EPISODE 3

Single European Sky Implementation support through Validation

Document information	
Programme	Sixth framework programme Priority 1.4 Aeronautics and Space
Project title	Episode 3
Project N°	037106
Project Coordinator	EUROCONTROL Experimental Centre
Deliverable Name	Simulation Report on 4D Trajectory Management and Complexity Reduction
Deliverable ID	D4.3.2-02
Version	1.00
Owner	
Cyril Allignol	DSNA
Contributing partners	
DSNA	

- This page is intentionally blank -

DOCUMENT CONTROL

Approval

Role	Organisation	Name
Document owner	DSNA	Cyril Allignol
Technical approver	DFS	Ralph Leemüller
Quality approver	EUROCONTROL	Frédérique Sénéchal
Project coordinator	EUROCONTROL	Philippe Leplae

Version history

Version	Date	Status	Author(s)	Justification - Could be a reference to a review form or a comment sheet
1.00	03/09/2009	Approved	Cyril Allignol	Approval of the document by the Episode 3 Consortium.

TABLE OF CONTENTS

EXECUTIVE SUMMARY **6**

1 INTRODUCTION **7**

1.1 Purpose of the document 7
1.2 Intended Audience 7
1.3 Scope and Structure of Document 7
1.4 Experiment Background and Context 7
1.5 Concept Overview 9
1.6 Glossary of Terms 10

2 SUMMARY OF EXPERIMENT AND STRATEGY PLANNING **12**

2.1 Expected Experiment Outcomes, Objectives and Hypotheses 12
  2.1.1 Description of Expected Experiment Outcomes 12
  2.1.2 Description of Experiment Objectives and Assumptions 12
  2.1.3 Description of Experiment Hypotheses 15
2.2 Choice of Metrics and Measurements 15
2.3 Choice of Methods and Techniques 15
2.4 Validation Scenario Specifications 17
2.5 Experimental Variables and Design 17

3 CONDUCT OF VALIDATION EXERCISE RUNS **18**

3.1 Experiment Preparation 18
3.2 Executed Experiment Schedule 18
3.3 Deviations from the Planning 18

4 EXPERIMENT RESULTS **19**

4.1 Measured Experiment Results 19
  4.1.1 Data processing 19
  4.1.2 Simulation 19
4.2 Confidence in Experiment Results 20
  4.2.1 Quality of Results of Experiment 20
  4.2.2 Significance of Results of Experiment 20
4.3 Unexpected Experiment Results 20

5 ANALYSIS OF EXPERIMENT OUTCOMES **21**

5.1 Analysis of Outcomes on the Basis of Determined Hypotheses 21
5.2 Analysis of Consequences of Outcomes for Experiment Objectives and Assumptions 21
  5.2.1 Analysis of the numerical results 21
  5.2.2 Standard and direct routes 22
  5.2.3 Robustness towards uncertainty 22

6 CONCLUSIONS AND RECOMMENDATIONS **24**

6.1 Key findings 24
6.2 Issues 24
6.3 Recommendations 24
  6.3.1 General recommendations 24
  6.3.2 Recommendations on supporting DODs and Operational Scenarios 24
6.4 Conclusions 25

7 REFERENCES AND APPLICABLE DOCUMENTS **26**

7.1 References 26
7.2 Applicable documents 26

LIST OF TABLES

Table 1-1 Details of the exercise 10
Table 2-1 Stakeholders expectations 12
Table 2-2 Summary of variables and exercise design. 17
Table 6-1 OI steps addressed and associated conclusions. 24
Table 6-2 Conclusions related to the main objectives of the exercise. 25

LIST OF FIGURES

Figure 2-1 Vertical and horizontal separation. Another aircraft cannot be inside the cylinder at the same time. 13
Figure 2-2 Illustration of the sliding window method for the takeoff time allocation .. 14
Figure 5-1 Distribution of the delays: percentage of flights (y axis) allocated each delay (x axis) over the day of traffic. Delays are expressed in minutes. 21
Figure 5-2 Distribution of delays averaged on 2006 and 2020 traffic. 22
Figure 5-3 Mean amount of delay (in minutes) allocated over the day of traffic, for direct and standard routes. 22
Figure 5-4 Percentage of remaining conflicts w.r.t. conflict extension and departure time error in minutes. 23
Figure 5-5 Total amount of delay (in minutes) w.r.t. conflict extension (in minutes). 23

EXECUTIVE SUMMARY

This document describes the work carried out conducting a fast-time simulation that tests a method to allocate takeoff times, which may lead to de-complexified En-Route traffic. These fast-time simulations are part of the Single European Sky Support through Validation Project Episode 3 (EP3). They belong to EP3 WP4.3, whose goal is to validate technologies, processes and procedures related to the En-Route parts of the execution phase.

One of the bottlenecks impeding ATC performance is the hourly capacity constraints defined on each En-Route ATC sector to limit the hourly number of aircraft entering this sector. Previous work was mainly focused on optimising the current ground holding slot allocation process devised to satisfy these constraints. The process proposed in this exercise is to estimate the amount of delay associated to an allocation of takeoff times that avoid potential conflicts in the upper airspace, provided that aircraft were able to follow their trajectory accurately.

In particular, this exercise:

- Assesses the feasibility of the method, i.e. shows that an appropriate allocation of takeoff times is likely to reduce complexity;
- Provides initial trends, i.e. on a simplified model, regarding efficiency and capacity.

The methodology employed is to use an optimisation algorithm to allocate takeoff times to aircraft from a simulated reference day of traffic. Results are expressed as trade-offs between delays and complexity measurements.

The results show that the concept described in this document enables enhancements for both capacity and safety for En-Route traffic: in all simulations, more than 95% conflicts were solved with a mean delay per aircraft between 2 and 10 minutes, depending on traffic.

However, the takeoff time allocations provided by the method described in this document are not robust enough to be operational. The attempt to build more robust solutions lead to allocations with very high delays, which is also not suitable for operations.

1 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

This document provides the Validation Exercise Report for EP3 WP4.3.2 FTS on 4D trajectory management and complexity reduction which will contribute to the elaboration of the Integrated Report of EP3 WP4.

1.2 INTENDED AUDIENCE

The intended audience includes:

- EP3 WP4: En-Route and Traffic Management:
    - EP3 WP4.1 – WP4 Management and Coordination leader;
    - EP3 WP4.2.1 – Validation Strategy and Support leader;
    - EP3 WP4.3 – WP4 Validation Activities leader;
    - EP3 WP4.4 – En-Route Results' Analysis and Report.
- EP3 WP2: System Consistency.
- EP3 WP4: Expert Group and FTS partners.

1.3 SCOPE AND STRUCTURE OF DOCUMENT

The document is composed as follows:

- Section 2 gives a summary of the experiment and strategy planning.
- Section 3 relates to the conduction of the experiment.
- Section 4 gives the results.
- Section 5 is the analysis of the experiment outcomes.
- Section 6 concludes the document and proposes some recommendations related to the exercise.

1.4 EXPERIMENT BACKGROUND AND CONTEXT

The Episode 3 project validation strategy focuses more on establishing consistency of validation process and ensuring that the necessary enablers are in place to allow the effective, concept focussed validation activity which must take place at the operational domain, EP3 WP3, WP4 & WP5. The validation activity is reflected through the following goals:

- Establish an understanding of SESAR Target Concept within the operational segment for which the WP is responsible.
- Identify validation activities and objectives based on existing research and best expert opinion on relevance for SESAR, to include:
    - a clear orientation towards objective data collection within the performance framework including the identification where possible of local targets;
    - provision of detail on key elements of the target concept; and
    - identification of issues of importance to the further development of the concept.

From these basic goals, the EP3 WP4 has derived a specific validation strategy for the work package. It provides the necessary link between the SESAR Concept of Operations and the validation activities in this project. The methodology is based on E-OCVM [7] (European Operational Concept Validation Methodology) Steps 0 and 1. This En-Route validation strategy describes an approach illustrating how the ATM Target Concept could be assessed and validated in terms of concept refinement and some selected performance areas.

The problem statement and the proposed solutions are derived from SESAR deliverables D1 [14] and D2 [15] and detailed in the relevant Detailed Operational Descriptions. They are expressed in terms of Lines of Change and Operational Improvement steps. A first mapping and scoping of the envisaged validation exercise towards the Lines of Change and the Operational Improvement steps has been done.

As SESAR follows a performance-oriented strategy, the targets are set in terms of Key Performance Areas. A more detailed breakdown defines the Focus Areas and the associated Key Performance Indicators. The contribution of this validation strategy towards the focus areas is provided. Finally, the validation tools and techniques for each exercise are defined.

The document reports on the validation exercise FTS on 4D trajectory management and complexity reduction which is done within WP 4.3.2: FTS on 4D Trajectory Management and Complexity Reduction.

In an already saturated European sky, the predicted growth of air traffic volume urges to improve Air Traffic Management (ATM) efficiency. Current ATM optimization strategies, like reducing the size of control sectors or the distance of separation, seem to have reached the structural limits of the system, while the automation of Air Traffic Control (ATC) has known few significant improvements over the last decades.

In this context, one of the key concepts identified to meet SESAR performance objectives is the planning of 4D trajectories. The objective of EP3 WP4.3.2 is to estimate how such regulations could benefit strategic de-confliction schemes over the current Air Traffic Flow Management (ATFM) process.

Currently, the Central Flow Management Unit (CFMU) in Brussels is in charge of optimizing the traffic by, among other strategic or tactical measures, providing departure slots for the flights involved in overloaded En-Route sectors. The purpose of this ground holding scheme is to respect the En-Route capacity constraints provided by each ATC Centre (ATCC) as a number of aircraft per hour, according to their daily schedule. One of the limitations of this regulation model is that the definition of sectors capacities (hourly rate of aircraft entering the sector) is poorly related to the complexity of the traffic with respect to the controllers' workload.

Instead of trying to satisfy En-Route capacity constraints, this exercise proposed to avoid the potential conflicts occurring between any two intersecting trajectories with departure time adjustment. A single delay would be associated with each flight, such that all potential conflicts occurring above a given flight level would be avoided. This very fine grain model would generate much larger constraints sets than the macroscopic model, but would guarantee conflict-free trajectories all along the flight path, provided that aircraft were able to scrupulously follow their predicted route in the four dimensions.

1.5 CONCEPT OVERVIEW

This validation exercise addressed specifically the following element of the SESAR ConOps (SESAR D3 [16]):

- Significantly reducing the need for controller tactical intervention by reducing the number of potential conflicts, using a de-confliction method.

The aim was to provide the Network Manager with a new delay allocation method, which took into account the structure of the traffic rather than macroscopic measurements such as sectors capacity.

The table below gives details on the exercise.

Validation Exercise ID and Title	**WP4.3.2 FTS on 4D Trajectory Management and Complexity Reduction**
Leading organization	DSNA
Validation objectives	Objective (Key Concept to be addressed and why): • De-confliction of the traffic is a key element of the SESAR concept on the basis of reducing traffic complexity. • The objective was to evaluate the postulate that a 4D planning of flights permit significantly reduced task load in ACC sectors while keeping the same level of capacity and safety.
Rationale	• Model-based simulation was suited to the assessment of 4D planning in execution phase. • Separation management measures were explored separately at the network and execution phases in order to evaluate its impact. • Arithmetic simulations using CATS/OPAS drove the validation process.
Expected results per KPA	KPA Capacity, FA-1 Airspace Capacity & FA-3 Network Capacity, KPA Safety, FA-1 ATM-related safety outcome, KPA Efficiency. With respect to the objectives mentioned above, this study: • Helped understand the impact of more dynamic de-complexification measures implemented via automation in the En-Route phase. • Provided inputs to expert groups. With the objective to reduce the sector task load or to reduce the number of conflicts, this study: • Proposed and studied several types of algorithms to execute ATFM slot allocation, when 4D plans were provided. • Evaluated the task load reduction that could be obtained according to the time dispersion allowed for take-offs. • Tested the robustness of the slot allocation against perturbations of the departure schedule and trajectory enforcement.
OI steps addressed	DCB-0205: Short Term ATFCM Measures. AUO-0204: Agreed Reference Business / Mission Trajectory (RBT) through Collaborative Flight Planning.

Validation Technique	Fast-time simulation.
Supporting DOD / Operational Scenario	DOD M2 [10] Medium/Short Term Planning. DOD E4 [11] Network Management in the Execution Phase. DOD E6 [12] Conflict Management in En-Route Operations.
Geographical area – performance framework level	ECAC airspace. Applicable to all En-Route airspace.

Table 1-1 Details of the exercise

1.6 GLOSSARY OF TERMS

Term	Definition
3D/4D	3 Dimensional / 4 Dimensional
ATCC	Air Traffic Control Centre
ANSP	Air Navigation Service Provider
AO	Airline Operator
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
BADA	Base of Aircraft Data
CATS/OPAS	Complete Air Traffic Simulator / Outils de Planification ATM et de Simulation
CENA	Centre d'Etudes de la Navigation Aérienne
CFMU	Central Flow Management Unit
ConOps	Concept of Operations
DOD	Detailed Operational Description
DoW	Description of Work
DSNA	Direction des Services de la Navigation Aérienne
ECAC	European Civil Aviation Conference
EEC	EUROCONTROL Experimental Centre
E-OCVM	European Operational Concept Validation Methodology
EP3	Episode 3
FA	Focus Area
FMS	Flight Management System
FTS	Fast Time Simulation
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
KPA	Key Performance Area

Term	Definition
MTOW	Maximum Take Off Weight
NATS	National Air Traffic Services
NOP	Network Operations Plan
OI	Operational Improvement
RBT	Reference Business Trajectory
SBT	Shared Business Trajectory
SESAR	Single European Sky ATM Research and Development Programme
STATFOR	EUROCONTROL Statistics and Forecast Service
WP	Work Package

2 SUMMARY OF EXPERIMENT AND STRATEGY PLANNING

2.1 EXPECTED EXPERIMENT OUTCOMES, OBJECTIVES AND HYPOTHESES

2.1.1 Description of Expected Experiment Outcomes

The table below shows the main stakeholders needs and expectations from a reduction of complexity for En-Route traffic.

Stakeholder	External / Internal	Involvement	Why it matters to stakeholder	Performance expectations
EP3 – WP4.4	Internal	- Consolidation of performance and operational results - Reporting of consolidated results for WP4	- Knowledge of the effect of optimised takeoff time allocation on complexity, safety and delays for En-Route traffic.	Trade-offs between solved conflicts (complexity) and delays. Recommendations for changes to the DODs.
EP3 – WP2.4.1	Internal	- Provide traffic data for the simulations	- Compatibility of the method with traffic forecast for 2020.	N/A
En-Route ATC	External	N/A	- Reduced complexity for En-Route sectors will lead to ability for the En-Route ATC to easily handle the growing traffic.	Evaluation of the possible de-confliction for En-Route traffic (achievable ratio of solved conflicts).
Airlines	External	N/A	- Reduced complexity will enable ATC to handle more traffic to better accommodate the airlines demand.	Trade-offs between de-confliction ratio and induced delays.
ANSP	External / Internal	Represented by DSNA as exercise leader	- Acceptance by the human actors (ATCOs).	Trade-offs between solved conflicts (complexity) and delays.

Table 2-1 Stakeholders expectations

2.1.2 Description of Experiment Objectives and Assumptions

The political goals of SESAR foresee that the target system should enable a three-fold increase in capacity, which will also reduce delays. The target system should also improve the safety performance by a factor of 10.

No study has yet demonstrated that these high level goals are achievable at network level given credible airline demand and airport infrastructure development in the future.

This validation exercise was a first theoretical approach to study whether adequately adjusting the departure time of aircraft could lead to a workload reduction, which would enable a traffic increase with still a sufficient safety factor.

In this context, the objectives of this exercise were:

- Propose and study an algorithm to execute ATFM slot allocation, when 4D flight plans are provided.

- Evaluate the workload reduction that can be obtained according to the time dispersion allowed for takeoffs.

The workload is here defined as the number of potential En-Route conflicts that could not be avoided.

More in details, this exercise determined whether an appropriate allocation of takeoff times was likely to reduce the number of potential conflicts for the En-Route phase. The fast-time simulations provided:

- Feasibility information: is it possible to solve all potential conflicts, or only part of them.
- Trade-offs between the percentage of solved conflicts and the delays associated.

For each simulation, departure delay for each aircraft was measured, as well as the amount of remaining conflicts. These data provided mean delay, percentage of delayed aircraft and percentage of solved conflicts.

The following paragraphs give the main assumptions made in this exercise.

Conflict detection

The data was provided by the CATS/OPAS simulator, which outputs 4D trajectories from the initial demand for a given airspace. Trajectories were sampled with a 15 seconds time step, which is the largest interval to guarantee that at least two points of the trajectories of facing aircraft at the highest possible speed will be closer than one separation norm (see Figure 2-1), i.e. even the shortest potential conflict is correctly detected.

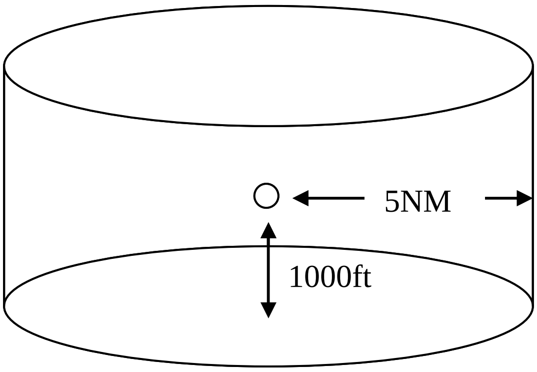

Figure 2-1 Vertical and horizontal separation. Another aircraft cannot be inside the cylinder at the same time.

Trajectories were then probed pair wise for potential conflicts (i.e. loss of separation norm), taking the maximum delay into account. The separation norm was thus tested for each pair of points of the two probed trajectories.

Though the maximal allowed delay can be seen as a parameter of the search algorithm only, it also affects the conflict detection. Actually, when the maximal allowed delay is increased, the size of the problem grows as well, as more and more flights are potentially in conflict.

More information about the model can be found in ATM2009 [4].

Aircraft equipment

All aircraft were supposed to be equally equipped with a precise enough FMS system. That means: each aircraft was able to follow a defined trajectory in x, y, z and t to the limit measurable in the simulation.

Optimisation parameters

The only variable parameters for the optimisation were the takeoff time of each aircraft. Thus each aircraft flew its preferred trajectory. However, the global performance of the network is not optimal, since lots of parameters would enable to enhance the quality of the allocation (e.g. flight level allocation, route allocation, etc).

Data handling

The optimisation algorithm was not able to handle an entire day of traffic since the amount of data is huge. To get round this issue, the data was handled by the use of a sliding window method. This method consists in the following steps:

1) Optimisation (and allocation of takeoff times) of a T_w minutes wide slice (or window) of the day of traffic considered.
2) Sliding of the optimisation window δ minutes ahead.
3) Starting again at first step until the end of the day of traffic is reached.

This method enabled to handle greater amount of traffic. The downside of it is that the allocation cost more in terms of delays than if the data was handled at once.

The values for T_w and δ are adjusted to the performance of the optimisation algorithm.

The figure below illustrates this method. The first time frame shows the takeoff times as they appear in the flight plans for aircraft a_i. The following time frames show the successive phases of the optimisation, with the already allocated takeoff times in red. The blue box in each time frame represents the sliding window: the takeoff times within this box are being processed. The last time frame shows the final allocation for the traffic considered. Takeoff times are only shifted ahead: flights were not allowed to take off before their scheduled takeoff time. Also, the exercise do not look at any time distance between two departures on the same runway.

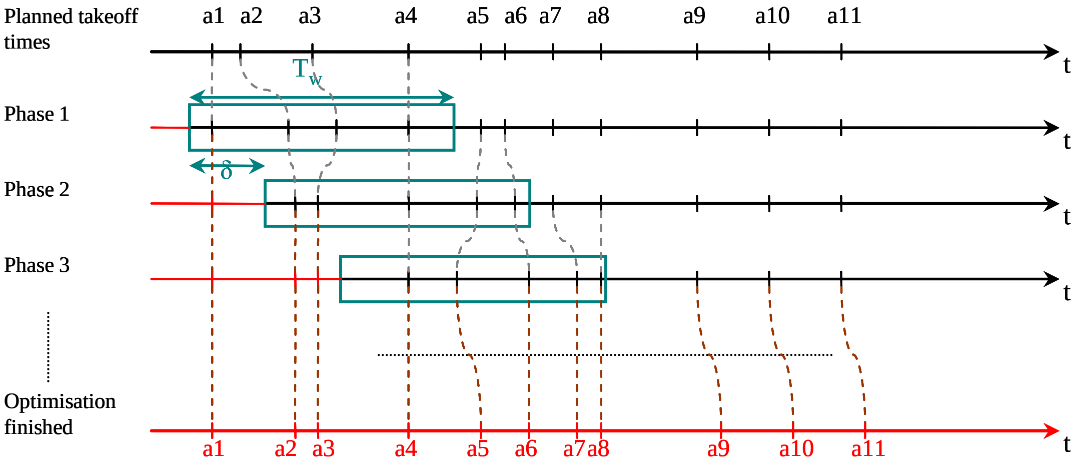

Figure 2-2 Illustration of the sliding window method for the takeoff time allocation

Iterations per scenario

In order to achieve a statistical confidence in the simulation results, suitable scenarios using a stochastic resolution method (i.e. an algorithm that includes some random operations) were run more than once. Indeed, two solutions issued from two different runs with the same set of parameters might differ. However, considering the huge data dimension, differences are limited regarding the metric to optimise.

Wind and weather modelling

Wind and other weather conditions were not taken into account in this exercise.

2.1.3 Description of Experiment Hypotheses

The main identified hypothesis for this exercise is:

H1 An adequate allocation of takeoff times can reduce workload for the En-Route phase.

2.2 CHOICE OF METRICS AND MEASUREMENTS

The exercise provided initial trade-offs between takeoff time delays and complexity reduction. The indicators that were selected to describe complexity essentially take into account the number of potential conflicts that could not be avoided by allocating takeoff times.

The following metric has been chosen from the Performance Framework Document [8] for this purpose:

- SAF.LOCAL.ER.PI 8: Number of resolutions.

For each scenario, the input traffic demand was processed in CATS/OPAS twice:

- The first run was made without any solving. 4D trajectories are directly built from the initial demand. The count of occurring conflicts was kept for later computation of avoided conflicts.
- The second run was made after solving, in order to verify the correctness of the solution found. The difference between the numbers of conflicts in the two runs gave the number of avoided conflicts.

2.3 CHOICE OF METHODS AND TECHNIQUES

The exercise consisted in a series of fast-time simulations carried out on the traffic samples described in the next section. Each simulation can be described as the sequence of the following steps:

- Generation of aircraft trajectories from initial demand, using CATS/OPAS simulator.
- Computation of all 3D crossings between these trajectories, using the method described in section 2.1.3.
- Computation of takeoff times, so as to ensure that there is no loss of separation at the above 3D crossings.
- Input the newly allocated takeoff time in CATS/OPAS to verify the correctness of the solution.

The following paragraphs describe the CATS/OPAS simulator and the optimisation algorithm used to realise these simulations.

Description of the CATS/OPAS traffic simulator

The CATS/OPAS simulator was developed in CENA[1], starting in the mid 90's. It has a very light structure, which makes it easy to maintain and fully adaptable.

---

[1] Centre d'Etudes de la Navigation Aérienne

The core of the CATS/OPAS system is an En-Route traffic simulation engine. It is based on a discrete, fixed time slice execution mode: the positions and velocities of aircraft are computed at fixed time steps (in this exercise, one position every 15 seconds). The simulator uses BADA performance tables, derived from the total energy model from EUROCONTROL.

Aircraft trajectories are computed from flight plans that can be either user-defined, or taken from historical data. Aircraft can use different navigation modes:

- Standard routes: they follow the sequence of navigation aids described in their flight plan.
- Direct routes to their destination.

The system records and computes several output information, among which:

- Aircraft trajectories.
- Conflicts statistics (geometry, duration, etc).
- Airborne separation statistics.

The simulator also provides build-in conflict detection modules and conflict resolution modules. These modules enable to automatically solve En-Route conflicts, using horizontal manoeuvres. For Episode 3 purpose, a new functionality was added to CATS/OPAS, enabling to take as input the delays allocated to aircraft. This new functionality was used to validate the solutions within the simulator.

More detailed information about CATS/OPAS can be found in CATS [3].

Description of the optimisation algorithm

The method chosen for the resolution and optimisation of the allocation problem is a genetic algorithm. A genetic algorithm is an optimisation algorithm based on techniques derived from natural evolution: crossover, mutation, selection, etc. This kind of algorithm searches for the extremum (or extrema) of a function. The following elements are needed to initiate such an algorithm:

- An encoding method for the population elements. This step associates a *chromosome* (structural data) to each point of the search space.
- A mechanism for generating an initial population. This mechanism creates a non-homogeneous population, which is the base for the future generations.
- A function to optimise, called *fitness* or evaluation function for the population element.
- Operators (crossover and mutation) that enable to transform the individuals through the generations, and therefore explore the search space.
- Dimensional parameters: size of the population, total number of generations, probabilities for crossover and mutation.

The functioning principle is the following. First an initial population is randomly generated. Next, to evolve from population k to population k + 1, the following operations are repeated for each population element:

- Couples of parents are selected according to their fitness. The crossover operator is applied with a probability Pc, which produces two new population elements.
- Other elements are selected. The mutation operator is applied with a probability Pm, which generates a new population element.

The algorithm stops when the predefined number of generations is reached.

2.4 VALIDATION SCENARIO SPECIFICATIONS

Airspace information

The exercise should have been ECAC wide. However, due to the limitation of large-scale fast-time simulations, it was decided to reduce the scope to a smaller area: the French territory.

Sectorisation and route structure are today's. Two types of simulations were carried out:

- Aircraft following standard routes.
- Aircraft following direct routes from their origin to their destination.

Traffic information

The reference traffic corresponds to 18th, 21st and 23rd of July 2006. The 2020 scenarios are built from the reference scenarios by applying the expected traffic growth provided by the EUROCONTROL Statistics and Forecast Service (STATFOR). This traffic is issued by EP3 WP2.4.1.

For practical reasons, the 18th, 21st and 23rd of July 2006 traffic samples will be labelled respectively 2006#1, 2006#2 and 2006#3, and the 2020 traffic samples built from these reference samples will be labelled respectively 2020#1, 2020#2 and 2020#3.

2.5 EXPERIMENTAL VARIABLES AND DESIGN

The main variables for the simulations were takeoff times. Secondary variable was the maximum delay allowed for the simulation. Others parameters varied depending on the amount of input data. These parameters were directly linked to the genetic algorithm: number of population elements and number of generations. The probabilities of crossover and mutation were fixed.

The table below gives a summary of the exercise design.

ID	Description
D_i	Delay for aircraft with identifier i.
D_{max}	Maximum allowed delay (constant during one given run, but variable from one run to another).
N_{elem}	Number of population elements for the genetic algorithm (shall be fixed, but could be diminished for larger instances).
N_{gen}	Number of generations for the genetic algorithm (shall be fixed but could be diminished for larger instances).
P_{cross}	Probability of crossover (constant).
P_{mut}	Probability of mutation (constant).
T_w	Width of the sliding time window
δ	Shift of the sliding time window
For every aircraft i, $0 \leq D_i \leq D_{max}$	

Table 2-2 Summary of variables and exercise design.

3 CONDUCT OF VALIDATION EXERCISE RUNS

3.1 EXPERIMENT PREPARATION

The conduction of the experiment needed some preliminary work. The following tasks were necessary to the preparation:

- Definition of the exercise, including selection of the SESAR ConOps elements, platform, scenarios. The main output of this activity is the Experimental Plan for this exercise [9].
- Implementation of the optimisation algorithm, and adaptation of this algorithm to the model.
- Adaptation of the platform CATS/OPAS to the experiment.
- Input data pre-processing (computation of 4D trajectories from initial demand, computation of potential conflicts).

3.2 EXECUTED EXPERIMENT SCHEDULE

The conduction of the experiment took place between April 2009 and May 2009.

3.3 DEVIATIONS FROM THE PLANNING

The initial target for this final report was not met. This is due to some technical problems that occurred during the research work inherent to this exercise. In particular, the tuning of the optimisation algorithm took more time than expected.

4 EXPERIMENT RESULTS

4.1 MEASURED EXPERIMENT RESULTS

4.1.1 Data processing

The model results in a very constrained problem, with single flights conflicting with more than 300 other flights. The exercise only handles conflicts occurring in upper airspace.

4.1.2 Simulation

There were two kinds of simulations: standard routes and direct routes.

For each simulation, the results are presented as follows:

- Traffic data set.
- Percentage of non-avoided conflicts, i.e. number of potential conflicts that could not be solved by the allocation algorithm.
- Maximum delay allocated during the simulation.
- Percentage of delayed aircraft.
- Mean delay per aircraft, i.e. total amount of delay allocated divided by number of aircraft in the simulation.

Delays are expressed in minutes.

Standard routes						
Traffic	**Number of flights**	**Remaining conflicts**	**Maximum delay**	**Delayed aircraft**	**Mean delay**	**Standard deviation**
2006#1	8470	0.50%	86’	53.80%	2’31’’	4.83
2006#2	9089	1.15%	86’	53.90%	2’29’’	4.84
2006#3	8407	0.07%	87’	59.13%	2’56’’	5.08
2020#1	14653	2.52%	89’	65.50%	8’02’’	12.76
2020#2	15269	3.18%	89’	67.85%	8’08’’	12.86
2020#3	14292	2.07%	87’	71.80%	8’57’’	13.53

Direct routes						
Traffic	**Number of flights**	**Remaining conflicts**	**Maximum delay**	**Delayed aircraft**	**Mean delay**	**Standard deviation**
2006#1	8470	0.46%	66’	52.93%	2’13’’	3.86
2006#2	9089	0.10%	89’	55.53%	2’32’’	4.17
2006#3	8407	0.09%	70’	58.23%	2’32’’	5.88
2020#1	14653	2.00%	84’	64.05%	6’54’’	10.47
2020#2	15269	2.31%	90’	65.62%	7’19’’	11.49
2020#3	14292	1.95%	90’	69.73%	7’56’’	11.74

In addition to the measurements, the allocations of takeoff times were recorded during the simulations. These data were used for the analysis given in the next section.

4.2 CONFIDENCE IN EXPERIMENT RESULTS

4.2.1 Quality of Results of Experiment

The CATS/OPAS simulator uses BADA tabulated performance data for aircraft performance modelling. This model gives sufficient accuracy for the En-Route phase with respect to the method used. Though the results can be accepted with confidence. However, these results are specific to the geographic area simulated, with no identified means to extrapolate these measurements to an ECAC wide context, as the measured parameters are very dependant to the structure of the traffic.

4.2.2 Significance of Results of Experiment

The results have a relatively low operational significance, due to the assumption on the precision of aircraft (a short analysis of the impact of uncertainties on the method is given in the next section). However, they give a hint on what is achievable in terms of complexity reduction with this kind of method. For a better operational significance, it would be interesting to study the coupling of such a method with other de-complexification methods, such as flight level allocation or automated tactical de-confliction.

4.3 UNEXPECTED EXPERIMENT RESULTS

There were no unexpected results in the context of E-OCVM step 3.2.

5 ANALYSIS OF EXPERIMENT OUTCOMES

5.1 ANALYSIS OF OUTCOMES ON THE BASIS OF DETERMINED HYPOTHESES

H1 An adequate allocation of takeoff times can reduce workload for the En-Route phase.

> The hypothesis is proven. However, solving all potential conflicts with this method exclusively is not operationally possible, due to the huge delays allocated for some aircraft. Also, the optimal solution is not operationally feasible as small perturbations will inevitably spoil the resolutions.

5.2 ANALYSIS OF CONSEQUENCES OF OUTCOMES FOR EXPERIMENT OBJECTIVES AND ASSUMPTIONS

5.2.1 Analysis of the numerical results

The simulations showed encouraging results with respect to the objective of avoiding the most potential conflicts: for all the simulations, the algorithm was able to solve more than 95% of conflicts. The average delay allocated per aircraft is under 3 minutes for 2006 traffic. For 2020 traffic however, the allocated delays have higher values, with an average delay around 6 minutes. Figure 5-1 shows the distribution of delays.

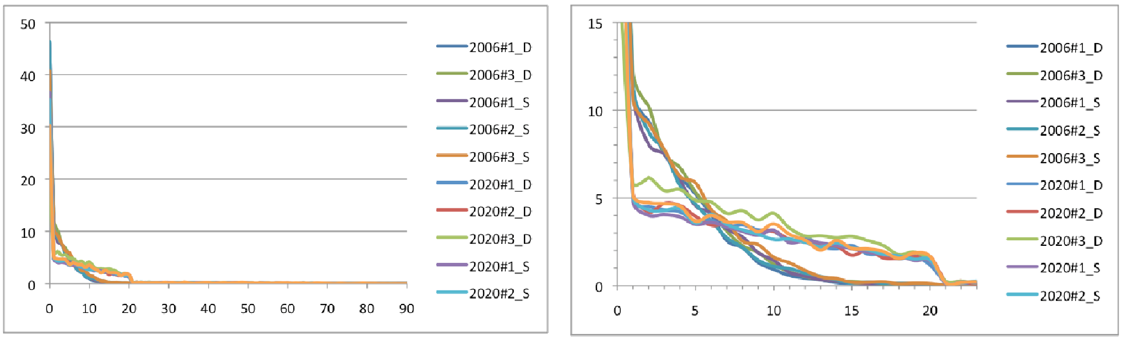

Figure 5-1 Distribution of the delays: percentage of flights (y axis) allocated each delay (x axis) over the day of traffic. Delays are expressed in minutes.

For 2006 traffic, this distribution is similar for all the simulations, and less than 2% aircraft have been allocated a delay higher than 10 minutes. For 2020 traffic, the distributions are also similar among all simulations, but there is still 10% flights with an allocated delay over 10 minutes.

For more clarity, Figure 5-2 gives the distributions of delays averaged respectively on 2006 and 2020 traffic samples, focusing on delays up to 20 minutes.

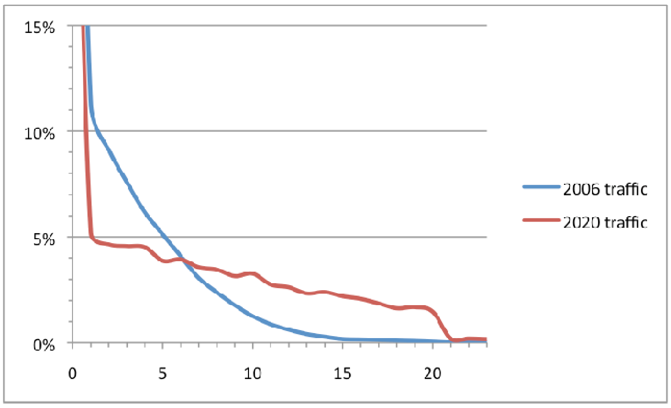

Figure 5-2 Distribution of delays averaged on 2006 and 2020 traffic.

The percentage of delayed flights is around 55%, with a mean delay *per delayed flight* lower than 5 minutes.

5.2.2 Standard and direct routes

Direct routes tend to generate less constrained instances than standard routes. It is interesting to observe that the total amount of delay allocated on direct route traffic is smaller than on standard route traffic (see Figure 5-3).

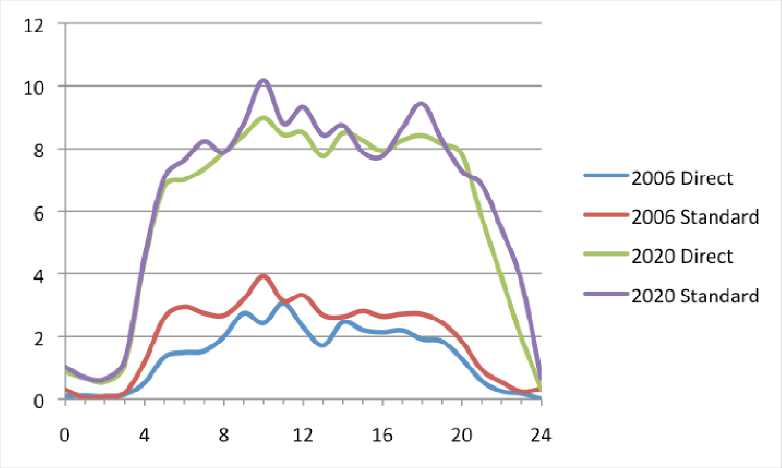

Figure 5-3 Mean amount of delay (in minutes) allocated over the day of traffic, for direct and standard routes.

Flights following standard routes tend to be on closer trajectories, suitable for the efficiency of current ATC procedures, but not using airspace to its full capacity.

5.2.3 Robustness towards uncertainty

The model and algorithm presented above were validated, by taking the generated solutions as input of the CATS/OPAS traffic simulator. However, this validation did not take into account any uncertainty with respect to departure time or aircraft navigation.

To improve the robustness of the solutions towards uncertainty on the departure times, an extra parameter *ext* was added to the model. This parameter extended the constraints such that a value of *ext* minutes allowed managing uncertainties of $\pm\frac{ext}{2}$ minutes.

To assess the robustness of the solutions, an uncertainty parameter *err* was added on departure times within CATS/OPAS. Takeoffs were randomly shifted by a bounded amount of time uniformly[1] chosen in the interval $\left[-\frac{err}{2};\frac{err}{2}\right]$.

Some new validation tests were carried out with various values of parameters *ext* and *err* to compensate for the uncertainties. As expected, Figure 5-4 shows that for *ext* ≥ *err*, very few conflicts remain: all points below the *ext* = *err* dashed line on the xy-plane exhibit a conflict percentage near to zero. Above this line, the ratio of remaining conflicts increases with *err* for a given *ext* and when *ext* diminishes for a given *err*, reaching 75% for the highest point.

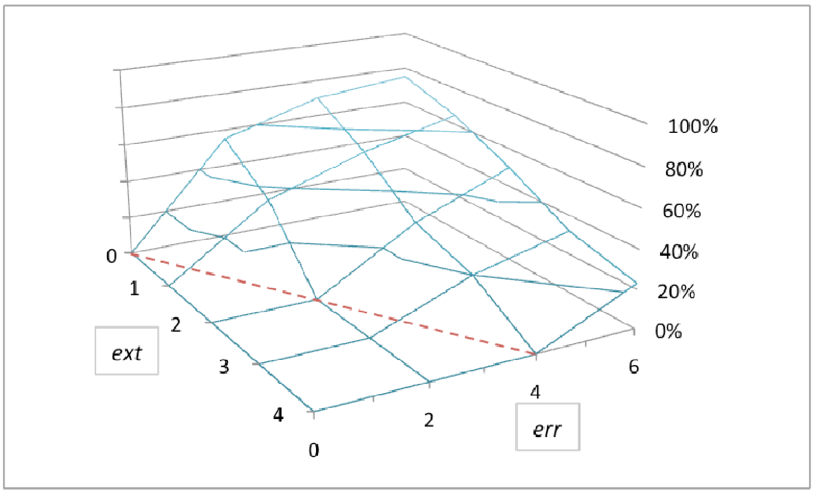

Figure 5-4 Percentage of remaining conflicts w.r.t. conflict extension and departure time error in minutes.

However, increasing the value of the *ext* parameter leads to an increase in the total amount of delay, as illustrated in Figure 5-5. The additional delays, i.e. delays induced by the introduction of *ext* parameter, can be far too costly for higher values of *ext*, especially for large instances. It is though not possible to solve all conflicts with the presented method alone within CFMU (-5/+10 minutes) or even SESAR (± 3 minutes) time slot objectives, as operational delays would be prohibitive.

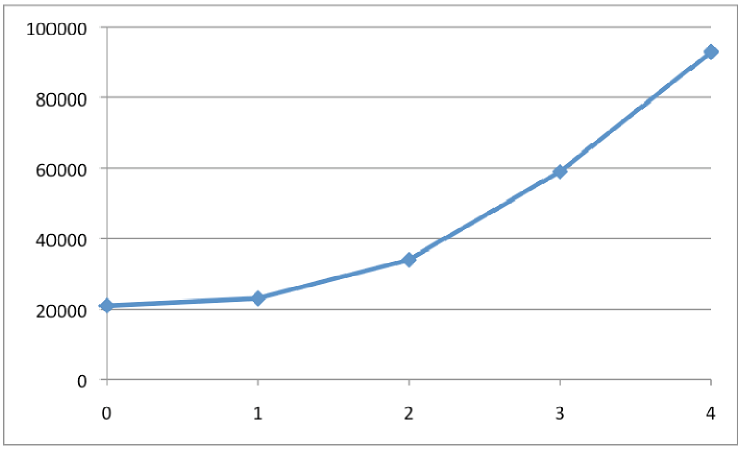

Figure 5-5 Total amount of delay (in minutes) w.r.t. conflict extension (in minutes).

---

[1] A better approach would involve a statistical analysis to approximate the probability distribution of the discrepancy between scheduled and actual takeoff times.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 KEY FINDINGS

The results show that the concept described in this document enables enhancements for both capacity and safety for En-Route traffic: both 2006 and 2020 traffic were de-complexified, generating delays within a reasonable bound.

The following table gives the conclusions for each OI step addressed.

OI	Description of conclusions
DCB-0205	The short term ATFCM measure tested in this exercise reduced the complexity of the traffic. This measure should be combined with other measures to have an operational benefit.
AUO-0204	A real-time application of the method described would require updates of the RBT, through collaborative decision making.

Table 6-1 OI steps addressed and associated conclusions.

6.2 ISSUES

The takeoff time allocations provided by the method described in this document are not robust enough to be operational. The attempt to build more robust solutions lead to allocations with very high delays, which is also not suitable for operations.

As it was finally not possible to run ECAC wide simulations in the scope of this exercise, it would be of great interest to do so, in order to see if the results of this exercise would apply on such a traffic and area.

6.3 RECOMMENDATIONS

6.3.1 General recommendations

In order to compensate for the huge amount of delay allocated when trying to build solutions that are robust towards uncertainties, it would be interesting to try coupling this method with other de-complexification methods. One intuitive proposition would be to allocate flight levels prior to takeoff times, in order to split the problem into smaller instances, easier to solve.

The method described in this report could be integrated in the CATS/OPAS traffic simulator. CATS/OPAS already provide built-in conflict resolution measures that can easily be combined. Adding this new method within the simulator would help integrate this 4D planning method in a more complete model. This way, experiments could be carried out, combining different resolution methods: 4D planning and horizontal manoeuvres.

6.3.2 Recommendations on supporting DODs and Operational Scenarios

The Operational Improvement steps addressed in this exercise have been validated against the hypotheses and metrics chosen for the simulations. The results presented in previous sections show that these OI steps are indeed enablers, in the scope of the simulations carried out, to increase capacity and safety in the En-Route phase. Though this exercise requires no changes to the DODs.

This exercise did not address SESAR operational scenarios.

6.4 CONCLUSIONS

The main objectives for this exercise were:

- O1: Propose and study an algorithm to execute ATFM slot allocation, when 4D flight plans are provided.
- O2: Evaluate the workload reduction that can be obtained according to the time dispersion allowed for takeoffs.

The table below gives a summary of the conclusions of the exercise related to the above objectives.

ID	Description of conclusions
O1	A genetic algorithm was proposed to execute the takeoff time allocation. The algorithm was implemented and adapted to the problem, and included in the fast-time simulation process.
O2	The exercise gave the value of a complexity measurement before and after the departure time allocation. A complexity reduction was observed: 96 to 99% of potential conflicts were solved for each simulated traffic sample. The delays allocated to de-complexify this traffic took values between 0 and 90 minutes, with very few flights delayed more than 10 minutes for 2006 traffic and 20 minutes for 2020 traffic. The attempt to build solutions that are robust with respect to uncertainties showed very high values for delays.

Table 6-2 Conclusions related to the main objectives of the exercise.

7 REFERENCES AND APPLICABLE DOCUMENTS

7.1 REFERENCES

[1] **EUROCONTROL –** Study report "Challenges to Growth" – Version 1.0, 12/2004

[2] **EUROCONTROL –** Long-Term Forecast Flight Movements 2006 – Version 1.0, 01/12/2006

[3] JM Alliot, JF Bosc, N Durand, L Maugis – CATS: A Complete Air Traffic Simulator. 16th DASC, 26/10/1997

[4] N Barnier, C Allignol – 4D-Trajectory Deconfliction Through Departure Time Adjustment. ATM 2009

7.2 APPLICABLE DOCUMENTS

[5] **Episode 3 –** Exercise Report Template (D2.5-03) – Version 1.00, 8/04/2009

[6] **Episode 3 –** Episode 3 DoW – Version 2.3, 15/03/2007

[7] **Episode 3 –** European Operational Concept Validation Methodology (E-OCVM) – Version 2.0, 17/03/2007

[8] **Episode 3 –** Performance Framework (D2.4.1-04) – Version 3.03, 03/03/2009

[9] **Episode 3 –** FTS on 4D trajectory management and complexity reduction Experimental plan (D4.3.2-01) – Version 1.01, 20/03/2009

[10]**Episode 3 –** SESAR Detailed Operational Description – Medium / Short Term Network Planning (DOD M2 – D2.2-033) – Version 1.0, 09/02/2009

[11]**Episode 3 –** SESAR Detailed Operational Description – Network Management in the Execution Phase (DOD E4 – D2.2-046) – Version 1.01, 01/04/2009

[12]**Episode 3 –** SESAR Detailed Operational Description – Conflict Management in En-Route Operations (DOD E6 – D2.2-038) – Version 1.02, 01/04/2009

[13]**SESAR –** The SESAR Performance Booklet (RPT-0708-001-01-01)

[14]**SESAR –** The Current Situation (SESAR D1 – DLM-0602-001-03-00) – Version 3.0, 31/07/2006

[15]**SESAR –** The Performance Target (SESAR D2 – DLM-0607-001-02-00) – Version 2.0, 22/12/2006

[16]**SESAR –** The ATM Target Concept (SESAR D3 – DLM-0612-001-02-00) – Version 2.0, 27/09/2007

[17]**SESAR –** ATM Deployment Sequence (SESAR D4 – DLM-0706-001-02-00) – Version 2.0, 01/02/2008

[18]**SESAR –** SESAR Concept of Operations (DLT-0612-222-02-00) – Version 2.0, 01/10/2007

[19]**SESAR –** Performance Assessment Task Report Capacity and Quality of Service – Version 0.04, 04/06/2007

END OF DOCUMENT