU      | 9939 |       | 122.7 |      | 9057      |       |
| 2005 | CTFM + RFM | 9921 |      | 122.7 |      | 9025      | -0.40% |
|      |           |      |       |     |       |           |       |
| 2012 | Baseline  | 10815 | 8.80% | 132.8 | 8.20% | 8420     | Ref.  |
| 2012 | CTFM + RFM | 10789 |      | 132.8 |      | 8391      | -0.30% |
|      |           |      |       |     |       |           |       |
| 2020 | Baseline  | 11247 | 13.10% | 133.8 | 9.00% | 8687    | Ref.  |
| 2020 | CTFM + RFM | 11106 |      | 133.8 |      | 8596      | -1.00% |

*Figure 17 Table with summary of results of departure/arrival delay reduction in hours/day due to CTFM/RFM*

- A decrease in flight duration and fuel consumption is observed by applying conceptual improvements (CTFM and RFM).

# 9   Conclusions

The approach taken in these experiments, was firstly to investigate the forecast scenarios and their consequences and secondly how operational enhancements could improve operations. The first investigation leads to the conclusion that even modest forecasts were showing structural deficiencies of capacity both at airport and sector level. Problems are stemming on the one hand from an underestimation of escalating queuing effects by saturation, on the other hand from a forecast of capacity that is likely to be improved yet. The forecasts were somewhat unbalanced for both categories, airports and sectors, without options for pragmatic solutions as applicable in real-life situations.

Capacity figures were input to the scenarios and were not subject of discussion. In the experiment there was only one way to solve unbalances and that was by imposing delays. The results yield sometimes very large delays, which can be interpreted partly as strategic delays and partly as tactical delays. Moreover, significant parts of the delays are bound to a small number of specific airports and sectors.

The experimental outcome of the Network Analysis Model could support the key issue that specific airports and sectors tend to get overloaded. This model showed clearly that the demand and available capacity scenarios were causing structural congestion behavior and that the bottlenecks tend to get more pronounced towards 2020.

The simulation of the three Baseline scenarios demonstrated the overload characteristics of future scenarios. The effect was shown in the simulations as increased operational delays and overloads of traffic load and workload. The delays were caused by congested airports, and the overloads by congested sectors.

The next investigation was how to mitigate the congestion problems by advanced concepts. Collaborative Traffic Flow Management (CTFM) and Refined Flow Management (RFM) were considered. It could be concluded, from the analysis of delays and workload, that a straightforward First-Come-First-Served (FC-FS) flow management model (N-FM) was no longer effective. A model based on a full network, including airports, and based on "extended" smoothing (A-FM) was better able to suppress flight-executive delays and to reduce the sector load, but at the price of high imposed pre-departure constraints or delays. What was missing indeed, was a clear optimization strategy. FC-FS must be considered as a somewhat arbitrary strategy based on ordering, whilst a strategy is needed that will focus on minimal delays. The

applied strategy was an ad-hoc adaptation of FC-FS that addressed all the flows and that
ensured sufficient distribution of traffic.

The applied full network CTFM model (A-FM) was effective in reducing delays by imposing
pre-departure constraints. The RFM model was ineffective, because delays were already
suppressed by CTFM. However, the mechanism of RFM is more subtle and provides its benefits
at the price of fewer delays than CTFM. Therefore further future study is recommended on:

- Optimization of the applicable network in terms of an optimal routing and a proper balance
  of capacities as an essential part of development of the SESAR operational concept for
  Europe.
- An optimization strategy for flow management (CTFM) to assign pre-departure constraints
  with minimal delaying effects.
- An optimization strategy to smooth arrival flows to congested destinations which is both in
  balance with CTFM and ensures minimal delays.

# 10  Acknowledgments

## 11  Abbreviations

| | |
|---|---|
| ARNV-5 | - Air Route Network Version 5 |
| ASM | - Airspace Management |
| ATM | - Air Traffic Management |
| A-FM | - NLR's Advanced version of N-FM |
| BENELUX | - Belgian, the Netherlands, Luxemburg |
| CASA | - Computer Assisted Slot Allocation |
| CDM | - Collaborative Decision Making |
| CFMU | - Central Flow Management Unit |
| CTFM | - Collaborative Traffic Flow Management |
| CTOT | - Calculated Take-Off Time |
| D&CB | - Demand and Capacity Balancing |
| ECAC | - European Civil Aviation Conference |
| FAP | - Future Air Traffic Flow Management Profile |
| FC-FS | - First-Come First-Served |
| FM | - Flow Management |
| KPA | - Key Performance Area |
| KPI | - Key Performance Indicator |
| LCIP | - Local Convergence and Implementation Plan |
| NLR | - National Aerospace Laboratory NLR, the Netherlands |
| NOP | - Network Operations Plan |
| N-FM | - NLR's experimental Flow Management model |
| R&D | - Research & Development |
| RFM | - Refined Flow Management |
| SESAR | - Single European Sky ATM Research Programme |
| STATFOR | - Statistical Forecast EUROCONTROL |
| TAAM® | - Total Airspace and Airport Modeller (*trademark Preston Group*) |
| TMA | - Terminal Maneuvering Area |
| TTA | - Target Time of Arrival |
| 4D | - in 4 Dimensions |

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