Project no. TREN/07/FP6AE/S07.71574/037180 IFLY

iFly

Safety, Complexity and Responsibility based design and validation of highly automated Air Traffic Management

Specific Targeted Research Projects (STREP)

Thematic Priority 1.3.1.4.g Aeronautics and Space

iFly Publishable Final Activity Report

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Executive Summay

Motivation

One of the most innovative and promising paradigms in Air Traffic Management (ATM) is to transfer the responsibility of maintaining separation with other aircraft from sector air traffic controllers to the pilots of each aircraft. In short, such a complete transfer of separation responsibility is referred to as airborne self separation. Since the invention of Free Flight in 1995, airborne self separation research has seen a tremendous development worldwide. Nevertheless, the current situation is of two schools of researchers holding different beliefs about airborne self separation:

- One school believes airborne self separation can be performed at sufficiently safe levels en-route and at traffic levels well above the current situation;
- The other school believes airborne self separation cannot be carried out at sufficiently safe levels above Europe.

In order to resolve this tie in beliefs held by two schools of researchers, iFly has first developed an advanced airborne self separation Concept of Operation for en-route traffic, aimed to manage a three to six times as high traffic demand than high traffic demand in 2005. Subsequently iFly has assessed this advanced concept of operations on safety and economy under three to six times the en-route traffic demand over Europe in 2005.

Description of work

iFly has performed two operational concept design cycles and an assessment cycle.

During the first design cycle, an Autonomous Aircraft Advanced (A^3) en-route operational concept has been developed which is based on the current “state-of-the-art” in aeronautics research. An important starting and reference point for this A^3 ConOps development was formed by a systematic analysis of human responsibilities under current ATM and under airborne self separation.

During the assessment cycle, the A^3 ConOps has been evaluated on cost-benefit and on safety as function of very high traffic demand.

During the second design cycle, the A^3 Conops has been refined by taking advantage of iFly studies on:

- Advanced conflict detection and resolution algorithms.
- Managing Multi-Agent Situation Awareness (SA).
- Prediction of complexity of air traffic situations.

Results and conclusions

First of all, iFly has demonstrated that advanced airborne self separation can safely accomodate very high en-route traffic demand [iFly report D7.4], and under a positive cost-benefit perspective [iFly report D6.4].

Complementary to this key result, the iFly project also has achieved several specific milestones that go beyond the state-of-the-art in advanced ATM development:

- The development of a well documented A^3 ConOps [iFly report D1.3];
- Setting out the principles to be adhered in the development of an A^3 directed HMI design in the cockpit, such that this HMI provides optimal support to the crew, in support of their new tasks and responsibilities [iFly report D2.4].
- Study of mathematical approach toward traffic complexity prediction [iFly report D3.2];
- Study into maintaining correct multi agent situation awareness [iFly report D4.2];
- Study of advanced conflict detection and resolution methods [iFly reports D5.3 and D5.4];
- Inventory of options for the refinement of an advanced ATM concept [iFly report D8.1];
- Innovative approaches towards traffic flow management in support of the A^3 ConOps, [iFly report D8.2];
- Development of a vision to integrate A^3 –equipped aircraft with the SESAR 2020 thinking [iFly report D8.3].
- SPR documents provide a novel level of detail and enhanced analysis (in particular, with respect to safety) of self separation operations comparing to the previous airborne self separation research [iFly report D9.1 - D9.3].

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1 Introduction

1.1 Key research objective

Air transport throughout the world, and particularly in Europe, is characterised by major capacity, efficiency and environmental challenges. With the predicted growth in air traffic, these challenges must be overcome to improve the performance of the Air Traffic Management (ATM) system. The air traffic capacity/safety wall has to be moved by a large factor in order to meet the growing demand for business and recreational travel without sacrificing established (very high) safety standards. The conventional approach of air traffic controllers being responsible for the safe and expeditious flow of air traffic in their sectors appears to have reached its limits. Hence the air transport industry is in need of developing a novel paradigm that indeed is able to significantly push the capacity/safety barrier. One of the most innovative and promising paradigm is to transfer the responsibility of maintaining separation with other aircraft from sector air traffic controllers to the pilots of each aircraft. In short, such a complete transfer of separation responsibility is referred to as airborne self separation. Since the invention of Free Flight [RTCA, 1995] airborne self separation research has seen a tremendous development worldwide. Nevertheless, the current situation is of two schools of researchers holding different beliefs about airborne self separation:

- One school believes airborne self separation can be performed at sufficiently safe levels en-route and at traffic levels well above the current situation;

- The other school believes airborne self separation cannot be carried out at sufficiently safe levels above Europe.

In fact these two opposite schools also agree on two key points:

1. For low traffic airspace areas the safety will be improved by equipping aircraft with the appropriate Airborne Separation Assistance System (ASAS); which resulted in a steady development and implementation of airborne self separation operations in some low traffic airspace areas around the world;

2. None of the schools exactly knows at which traffic levels the safety/capacity barrier of airborne self separation lies. Hence both schools are in need of receiving an answer to the question “At what traffic level the safety of advanced airborne self separation based operation falls short?”

Without having a proper answer to the latter question, there is large uncertainty to the strategic direction to be taken regarding the further development of airborne self separation, and this may even tend to stall its further development. Even worse, this may have negative impact on the development referred to under 1, although the two schools do not differ. The very reason is that investments by airlines in an advanced system that can be used in airspace where their aircraft hardly fly is economically very unattractive. Hence both for developments 1 and 2 there is an urgent socio-economic need for the aviation industry to know how far airborne self separation can safely support increasing traffic demands.

From a societal perspective, citizens expect air transport to be affordable and safe in the future as well as it is now. Hence, a potential stall or delay in the further investment by the air transport industry into airborne self separation, eventually may have a very negative impact on the users of the air transport system, and thus on human society. Hence it is human society that benefits significantly from a continuation of effective strategic investments of the aviation industry into advanced air traffic operations. A key condition which has to be fulfilled is that the two schools are able to present a joint view to the air transport industry. iFly aims to develop the key missing scientific pieces of knowledge that solve the puzzles of both schools, this means that iFly frees the ASAS developments from this very expensive stall, and makes rationale investments into strategic development of ASAS possible again.

1.2 iFly project

The iFly project has developed and assessed an advanced airborne self separation Concept of Operation for en-route traffic, aimed to manage a three to six times as high traffic demand than high traffic demand in 2005.

iFly has performed two operational concept design cycles and an assessment cycle comprising human factors, safety, efficiency, capacity and economic analyses. The general work structure is illustrated in Figure 1. During the first design cycle, state of the art Research, Technology and Development (RTD) aeronautics results have been used to define a "baseline" operational concept. For the assessment cycle and second design cycle, innovative methods for the design of safety critical systems have been used to refine the operational concept with the goal of managing a three to six times increase in traffic demand of 2005. These innovative methods find their roots in robotics, financial mathematics and telecommunications.

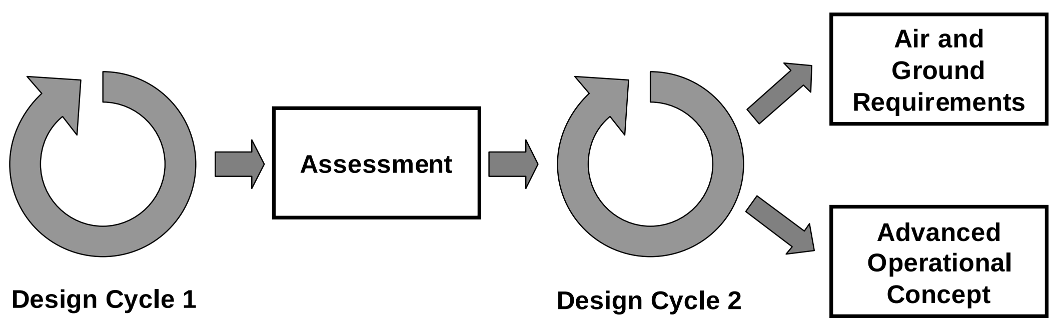

Figure 1. iFly Work Structure.

As depicted in Figure 2, iFly work is organised through nine technical Work Packages (WPs), each of which belongs to one of the four types of developments mentioned above:

<u>Design cycle 1</u>

The aim was to develop an Autonomous Aircraft Advanced (A^3) en-route operational concept which is initially based on the current "state-of-the-art" in aeronautics research. The A^3 ConOps has been developed within WP1. An important starting and reference point for this A^3 ConOps development was formed by the human responsibility analysis in WP2.

Innovative methods

Develop innovative architecture free methods towards key issues that have been addressed by an advanced operational concept:

- Develop a method to model and predict complexity of air traffic (WP3).
- Model and evaluate the problem of maintaining multi-agent Situation Awareness (SA) and avoiding cognitive dissonance (WP4).
- Develop conflict resolution algorithms for which it is formally possible to guarantee their performance (WP5).

Assessment cycle

Assess the state-of-the-art in Autonomous Aircraft Advanced (A^3) en-route operations concept design development with respect to human factors, safety and economy, and identify which limitations have to be mitigated in order to accommodate a three to six times increase in air traffic demand:

- Assess the A^3 operation on economy, with emphasis on the impact on organisational and institutional issues (WP6).
- Assess the A^3 operation on safety as a function of traffic density increase over current and mean density level (WP7).

Design cycle 2

The aim was to refine the A^3 ConOps of design cycle 1 and to develop a vision how A^3 equipped aircraft can be integrated within SESAR concept thinking (WP8). WP9 has developed preliminary safety and performance requirements on the applicable functional elements of the A^3 ConOps, focused on identifying the required technology.

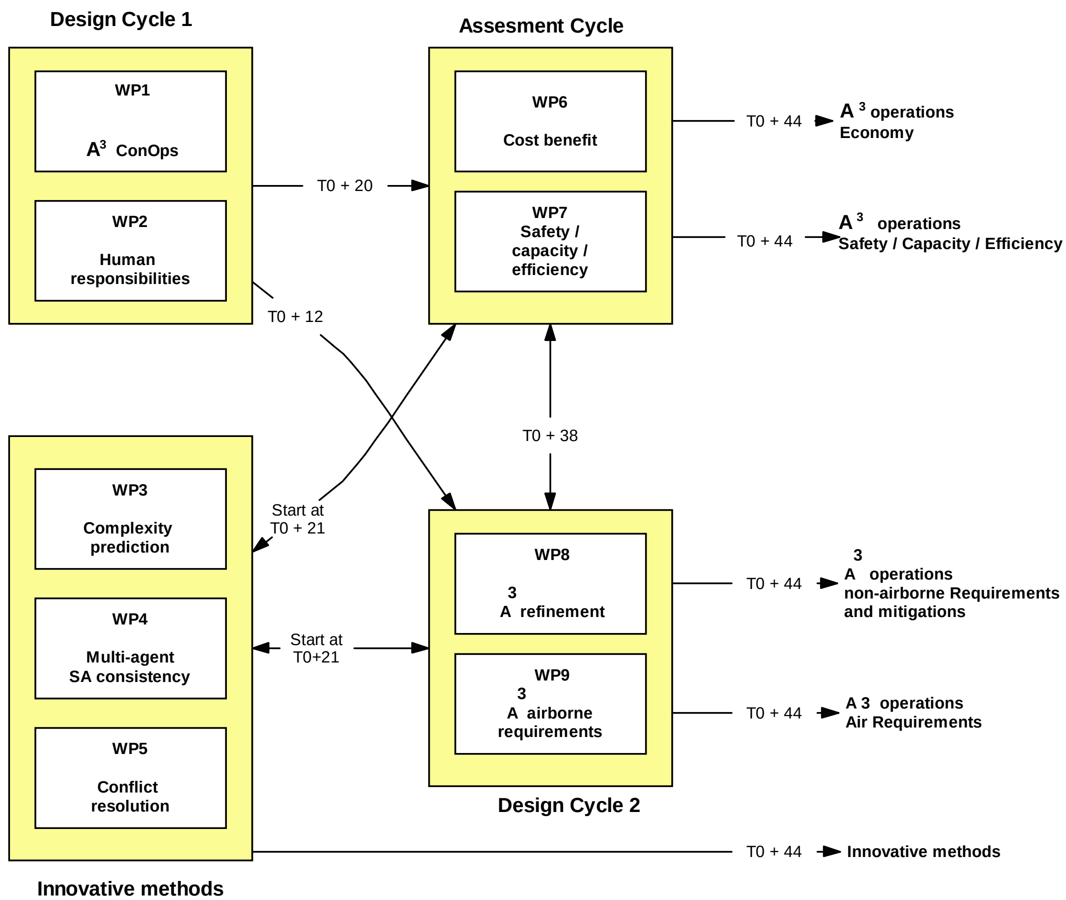

Figure 2. Organisation of iFly research.

1.3 iFly project partners

The iFly project has 18 consortium partners, which are listed in Table 1.

Table 1. iFly Consortium Partners

List of Participants

Partic. no.	Participant name	Participant short name	Country
1	National Aerospace Laboratory NLR (Coordinator)	NLR	NL
2	Honeywell	HNWL	CZ
3	Isdefe	Isdefe	ES
4	University of Tartu	UTartu	EE
5	Athens University of Economics and Business Research Centre	AUEB	GR
6	Eidgenössische Technische Hochschule Zürich	ETHZ	CH
7	University of l'Aquila	AQUI	IT
8	Politecnico di Milano	PoliMi	IT
9	University of Cambridge	UCAM	UK

10	National Technical University of Athens	NTUA	GR
11	University of Twente	TWEN	NL
12	Ecole Nationale de l'Aviation Civile	ENAC	FR
13	Dedale	Dedale	FR
14	NATS En Route Ltd.	NATS	UK
15	Institut National de Recherche en Informatique et en Automatique	INRIA	FR
16	Eurocontrol	EEC	FR
17	DSNA-DTI-SDER	DSNA	FR
18	University of Leicester	ULES	UK

1.4 Aim and organisation of this report

The aim of this report is to provide a complete picture of the research performed and results obtained within the iFly project and in each of the ten technical WP's. In order to accomplish this, the report provides a separate picture of the research performed and results obtained in the ten technical WPs. This is done in Sections 2 through 11. Finally, Section 12 relates the achievements of the project to the state-of-the-art and the impact of the project on its industry or research sector.

2 Project execution for WP1: Autonomous Aircraft Advanced Concept

2.1 Objectives

The objective of WP1 is to develop an autonomous aircraft advanced (A^3) Concept of Operations (ConOps) including an airline strategy concept for autonomous aircraft operations, using state-of-the-art aeronautics research and technology results. The A^3 ConOps developed here focuses on the en-route phase of flight, for a potential shift into autonomous en-route operations in airspace that is busy according current standards. The airline strategy concept offers opportunities for airlines to harness the greater autonomy to improve on customer service.

2.2 iFly Partners involved

WP1 has been conducted under the leadership of Isdefe. Within WP1, the main research has been performed by Isdefe, HNWL, NLR and UTartu. Critical reviews of research reports have been provided by NLR, Dedale, ETHZ, EEC, ENAC, AUEB and NATS.

2.3 Work performed and approaches employed

The work has been organised in three sub-WPs. WP1.1 called “High level ConOps” addressed the available options towards autonomous en-route aircraft advanced operations. WP1.2 called “Airline Strategy Concept” addressed the strategy concept for airline operations in an autonomous aircraft environment. WP1.3 called “ConOps” addressed the overall concept of operations within the autonomous en-route ATM environment.
The activities performed in these sub-WPs are:

WP1.1 A^3 High-level ConOps

This sub-WP has outlined the vision in terms of potential solutions towards a shift to autonomous aircraft operations en-route which might or might not lead to the required capacity breakthrough.
The activities that have been outlined in the High-level ConOps are:

- Assessment and definition of a common basis, e.g.: terminology and functionality.
- Identification of candidate concepts or concept elements from previous state-of-the-art aeronautics Research and Technology projects.
- Operational environment description of autonomous aircraft operations en-route.

WP1.2 A^3 Airline Strategy Concept

This sub-wP has addressed the following problem. Air traffic demand is highly dependent on customer demand. Customers want to fly directly to their destination within their preferred time constraints. Airlines try to accommodate these preferences mainly within hub-and-spoke strategies resulting in periodic peak demand levels. This kind of behaviour has been accommodated within the autonomous aircraft environment. It is taken into account that any limitations of the autonomous aircraft operations can induce delays and reductions in connection probabilities. On the other hand, autonomous aircraft operations offer also new opportunities to improve on the effectiveness of hub-and-spoke strategies, for instance through improved arrival timing. So it has also been identified how airlines will react with their movement strategies.

This sub-WP has identified

- Novel ways for airlines to make effective use of autonomous aircraft operations.
- Airline operational environment description for autonomous aircraft operations.
- Identifying a strategy concept for airline operations in an autonomous aircraft environment.
- Identifying the expected benefits and limitations for the proposed strategy concept.

WP1.3 A^3 ConOps

This sub-WP has produced the A^3 ConOps by integrating candidate concepts or concept elements into an overall concept of operations, with the target to accommodate 3 to 6 times busy European en-route traffic demand in 2005. This development has benefitted significantly from an advanced ATM concept development by NASA.

Deliverables

D1.1 Autonomous Aircraft Advanced (A^3) High Level ConOps by Isdefe, Honeywell, NLR, UTartu, EEC, Dedale, ENAC

D1.3 Autonomous Aircraft Advanced (A^3) ConOps by G. Cuevas, I. Echegoyen, J.G. García, P. Cásek, C. Keinrath, R. Weber, P. Gotthard, F. Bussink, A. Luuk

2.4 How the MTR review has influenced the work

Following requests by the Mid Term Review (MTR) in D1.3 it has been made explicit that the baseline is formed by the traffic demand in 2005 (the year of iFly proposal submission). This corresponds well to the 2005 baseline of SESAR. The iFly aim to accommodate a factor 3 through 6 over this baseline traffic demand clearly goes beyond the SESAR factor of accommodating the expected factor 2 traffic increase for 2020. Also upon request by the MTR, the outcome of the WP7 hazard brainstorming session has been used to further improve the A^3 ConOps in the D1.3 report.

2.5 End results, elaborating on the degree to which the objectives were reached

Deliverable D1.3 has fully realized the WP1 objective to develop an A^3 en-route operational concept which is initially based on the current "state-of-the-art" in aeronautics research, with the focus on the en-route phase of flight, for a potential shift into autonomous en-route operations in airspace that is busy according current standards.

Deliverable D1.2 has fully realized the WP1 complementary objective to develop an airline strategy concept which offers opportunities for airlines to harness the greater autonomy to improve on customer service.

3 Project execution for WP2: Human responsibilities in autonomous aircraft operations

3.1 Objectives

The objective of WP2 is to develop the anchor points for the A^3 ConOps development that can be defined from the human responsibility and goal setting, and later to verify how well these anchor points are used in the A^3 ConOps, and where needed to provide potential solutions.

Work package 2 is divided into two parts: "Part A: airborne responsibilities" and "Part B: bottlenecks and potential solutions".

Part A: Airborne responsibilities

1. To identify current and new responsibilities of cockpit crew during en-route phase of flight
2. To analyse Situation Awareness, Information, Communication and cockpit crew tasks.

Part B: Bottlenecks and potential solutions

3. To identify bottlenecks in responsibility issues.
4. To develop potential directions for improvement.

3.2 iFly Partners involved

WP2 has been conducted under the leadership of UTartu. Within WP2, the main research has been performed by UTartu, HNWL, Dedale and NLR. Critical reviews of research reports have been provided by NLR, Isdefe, AQUI, NATS, EEC and DSNA.

3.3 Work performed and approaches employed

Changes in the air traffic management system irrevocably cause changes in the role of the human involved in that system as a result of technological changes. When the system becomes more and more automated, a shift in tasks and responsibilities of the human controlling the system occurs. The human operator – in case of an aircraft, the cockpit crew – is responsible for the actions and tasks he/she performs. This responsibility is a core issue in (aerospace) operations, because it determines who makes what decision and can take action if required without being required to request permission from another actor.

Important in this, is that many functions in autonomous aircraft operations will be supported by automation on the flight deck and there should be a balance between automation and responsibility. As long as the human remains responsible for the resulting actions of the human-machine system, he/she also needs to be able to control the system. When the system is fully automated and the human is out of control, it is not possible to hold him/her responsible for the resulting outcomes. On the other hand, automating (parts of) a system can also support the human to maintain control over the situation, especially in complex systems like an aircraft.

Therefore, in conducting this sub-WP, human responsibility was a key factor in determining to what extent a system can be automated. In an air traffic management environment this responsibility could be spread among the airborne and ground side of the system. Current developments in ATM showed a shift towards a more decentralised system, with increasing tasks and likely more responsibilities for the airborne side, i.e. the cockpit crew. Because this side formed the starting point for the iFly project, the question that has been addressed is: "What responsibilities can be assigned to the airborne side of the system assuming a new task distribution implied by autonomous ATM?" WP Parts A and B have considered these issues in more detail.

Part A: Airborne responsibilities

WP2.1 To identify current and new responsibilities of the cockpit crew during the en-route phase of the flight

An analysis has been carried out to identify the responsibilities of the cockpit crew during the en-route phase of the flight. In support of defining a new air traffic management concept, first of all, current responsibilities of the cockpit crew have been identified.

Subsequently it has been identified what tasks the crew currently has to perform. A task analysis conducted for the en-route flight phase has provided the information to map out the tasks of the cockpit crew during this phase of flight.

In addition to the description of tasks, also a description of the goals of the crew has been developed as valuable input to the identification of responsibilities. These goals provided the framework within which the crew performs their actions. One of the most important goals has been to ensure a safe and efficient flight.

This provided a basic overview of the current situation. The already existing responsibilities have been adopted into the new concept. To achieve a highly automated air traffic management system, the possibility for assigning more responsibilities to the airborne crew than in the current situation, has been investigated. This was a necessity for a more autonomous operation of the aircraft. The proposed concept has adopted the view that as much as possible, responsibilities should be assigned to the airborne side, not to the ground side. Eventually, all issues that are in current operations accounted for by the ground, have been assigned to the airborne crew and became their responsibilities.

Responsibilities of a cockpit crew go beyond issues related to air traffic management only. For example, the cockpit crew is responsible for monitoring the functioning of the system (i.e. the aircraft). A shift in responsibility with respect to ATM issues should never result in conflicts with other responsibilities. Therefore, consequences of this responsibility shift have been reviewed and resulting bottlenecks – when consequences appeared to be outside acceptable limits – have been identified.

WP2.2 Situation Awareness (SA), Information, Communication and Pilot Tasks

This sub-WP has identified the SA to be maintained by the crew, the information and communication needs and the tasks of the controller. This involved taking into account several questions.

While a total situation awareness would be prohibitively costly in terms of both financial and human workload costs, it was recognized that for the A3 operations there will be some minimum prerequisites for satisfactory situation awareness of the flight crews. In order to resolve this, various questions have been addressed, such as:

How does one create active and engaged pilots? How to get pilots sensitive not only to their own aircraft but also those around? How does the system support pilots so that they can make the appropriate delegation of tasks with the A3 ConOps automation, particularly when the pilots are not exactly sure what their neighbours will be doing? How will a crew station effective support recognition and projection of future automation actions? How will they be able to intuitively predict how neighbouring A3 equipped aircraft will perform?

How will an A3 crewstation support information abstraction and distillation to the appropriate level for effective A3 operation. How will A3 support salient mode transitions so the pilots will know how their own aircraft and those around them will be behaving so they know what to expect next? What type of human cognitive support will be necessary for the flight crew to be an effective A3 participant? What will be the best way of presenting system uncertainty "information" to the flight crew? Considering the potential state-of-the-art of avionic technology and the supportable human-system interface 1) what will the flight crew information needs be and to what extent will it be possible to meet or support those needs? How does one make clear the level of responsibility and related roles as a function of time and place in the system? How does one assure that the information available matches with the responsibility at the moment? What does the crew station need from system wide information management and what will crew contribute? What new roles will the flight crew take on and how will the needs of those tasks to be supported?

The answers obtained by addressing these questions have been documented and provided as guideline input to WP1.3. Subsequently, WP1.3 has used this to develop the A^3 ConOps.

Part B: Issues and potential solutions

WP2 part B has assessed the A^3 ConOps developed by WP1.3 against the human responsibilities that had been identified in WP2 part A. Thanks to this analysis, WP2 part B has identified those elements of the A^3 ConOps where issues with respect to human responsibility issues could arise. Finally, potential directions for mitigating these issues have been developed.

WP2.3 To identify bottlenecks in responsibility issues

By using the identified responsibility issues arising in a highly automated ATM environment, bottlenecks have been identified for which mitigating measures should be developed. Issues like safety and capacity have been investigated, which has resulted in identifying the conditions under which these bottlenecks arise. Since these should remain within acceptable limits, changes in task allocation have been proposed. In doing so, task analysis served as input. Within the task allocation, tasks have been allocated to the airborne crew and to the supporting airborne or non-airborne systems.
As the initial options for allocating responsibility to the cockpit crew have been identified in WP1.3, WP2.3 has been searched for inconsistencies in these options and has questioned them, to prepare the second design cycle for improvement of the A^3 concept. This approach was in contrast with the common way, in which first a concept is fully developed regarding the technical systems, and after this, responsibilities are assigned to the applicable actors.

WP2.4 To develop potential human factors improvements for A^3 ConOps

After WP2.3 has identified human factors responsibility bottlenecks where additional ground support is required (in the tasks and functions, where it is impossible to allocate all responsibility to the airborne side of the system), WP2.4 has developed potential mitigating human factors related measures of these bottlenecks for the A^3 ConOps. These potential mitigating human factors measures have been documented in D2.4 report.

Deliverables

D2.1 Description of airborne human responsibilities in autonomous aircraft operations by A. Luuk, J.A. Wise, F. Pouw and V.Gauthereau

D2.2 Situation Awareness, Information, Communication and Pilot Tasks of under autonomous aircraft operations by J. Wise, C. Keinrath, F. Pouw, A. Sedaoui, V. Gauthereau and A. Luuk

D2.3 Identification of human factors for improvement of the A^3 ConOps by C. Keinrath, J. Wise, A. Sédaoui, A. Luuk

D2.4 Potential human factors improvements for A^3 ConOps by A. Luuk and C. Keinrath

3.4 How the MTR review has influenced the work

MTR review took place when WP2 had prepared first three deliverables and was at the stage of finishing the fourth deliverable. MTR review gave some useful suggestions for improvement of D2.3 and D2.4, which were taken into account and resulted in improved versions of the last two deliverables of WP2.

3.5 End results, elaborating on the degree to which the objectives were reached

In order to realize the WP2 Part A objectives, a proper understanding has been developed regarding changing pilot responsibilities and tasks due to introducing pure airborne self separation. These changes were analyzed in D2.1 by using theoretical approach together with elements of pilot task description and analysis. Subsequently, the central role of situation awareness in carrying out pilot tasks together with the information and communication contributors to situation awareness in flying A^3 self separation airspace was analyzed theoretically in D2.2.

In order to realize the WP2 Part B objectives, the possible impact of applying the approach of autonomous flying to pilot situation awareness and performance was analyzed in D2.3. Subsequently a lot of issues to be addressed in the further refinement of the A^3 ConOps were identified together with some potential solutions suggested. On this basis, suggestions for potential human factors improvements of A^3 ConOps development were identified in D2.4, at a high level.

4 Project execution for WP3: Prediction of complex traffic conditions

4.1 Objectives

The objective of WP3 is to study and develop methods for predicting air traffic conditions that may be over-demanding to the airborne self separation design. This is a crucial task for avoiding encounters that appear safe from the individual aircraft perspective, but are actually safety-critical from a global perspective.

The characterization of globally safety-critical encounters can provide useful information for trajectory management and conflict resolution operations, and can also help in identifying the potential ground support needs within the Autonomous Aircraft Advanced Concept of Operations (A3 ConOps) developed in WP1. Within WP3, no specific choice is made regarding where to use the novel air traffic complexity methods, airborne and/or on the ground.

4.2 iFly Partners involved

WP3 has been conducted under the leadership of PoliMi. Within WP3, the main research has been performed by PoliMi, ENAC and HNWL. Critical reviews of research reports have been provided by NLR, Isdefe, UCAM and EEC.

4.3 Work performed and approaches employed

The work under WP3 was structured into two sub-work packages corresponding to the two phases of 1) critical study of existing methods to air traffic complexity prediction (WP3.1) and 2) development of methods that are suitable for airborne self separation ATM systems (WP3.2).

WP3.1: Comparative study of complexity metrics

The goal of WP3.1 is to carry out a critical survey of different metrics proposed in the literature for complexity modelling and prediction in Air Traffic Management (ATM). Most of the current complexity metrics address ground-based ATM and are conceived so as to assess the impact of a given air traffic configuration on the workload of the air traffic controllers in charge of safely handling it. Though this is reasonable within the current centralized ATM system, it becomes restrictive within airborne self separation ATM systems, where part of the responsibility in maintaining the appropriate separation between aircraft is delegated to the pilots.

Work under WP3.1 is documented in the public Deliverable D3.1.

WP3.2: Timely predicting complex conditions

The goal of WP3.2 is to study the problem of predicting complex conditions in airborne self separation and developing appropriate complexity metrics.

The work under WP3.2 was based on a preliminary analysis of possible applications of complexity evaluation in the A3 ConOps, and on the survey work in WP3.1 on the approaches to complexity evaluation that have been proposed within the current human-based centralized ATM system and may be appropriate also for the foreseen automated airborne self separation.

Work was structured into two parallel streams of activities, that is

i) the further development of a method for intrinsic air traffic complexity characterization that was pointed out as promising in Deliverable D3.1; and
ii) the introduction of innovative approaches to complexity evaluation, better tailored to the intended A3 ConOps applications.

The identified method for intrinsic complexity characterization rests on the interpretation of the aircraft trajectories as executions of a dynamical system starting from different initial conditions. The maximum Lyapunov exponent of this dynamical system at a position x is taken as a local measure of complexity. Complexity maps can then be built and used to determine hot spots in the airspace (see Figure 3).

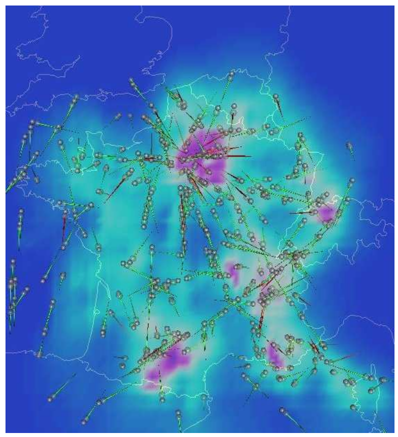

Figure 3: Complexity map over France: hot spots are identified

Two novel measures of complexity were introduced based on a probabilistic approach and a geometric approach. The distinguishing feature of the probabilistic approach is that uncertainty in trajectory prediction is accounted for when evaluating complexity, whereas the geometric approach relies on the reference business trajectory for complexity evaluation.

According to the probabilistic approach, complexity is evaluated in terms of proximity in time and space of the aircraft as determined by their intent and current state, while taking into account the uncertainty in the aircraft future position due to possible deviations from the intended trajectory
Regions with limited manoeuvrability space can be identified and this information can be used for providing guidance for trajectory design and detecting critical encounter situations that would be difficult for the aircraft to solve autonomously.
In Figure 4, an example of evaluation of the manoeuvrability space of an aircraft entering an airspace region with other 6 aircraft is reported. Complexity experienced by that aircraft as a function of its heading at a point along its straight line trajectory is plotted.

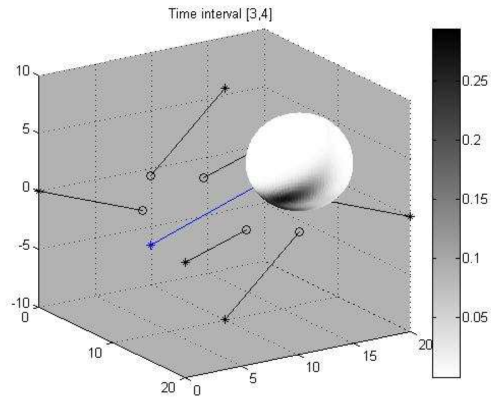

Figure 4: Evaluation of the manoeuvrability space in terms of possible heading changes

According to the geometric approach, complexity at position x and time t is evaluated as the weighted sum of the contributions of those aircraft that will be within some ellipsoid centred at x at time t, with weights depending on the distance from x and direction of flight. Spatial complexity maps can be obtained at different time instances, and areas with high complexity can then be extracted using segmentation techniques with predefined thresholds (see Figure 5).

The goal is to support the strategic trajectory management operations by detecting critical areas that should better avoided in order to reduce the need for excessive tactical maneuvering. Work under WP3.2 is documented in report deliverable D3.2.

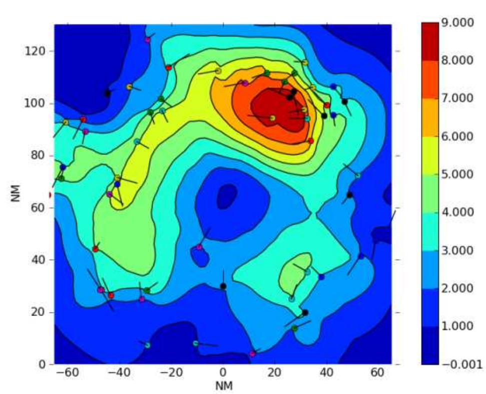

Figure 5: Complexity map of an air traffic scenario with about 50 aircraft

Deliverables:

D3.1 Complexity metrics applicable to autonomous aircraft by M. Prandini, L. Piroddi, S. Puechmorel, S.L. Brázdilová

D3.2 Final report on timely prediction of complex conditions for en-route aircraft

4.4 How the MTR review has influenced the work

No comments on the work under WP3 were provided in the MTR review. Hence, MTR did not influence WP3 work.

4.5 End results, elaborating on the degree to which the objectives were reached

Table 2 provides a schematic classification of the main approaches to air traffic complexity evaluation presented in the literature according to the characteristics relevant to airborne self separation, that is:

- accounting for traffic dynamics and not only aircraft density,
- being independent of the airspace structure,
- not being directly dependent on the controller in place (air traffic controller in the current ground-based ATM systems; conflict solver in self separation ATM systems),
- having a goal-oriented output form (spatial complexity maps for trajectory management applications; scalar-valued measures of the complexity encountered along each aircraft trajectory for supporting distributed CD&R operations)
- being tailored to the look-ahead time horizon (long term complexity measures for strategic trajectory management; mid term complexity measures for supporting distributed CD&R operations)

Besides all those characteristics, appropriate trajectory prediction models should be adopted, possibly accounting for uncertainty in trajectory prediction.

The outcome of this analysis is that most of the complexity measures that have been, to some extent, successful within the current human-based centralized ATM system are inappropriate within an airborne self separation context and novel metrics must be defined to meet the new challenges posed by new ATM systems.

In order to comply with the novel challenges, within WP3, three novel complexity metrics have been developed:

- Lyapunov based complexity
- Probabilistic conflict based complexity
- Geometric conflict based complexity

Lyapunov based complexity interpretes air traffic as a dynamical system for which a Lypaunov exponents computation is identified which takes the control provided by ATM into account. The WP3 investigations showed that a main drawback of this method is that it is computationally intensive, which hampers its application to a distributed ATM framework. The bottleneck is represented by the computation of a smooth vector field that matches the (observed or predicted) values of the aircraft velocities at the sample points. Computational aspects were improved within iFly, but still remain critical for application to high density airspace. Furthermore, an extension to a time-varying dynamical system interpretation is needed to avoid that situations where two aircraft get close to the other rather than occupy positions that are close but in different time slots appear undistinguishable.

Table 2. Main complexity metrics in literature

metric	input data	method	accounting for traffic dynamics	sector-independent	look-ahead time horizon	control-independent	output form
Aircraft density	number of aircraft in the sector	comparison with a workload-based threshold	no	no (evaluated per sector)	instantaneous measure, extendable with trajectory prediction	no (threshold tuned on workload)	scalar value
Dynamic density	number of aircraft and other indicators of traffic characteristics in the sector	linear and nonlinear regression tuned on workload data	yes (through synthetic indices)	no (tuned to the specific sector)	instantaneous measure, extendable with trajectory prediction	no (regression weights tuned on workload)	scalar value
Interval complexity	number of aircraft and other indicators of traffic characteristics in the sector over a 5 to 10 minutes horizon	linear and nonlinear regression tuned on workload data, plus averaging	yes (through synthetic indices)	no (tuned to the specific sector)	short/mid term	no (regression weights tuned on workload)	scalar value
Fractal dimension	aircraft trajectories	covering measure	yes	yes	long term	yes	scalar value
Input/output approach	aircraft timed trajectories	optimization of conflict resolution maneuvers for all possible initial conditions of an additional aircraft	yes (indirectly through trajectory changes to accommodate a new aircraft)	yes	short/mid term	no (based on control effort evaluation)	map (control effort to accommodate an additional aircraft as a function of its initial conditions)
Lyapunov exponents	aircraft timed trajectories	dynamical systems modelling of trajectories and calculation of Lyapunov exponents	yes	yes	short/mid/long term	yes	map (largest Lyapunov exponent as a function of airspace position)

The probabilistic and a geometric approach satisfy the feature relevant to airborne self separation. They both provide local measures of complexity that depend on the aircraft density and the traffic evolution, and not on the way the traffic is controlled. A key difference is that, whereas in the probabilistic approach the uncertainty affecting the aircraft predicted position is accounted for, in the geometric approach complexity is determined based on the nominal aircraft trajectories and neglecting uncertainty.

Since the goal of the geometric approach to complexity is to assess whether or not it would be convenient (from a tactical manoeuvring perspective) for an aircraft to be at a specific position in a specific time, the corresponding metric appears suitable for trajectory management and, more specifically, for the identification of those complex areas that should better avoided in order to reduce the need for excessive tactical manoeuvring.

Through a correlation analysis with collision risk, the probabilistic method was found to be better suited for supporting the ASAS mid term CD&R resolution operations by predicting those air traffic configurations that are difficult to control and may overload the ASAS CR module. Experiments were performed on an hypothetical Autonomous Mediterranean Free Flight (AMFF) air traffic scenario.

For none of the three novel complexity metrics experiments have been run yet on an A3 ConOps scenario. Hence, the specific applicability of any of them for the advanced airborne self separation concept developed within the iFly project remains unclear.

5 Project execution for WP4: Multi-agent Situation Awareness consistency analysis

5.1 Objectives

The main goal of WP4 is to model and evaluate the problem of maintaining multi-agent situation awareness and avoiding cognitive dissonance within en-route A^3 operations. The main challenge is to systematically analyse the A^3 ConOps operation developed within WP1 and WP2 according to a novel safety critical observability method for hybrid systems, which extends the results developed within the HYBRIDGE project. The specific objectives of WP4 are summarized as follows:

1. To provide a formal mathematical framework to model:
    a. agents, including both human operators and technical devices, in ATM systems and in particular in A^3 ConOps scenarios in nominal operating modes.
    b. agents in non-nominal operating modes.
    c. interaction among agents in complex multi-agent ATM systems.
    d. situation awareness of each agent in ATM systems.
2. To provide formal mathematical methods to:
    a. analyse situation awareness inconsistencies in the agents involved in the ATM systems.
    b. analyse the impact of such situation awareness inconsistencies on the safety of the scenario.
    c. isolate the weak points of the procedures, which may lead to unsafe or catastrophic events, and propose alternative solutions to cope with the weaknesses of the procedure.
3. To provide efficient algorithms for the analysis of ATM procedures with a realistic number of agents.
4. To test the proposed methodology on concrete ATM procedures and in particular on A^3 ConOps scenarios.

5.2 iFly Partners involved

WP4 has been conducted under the leadership of AQUI. Within WP4, the main research has also been performed by AQUI. Important inputs have been provided by DSNA and HNWL. Critical reviews of research reports have been provided by NLR, HNWL, Isdefe, PoliMi, DSNA and EEC.

5.3 Work performed and approaches employed

WP4 approached the problem of multi-agent situation awareness consistency management by using a number of relevant hybrid system techniques including hybrid modelling and hybrid observer synthesis. While aircraft dynamics are generally described by differential equations, pilots' and air traffic controllers' behaviours are well modeled by finite state machines, whose states and transitions mimic the procedure the agents are requested to follow. It is evident then that a unique mathematical model for describing ATM systems needs to deal with both continuous and discrete dynamics. Hybrid systems' formalism, featuring both discrete and continuous dynamics, is characterized by an expressive power that in WP4 was proven to be general enough to adequately describe ATM systems. Hybrid systems formalism was used to model agents acting in a number of ATM procedures both in nominal and non-nominal conditions. While nominal modes of operation of the agents are dictated by the procedure they are supposed to follow, non-nominal modes may stem from several causes, including malfunction or disruption of technical devices or unpredictable behaviour of human operators in-the-loop. Identification of non-nominal conditions of operation is a not easy task in general. They are generally identified through historical data available at ATM research centers, which include interviews to the pilots and air traffic controllers and a posteriori analysis of ATM scenarios that lead to accidents. The collaboration with DSNA-DTI-SDER (France), partner of the iFly Consortium, has led to an appropriate hybrid systems' modelling of agents acting in the Airborne Traffic Situational Awareness In-Trail Procedure (ATSA-ITP) and the Airborne Separation-In Trail Procedure (ASEP-ITP). The proposed hybrid systems correctly model both nominal and non-nominal modes of operation of the agents involved. The collaboration with the National Aerospace Laboratory NLR (The Netherlands), partner and leader of the iFly Consortium, and with Honeywell (Czech Republic), partner of the iFly Consortium, has led to an appropriate hybrid systems' modelling of agents acting in the A^3 ConOps Scenario 1 studied in Deliverable D9.1. The proposed hybrid systems correctly model both nominal and non-nominal modes of operation identified in iFly report D7.1b.

The obtained mathematical models can be employed to simulate the ATM procedures through the use of software tools for hybrid systems, as for example UPPAAL, CHARON, HYSDEL, CheckMate among many others. In WP4 the toolbox UPPAAL was successfully employed to simulate the ASEP In-Trail-Procedure in both nominal and non-nominal conditions of operation. The use of simulation tools is important in predicting the behaviour of complex ATM systems. On the other hand, their use exhibits the following drawbacks:

- Using simulation tools may be expensive in terms of computational complexity.
- Even when an extensive number of simulations would suggest the correct working of an ATM procedure, there is no guarantee that there does not exist any other simulation that contradicts the conclusions obtained.

These drawbacks ask for alternative methods for the analysis of complex ATM systems. In this regard, WP4 leveraged a number of results concerning the analysis and control of hybrid systems to prove or disprove formal correctness of the ATM scenarios under study. The approach proposed in WP4 provides a systematic method to address a number of crucial issues, as for example:

- Can a configuration of an ATM procedure, leading to unsafe or even catastrophic conditions, occur?
- If so, are the agents involved aware in advance, of the occurrence of the safety-critical situation?

The answer to the above questions can be formally addressed by rephrasing them in terms of structural mathematical properties of the hybrid systems, modelling agents in the ATM procedures:

- Is an unsafe configuration of an ATM system "reachable" from an initial configuration?
- If so, is the safety-critical situation "observable" from the information available at the agents involved in the ATM scenario?

The work of WP4 mainly focussed on providing satisfactory answers to the last question. To this purpose, the notion of "critical observability" was introduced and characterized. Critical observability is a structural property of a hybrid system, which corresponds to the possibility of detecting if the current state is in a set of critical states that represent unsafe, unallowed or non–nominal situations. When a hybrid system enjoys this property, a hybrid observer can be constructed which automatically detects whether the hybrid system is in a critical state or not. This property has been analyzed in detail and also defined efficient algorithms that are able to test this property in polynomial time (other algorithms available in the literature test this property in exponential time). Finding algorithms that are efficient from the computational complexity point of view is particularly relevant in the analysis of ATM systems that are typically characterized by a large number of variables.

Next, the proposed methodology to the analysis of the ATSA and ASEP In-Trail Procedures was applied. The results obtained showed that the two procedures are not critically observable. This means that there are safety-critical configurations of the ATM systems which cannot be detected by the pilots or the air traffic controller. This analysis also pointed out the weaknesses of the procedures and proposed alternative solutions which guarantee a correct situation awareness of the pilots when safety-critical situations occur. These results are reported in iFly report D4.1.

First investigations of critical observability of hybrid systems considered each agent in an ATM system in isolation. This approach is not adequate for multi-agent ATM scenarios, because agents' interaction is responsible of the occurrence of unsafe situations. Here, interaction is to be understood in a broad sense. For example, two agents are considered to interact if:

- there is communication among them (e.g. radio or vocal communication);
- one of the agent can measure some of the variables determining the configuration of the other agent;
- some agents share the same sky area resources.

It is therefore evident that dealing with interaction among agents in ATM scenarios asks for formal mathematical paradigms that appropriately model each agent acting in an ATM scenario as well as their interaction. Interactions in mathematical systems are often modelled in the literature through appropriate notions of composition. While several notions of composition have been exploited for purely continuous systems and for purely discrete systems, the literature concerning composition of hybrid systems is rather scant at present. This is the reason why a novel compositional hybrid systems' framework was proposed, which appropriately captures the interaction among agents in ATM systems. The proposed interaction mechanism has been inspired by classical notions of parallel composition for discrete-event systems and input–output composition for nonlinear control systems. In the compositional setting, a direct link (or a communication flow) is put from an agent A1 to an agent A2 whenever the evolution of agent A1 influences directly the evolution of agent A2. It is easy to see that this definition of composition is general enough to capture the different types of interaction that may occur among agents. The proposed compositional hybrid systems' framework provides a systematic way to study critical observability of multi-agent ATM systems. Indeed given a multi-agent ATM scenario, one first defines a hybrid system modelling each agent, then applies the compositional rules, modelling the interaction among the agents, to finally obtain a unique hybrid system. A critical relation is then defined which captures the occurrence of safety-critical situations in the composed hybrid system. These safety-critical situations arise from the non-nominal behaviour of each agent, and also from the interaction of the agents. Then, studying situation awareness inconsistencies in multi-agent ATM scenarios translates to studying critical observability of the obtained (composed) hybrid system with respect to the critical relation.

Although formally sound, this approach is applicable only with great difficulty to realistic ATM scenarios because the number of variables in the composed hybrid system scales exponentially with the number of agents involved, which is generally large. This implies serious difficulties in the applicability of the proposed methodology to concrete and realistic ATM scenarios. To overcome these problems, formal results were proposed that guarantee in many cases a drastic computational complexity reduction in checking critical observability of multi-agent ATM scenarios. The key idea is to decompose the critical relation into smaller sub-relations. Checking critical observability of the original multi-agent ATM system translates then to checking critical observability of suitable sub-multi-agent ATM systems extracted from the original one, with respect to the critical sub-relations. In some cases this approach provides a method to formally analyze critical observability of multi-agent ATM systems with an arbitrary large number of agents.

This approach was successively applied to the analysis of the ASEP In-Trail-Procedure and the ASAS Lateral Crossing Procedure in a multi-agent setting. In particular, a scenario of ASEP In-Trail-Procedure was analyzed with four aircraft and one air traffic controller. Standard methods to check critical observability of this multi-agent scenario would require the construction of a hybrid observer for the composed hybrid system that consists of about 1.78 million of discrete states. The proposed complexity reduction tools reduce the original problem to the analysis of critical observability of one hybrid system modelling the pilot (consisting of thirteen discrete states) and of one hybrid system modelling the air traffic controller (consisting of five discrete states). Our analysis revealed that the two ATM procedures are not critically observable and proposed alternative solutions which guarantee a correct situation awareness of the pilots when safety-critical situations occur.

The proposed methodology was finally applied to the A^3 ConOps Scenario 1 studied in Deliverable D9.1. WP4 proposed an appropriate mathematical model that takes into account situation awareness inconsistencies identified in iFly report D7.1b. The analysis carried out, showed that this ATM scenario is not critically observable. In collaboration with Honeywell (Czech Republic), partner of the iFly consortium, some mitigation means were proposed that can render the scenario critically observable.

These results together with the theoretical results on critical observability of compositional hybrid systems and the analysis of the ASEP-ITP and the ASAS Lateral Crossing Procedure are reported in iFly report D4.2.

Deliverables

D4.1 Report on hybrid models and critical observer synthesis for multi-agent situation awareness by M. Colageo, M.D. Di Benedetto, A. D'Innocenzo

D4.2 Report on Observability Properties of Hybrid-System Composition by M.D. Di Benedetto, A. Petriccone, G. Pola

5.4 How the MTR review has influenced the work

The MTR review was very fruitful and allowed interesting discussions with the iFly partners and the EU representatives. In particular, feedback from the reviewers about WP4 has been useful for AQUI researchers in better understanding key issues arising in the analysis of multi-agent situation awareness inconsistencies of ATM procedures. The feedback gained from the MTR review translated to a calibration of the research direction of AQUI with the goal of rendering the proposed methodology effective in the analysis of multi-agent ATM systems.

5.5 End results, elaborating on the degree to which the objectives were reached

The final results achieved are summarized as follows:

- D4.1 proposes a compositional hybrid systems' mathematical framework which appropriately describes complex multi-agent ATM procedures in both nominal and non-nominal conditions of operation. In addition, D4.1 exploits formal results in the context of compositional hybrid systems, which allow the analysis of multi-agent situation awareness inconsistencies arising in ATM scenarios with a realistic number of agents.

- D4.2 demonstrates that the proposed mathematical framework can be applied to A^3 ConOps. In this regard WP4 provides formal analysis of: the Airborne Traffic Situational Awareness In-Trail Procedure, the Airborne Separation-In Trail Procedure, the Lateral Crossing Procedure and a specific A^3 ConOps Scenario. This way, some potential weak points of the operation has been identified and, in collaboration with A^3 ConOps experts, mitigations means are proposed.

In conclusion, WP4 has developed innovative architecture free methods towards modelling and evaluating the problem of maintaining multi-agent Situation Awareness and avoiding cognitive dissonance within an advanced operational concept in general, and also specifically for the en-route A^3 ConOps.

6 Project execution for WP5: Pushing the limits of conflict resolution algorithms

6.1 Objectives

The objective of WP5 is to investigate and push the limits of conflict resolution algorithms for the autonomous aircraft operational concept developed in iFly. For this purpose, the most advanced conflict resolution methods that had already been developed within the free flight community, together with methods from other research areas that were identified as potentially applicable to air traffic management have been carefully examined. Based on the findings, several research alternatives were explored and the most promising methods were extended in an effort to make them applicable to the future increased air traffic demand and the iFly concept of operations. The studies evolved around the two basic reference points:

- The requirements stemming from the autonomous aircraft concept developed within WP1, WP2 and WP8
- The enhancement and further development of methods that were identified as relevant in the autonomous aircraft community and other relevant fields. Special emphasis was put on methods that not only address the needs of the autonomous aircraft concept but also hold the promise of establishing theoretical guarantees regarding their performance.

The work is organized in the following steps:

- Identify and compare the state-of-the-art in key methodologies for conflict resolution relevant to air traffic and potentially applicable in an autonomous aircraft environment.
- Identify the conflict resolution needs of the autonomous aircraft concept developed by WP1 and WP2 (and early developments within WP8).
- Compare the advanced conflict resolution methods versus these requirements and identify strengths and weaknesses of each approach.
- Adapt and extend the most promising conflict resolution approaches to accommodate the autonomous aircraft concept, taking advantage of complementary capabilities of the different conflict resolution methods as much as possible.
- Compare the resulting conflict resolution methods against the requirements and against the best currently known methods in the autonomous aircraft research community.

6.2 iFly Partners involved

WP5 has been conducted under the leadership of ETHZ. Within WP5, the main research has been performed by ETHZ, UCAM and NTUA. Important inputs have been provided by ULES. Critical reviews of research reports have been provided by NLR, ULES, HNWL, PoliMi and EEC.

6.3 Work performed and approaches employed

The work was organized in the following four sub-WPs:

WP5.1: Comparative study of conflict resolution methods

A survey of the most important methods proposed for conflict resolution was carried out. The methods were reviewed and analyzed in terms of their capabilities, limitations and complementarities from a general autonomous aircraft conflict resolution perspective. Advantages and disadvantages of various conflict resolution methods were identified, focusing on the applicability with the iFly concept of operations. The results of the study were documented in Deliverable D5.1.

WP5.2: Analysis of conflict resolution needs of A^3 operations

The operational requirements of the conflict resolution algorithms were identified based on the iFly concept developments under WP1 and WP2. The requirements provided the guidelines for selecting different strategies and algorithms to perform conflict resolution under the A^3 concept of operations. The study was divided according to the time horizon of conflict resolution. Emphasis was placed on mid- and short-term conflict resolution methods since these levels were perceived as placing the most demanding requirements in terms of the iFly operational concept developments. The methods available were compared against the requirements of the iFly concept for each time horizon and recommendations on methods to explore further were made. In summary, methods based on optimization (in particular the so-called model predictive control methods) were selected for further investigation at the mid-term level and methods based on robotic path planning (in particular methods based on the so-called navigation functions) were selected for further investigation at the short-term level. The results of the study and recommendations were documented in Deliverable D5.2.

WP5.3: Further development of conflict resolution methods

This task covered the main part of the work undertaken in WP5. The most promising conflict resolution methods identified in WP5.2 were adapted and developed further to match the requirements of the concept of operations and become applicable to dense traffic situations predicted for the future. In total, four different methods were examined and developed: Two methods in the MPC framework proposed in WP5.2 for mid-term conflict resolution, one method in the robotic path-planning framework proposed in WP5.2 for short-term conflict resolution, and one method for coupling short- and mid-term conflict resolution into a unified framework.

For short-term conflict resolution, Navigation Functions were adapted and further developed to accommodate constraints relevant to air traffic management situations (such as the requirement to maintain a certain minimum airspeed), which are not relevant to robotic path planning, the field where Navigation Function methods originated.

In the mid-term, two different alternatives have been introduced, all based on the control theoretic approach of Model Predictive Control (MPC). MPC is an optimization-based methodology, which allows one to handle hard constraints (such as conflicts or limits on the airspeed), while at the same time minimize a desired cost function (for example, travel time or fuel consumption). The first method is based on the so-called multiplexed MPC and generates maneuvers with formal guarantees regarding conflict avoidance and maneuver completion time. The method has the advantage of resting on solid theoretical foundations; however, the conservativeness and safety margins of the resulting maneuvers needed to provide the theoretical guarantees imply that the resulting optimization problem tends to become infeasible in dense traffic, making it difficult to apply the method to future traffic scenarios.

The second method involves an MPC scheme that explicitly incorporates priorities, based on the priority scheme described by the concept of operations. Due to the computational complexity of the resulting optimization problem, steps were taken to simplify the formulation, leading to a mixed integer linear program (MILP). This means that the resulting maneuvers are no longer supported by explicit theoretical guarantees. On the positive side, the method does fulfill the concept requirement for priorities and is applicable to large traffic samples.

Finally, the issue of concurrent operation of conflict resolution methods on different time scales was tackled, in order to produce a mid-term method that takes into account the actions of the lower level short-term conflict resolution algorithms. While no new developments of the short-term methods were necessary to accomplish this, the mid-term, MPC based algorithms had to be adapted to accommodate the complex behavior of the short-term algorithms. Due to the complexity of the resulting optimization problem, randomized optimization algorithms had to be deployed to solve it. While the results on benchmark problems clearly indicate that this is a viable alternative for combining short- and mid-term conflict resolution methods, computational complexity restrictions suggest that deploying such a scheme in practice may be very challenging.

The results of successive development stages were documented in a series of interim reports, leading up to deliverable D5.3, which concluded the study.

WP5.4: Validation of conflict resolution methods against the requirements

The different methods were tested in simulations, both under test-examples, as well as with more realistic traffic samples. For the latter task, the full European traffic sample on a full busy day in 2006 has been used as baseline scenario. All flights in this baseline scenario have been tripled in order to mimic a factor 3x traffic increase relative to the year 2006. Subsequently from this tripled set of flights, subsets (in time and location) have been extracted upon which the developed conflict resolution methods have been applied. The results obtained were documented in Deliverable D5.4.

Deliverables:

D5.1 Comparative Study of Conflict Resolution Methods by G. Chaloulos, J. Lygeros, I. Roussos, K. Kyriakopoulos, E. Siva, A. Lecchini-Visintini and P. Cásek

D5.2 Analysis of conflict resolution needs of the A^3 operational concept by N. Kantas, J. Maciejowski, A. Lecchini-Visintini, G. Chaloulos, J. Lygeros, I. Roussos, K. Kyriakopoulos, P. Cásek

D5.3 Report on advanced conflict resolution mechanisms for A^3 ConOps

D5.4 Final WP5 report including validation

6.4 How the MTR review has influenced the work

The MTR review triggered updating of deliverables D5.1 and D5.2 according to review comments received. Furthermore, motivated by the reviewer comments a closer collaboration with WP8 was established in order to better incorporate the concept requirements into the conflict resolutions algorithms developed under WP5.3 above. The most prominent example of this interaction was the decision to develop a novel MPC based strategy for mid-term conflict resolution to incorporates priorities as envisioned in the iFly concept of operations; until the MTR work had concentrated on “round-robin” type distributed MPC schemes where the interpretation of “priority” is incompatible with that of the concept. This change in direction required a significant development effort, but led to algorithms that better embody the spirit of the iFly concept. Finally, to help put the results of WP5 in the SESAR context as suggested by the reviewers, a decision was made to base the final validation under WP5.4 above on the traffic sample generated by SESAR to capture future traffic patterns.

6.5 End results, elaborating on the degree to which the objectives were reached

After a careful review of the available methods, the most relevant ones, in terms of performance and potential for use in the iFly project, were identified. After carefully comparing the state-of-the-art in conflict resolution with the concept requirements, shortcomings of the existing methods were identified and work towards overcoming those problems was conducted. Thus, the most relevant methods were further developed within WP5 and some novel alternatives were also introduced to deal with the concept requirements.

For the short-term conflict resolution level, Decentralised Navigation Functions have been used to handle conflict resolution in a real-time, distributed feedback manner. To accomplish this task, navigation functions, previously developed for path planning in the field of robotics, were extended to incorporate dynamic constraints of paramount importance to air traffic control scenarios (such as, for example, limits on the aircraft airspeed). Moreover, practical considerations such as the sensing and communication radii envisioned by the concept were also incorporated in the method. While these modifications weakened the strong theoretical guarantees that navigation functions provide in the robotics context (collision avoidance and convergence to the goal) they enabled the method to be applied to realistic air traffic situations. The validation exercise demonstrated that the method is able to deal with encounters involving a large numbers of aircraft (up to 100); due to computational limitations, however, it was not possible to test the method in the highest densities of the SESAR 2035 traffic sample. Still, taking into account the fact that the method is naturally decentralized and the necessary computation will be divided equally among the aircraft involved, the method demonstrated provides good potential for real time application; in the validation the entire computation for all aircraft was executed on a single computer, hence became prohibitively long when the number of aircraft exceeded 100 whereas in reality the same computation would be divided to 100 computers, one on each aircraft. On the theoretical front, follow-on research should be able to recover the theoretical guarantees offered by Navigation functions in robotics despite the presence of the additional constraints introduce to accommodate the iFly concept requirements.

For the mid-term level, two approaches were developed and tested in simulations. Those methods were both based on the control theoretic concept of MPC. MPC has a long history in the wide range of application areas (chemical process control, power electronics, automotive etc.) but its impact on air traffic management has been very limited; the work in WP5 served to introduce this approach to the air traffic management arena and demonstrate its potential.

The first of the two approaches is based on robust multiplexed MPC, a novel algorithm originally proposed in the context of uninhabited aerial vehicles, that can produce conflict resolution manoeuvres with formal guarantees on conflict avoidance and the duration of the manoeuvre. The method was successfully tested on a subset of the SESAR 2013 traffic sample. However, the validation also showed that as traffic densities increase the optimization problems that one needs to solve to compute the resolution manoeuvre tend to become infeasible and the method does not seem to be applicable to the highest densities of the 2035 traffic sample. This is in sense an unavoidable consequence of the strong theoretical guarantees provided by this method, which force one to make worst-case assumptions about the disturbances that enter the system leading to large safety margins. Follow on research could concentrate on establishing a trade-off between the theoretical guarantees and the conservativeness of the method and testing the resulting algorithms in dense traffic samples.

The second alternative explored for mid-term conflict resolution was prioritized MPC, an novel approach specifically designed and developed to match the concept of operations requirement for aircraft priorities. Several design alternatives had to be tested to develop a method that is both intuitive and feasible to implement in high traffic densities. For example, early attempts to formulate conflict resolution as a nonlinear programming problem (the most natural way to proceed) had to be abandoned, since computational complexity limited the resulting algorithms to small numbers of aircraft. Instead, simplified aircraft dynamics were used and constraints such as conflict avoidance, airspeed bounds etc. were approximated, leading to a Mixed Integer Linear Program, which could be solved effectively for large traffic samples. In a similar way, unsolved problems that previously developed methods in literature faced, like identifying the conflicting situations efficiently and dynamically clustering the airspace to reduce computational complexity and handle high traffic densities have been resolved within the work package. Validation was carried out on the SESAR 2035 traffic sample, using a simulator with realistic aircraft, FMS and weather dynamics. The results, documented in D5.4, clearly demonstrate that the prioritized MPC method has the potential for dealing with high aircraft densities, putting traffic projections of SESAR 2035 well within reach.

Finally, another valuable result obtained in the work was the methodology for combining mid-term and short-term conflict resolution in a coherent, hierarchical multi-layer scheme. This methodology makes use of the knowledge that conflict resolution is carried out in several separate layers, allowing the designer to include the actions of the short-term resolution algorithms in the decision making process of the mid-term resolution algorithms. Initial validation results on small traffic samples (documented in Deliverable D5.3) demonstrated that this could reduce conservativeness of two methods, as well as produce coherent resolutions throughout different horizon layers. Due to computational complexity however (by definition testing the method is at least as complex as testing the short term algorithms by themselves) it was not possible to validate this combined approach on a realistic traffic sample.

In summary WP5 was able to demonstrate that:

1. Navigation Functions (NF) recover the strong theoretical guarantees that the method provides in robotics while maintaining the crucial additions (dynamic constraints, sensing and communication ranges, etc.). It has been demonstrated that NF can be made applicable to an autonomous control setting (i.e. when pilot is not in the control loop). Then it is demonstrated that NF has significant potential in resolving large encounters. However, further research is necessary to find a way for integrating NF approach with pilots in the loop concepts such as A3 ConOps is.
2. Prioritized MPC provides a viable alternative for mid-term conflict resolution in an autonomous aircraft environment. The method relies on optimization and introduces simplifying assumptions to formulate the conflict resolution problem as a Mixed Integer Linear Program that can be solved efficiently on-line. Due to the simplifying assumptions the theoretical guarantees that the method can offer are fairly limited. Still extensive validation by simulation with realistic aircraft, FMS and weather models indicates that the manoeuvres produced by the method tend to be safe and efficient.

Moreover, the computational complexity of the approach is manageable, bringing even the highest densities envisioned in the SESAR 2035 sample well within reach.

3. Multiplexed MPC provides very strong theoretical guarantees for the quality of conflict resolution manoeuvres at the mid-term level (the strongest among all the methods considered). This however makes the method conservative and applicable only to relatively small encounters. Further research will be necessary to remove this obstacle and deploy the method to dense traffic.
4. It is possible to develop methods that seamlessly combine the actions of short- and mid-term conflict resolution algorithms; an example of such a combination using Navigation Functions at the short-term level and MPC at the mid-term level was developed in the project. However, the computational complexity of the resulting algorithm is by necessity higher than that of the individual short- and mid-term algorithms. Additional testing and development is necessary to established whether such a combined approach is viable in dense traffic scenarios.

In conclusion, WP5 has developed innovative conflict resolution algorithms for which it is formally possible to guarantee their performance for an advanced airborne self separation ConOps in which the flight crew is not in the loop. These algorithms form a significant extension over the state-of-the-art in conflict resolution algorithms in aeronautics literature. An explicit design feature of the A3 ConOps is that flight crew has to be in the control loop. Hence it remains to be investigated which of the developed innovative conflict resolution methods can be made of use to the A3 ConOps. The expectation is that this might be quite easy for the prioritized MPC approach, though this remains a challenge for the NF and the Multiplexed MPC approaches.

7 Project execution for WP6: Cost-Benefit analysis

7.1 Objectives

The objective of this work package is to assess the cost-benefit of en-route A^3 operations. The operational benefits and costs associated with the introduction of A^3 the concept will be identified and the conditions under which the proposed concept is viable will be determined. The WP will assess the cost related to the avionics baseline used by early ADS-B implementations in Europe and USA, (regulated respectively by EC surveillance implementing rule and FAA ADS-B mandate)

7.2 iFly Partners involved

WP6 has been conducted under the leadership of AUEB. Within WP6, the main research has been performed by AUEB. Important inputs have been provided by HNWL, Isdefe and EEC. Critical reviews of research reports have been provided by NLR, HNWL, UCAM, ETHZ, Isdefe and EEC.

7.3 Work performed and approaches employed

The ATM system involves a set of operations that aim at the safe and efficient planning and management of the air traffic. The ATM stakeholders, the relevant institutional and organizational framework and the operational and technological issues constitute the critical factors that affect the performance of the ATM system. The transition from the managed airspace to the self-separation airspace as described in the Autonomous Aircraft Advanced Concept of Operations (A^3 ConOps) signifies major changes in the role and responsibilities of the ATM stakeholders, the ATM technologies and systems used, and the operations performed during the en-route phase of a flight. Thus an essential prerequisite before the full scale development and implementation of the proposed ATM ConOps is to assess the institutional implications and economic viability of the proposed ConOps. Based on the Description of Work, the objectives of WP6 were: i) to identify institutional and organizational barriers and enablers and the associated changes needed for the implementation of the A^3 ConOps, and ii) to assess the economic viability of the proposed concept on the basis of analyzed scenarios. The determination of the institutional and organizational issues relevant to the A^3 ConOps was achieved through the assessment of the compatibility of the A^3 ConOps operational changes with the existing institutional framework. Moreover, the assessment of the economic viability of A^3 ConOps was facilitated by performing a scenario-based cost-benefit analysis. The work required for achieving the WP6 objectives was organized into the following sub-WPs: i) WP6.1 Development of a methodological framework for cost-Benefit analysis, ii) WP6.2 Institutional and Organizational analysis for the implementation of the autonomous aircraft operations, iii) WP6.3 Data collection for cost-Benefit analysis, iv) WP6.4 Cost Benefit analysis and results assessment.

The assessment of the potential economic, institutional, and organizational impacts emerging from the introduction of the A^3 ConOps to the ATM were achieved through two major streams of work:

- Identification of the Institutional and Organizational barriers and enablers for the effective implementation of the A^3 Concept and determination of recommendations for potential institutional/organizational changes in the existing ATM framework in order to facilitate the implementation of the A^3 ConOps in WP6.2.

- Estimation of the potential positive (benefits) and negative (costs) impacts of the A^3 Operational Concept and assessment of the performance of the A^3 Operational Concept in terms of cost-benefit analysis in WP6.1, WP6.3 and WP6.4.

Figure 6 presents the methodology for the A3 ConOps assessment performed in WP6.

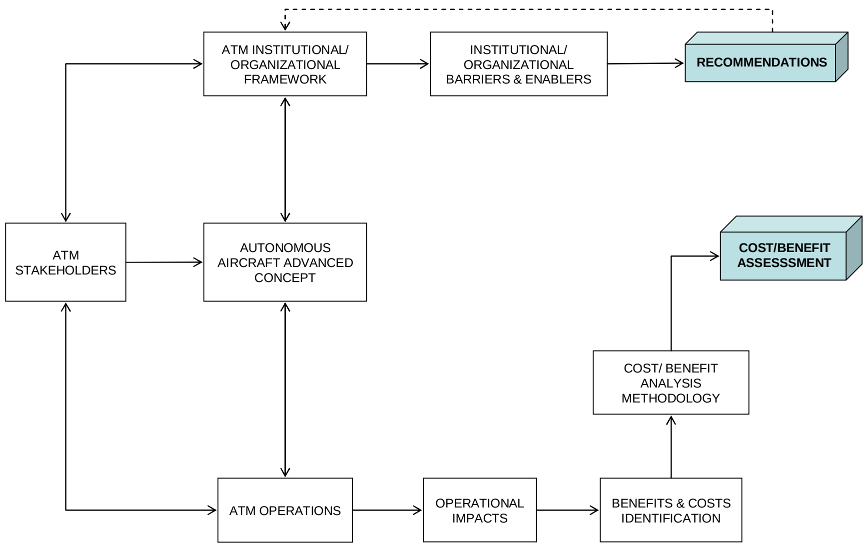

Figure 6. Overall Methodological Approach of WP6.

The remainder of this section outlines the major activities performed in each of the two streams of work presented above.

Institutional and Organizational Issues and Recommendations

The analysis of the enablers and barriers encountered for the implementation of the A^3 ConOps was achieved through the assessment of the compatibility of the proposed ConOps with the existing regulations and stakeholders' responsibilities. The determination of the existing institutional framework of the ATM operations affected by the A^3 ConOps involved the following tasks: i) specification of the bundles of regulations that dominate the existing ATM system, and ii) assessment of the identified regulations in terms of affecting any of the A^3 ConOps elements. This step involved the identification of the international and European regulations which rule the ATM operations, including the Single European Sky framework, the ICAO annexes, and the European ATM Master Plan. A long list of regulations emerged by considering the above bundles of regulations. Thus, a screening process was implemented to identify those regulations that are relevant to the ATM operations potentially affected by the Self Separation ConOps. The screening process was facilitated by identifying the changes of the induced by the proposed ConOps. The outcome of this process was the identification of the regulations relevant to each ATM component potentially affected by the A^3 ConOps. The core part of the proposed analysis involved the assessment of the proposed changes in ATM operations and stakeholders' role in terms of complying with the associated prevailing bundles of regulations. This analysis led to the identification of the following issues: i) the changes in the ATM system that are inconsistent or that contravene with any of existing regulations (barriers), ii) the elements (regulations or bundles of regulations) of the institutional framework that could potentially expedite and facilitate the implementation of the proposed changes (enablers), and iii) the elements of the concept not covered by the existing institutional framework (gaps). The results of this analysis led to conclusions and recommendations about the bundles of regulations that should be updated or revised and the issues that they should cover in order to accommodate the implementation of the Self Separation ConOps. The relevant analysis concluded that the implementation of the A^3 ConOps in Europe requires institutional changes, involving the adaptation of the ATM legislation (Single European Sky framework), regulative updates (ICAO Annexes relevant to the rules of the air, the navigation systems, and the role of the ANSPs), and reform of the existing conventional role of the ATM stakeholders. The results of this work are provided in Deliverable D6.2 "Institutional and Organizational analysis for the implementation of the autonomous aircraft concepts".

A^3 ConOps Cost-Benefit Analysis

The validation of the economic viability of the A^3 ConOps involves the assessment of the performance of the new ATM system in terms of costs and benefits. The objective of the proposed cost-benefit analysis was to explore if the benefits emerging from the improvement of the ATM performance due to the introduction of the A^3 concept, exceed the associated costs of implementing, operating and maintaining the system resulting from the implementation of the A^3 ConOps.

A methodological framework was developed aiming to identify the major cost and benefits indicators and metrics for each category of stakeholders (utilising standard ATM operational concept validation methodologies like the E-OCVM and the EMOSIA) and the identification of the input variables and the associated data requirements for each category of stakeholders (ANSPs and Airlines). The costs and benefits in the proposed analysis refer to the additional expenses and the cost savings/avoidance resulting from the potential implementation of the A^3 ConOps ATM system considering the SESAR enhanced ATM system as the baseline system. The data collection process for assessing the costs and benefits induced by A^3 ConOps to Airlines and ANSPs involved the identification of input values for the following categories of variables: i) Global variables used as input metrics in calculating various cost and benefit variables, (e.g. air traffic growth, discount rate), ii) Time variables (e.g., Start year of the analysis, Pre-implementation period of A^3, Implementation period of A^3), iii) Baseline variables which refer to performance measures of ATM under the baseline scenario (e.g., annual baseline en-route ATFM delay, annual baseline Flight Inefficiency), iv) Cost and Benefit variables, which refer to various cost elements (e.g., forward-fit cost per aircraft) and cost savings (e.g., Reduction of ANSPs charges) respectively. Various information sources were investigated in obtaining data for estimating the variables involved in the CBA for the Airlines and ANSPs. However, limited data availability was encountered for estimating various benefits and costs for both ANSPs (e.g. % reduction of the en-route ANSPs staff and operating (non-staff) cost, ANSPs one-off implementation cost) and Airlines (e.g., :% Reduction of the en-route ATFM delay,% reduction of the Horizontal and Vertical Flight Inefficiency,% Reduction of the Vertical Flight Inefficiency % Reduction of the en-route ANSPs charges, retro-fit and forward-fit costs for the Airlines). Given that no measured data were available for the above stated variables, experts were asked to provide judgments. A template was developed to collect experts judgments required for estimating the corresponding cost and benefit variables. The task of completing this template was assigned to organizations participating in WP6. Only data regarding the ANSPs one-off implementation cost were obtained through this process. However, the relevant estimates referred only to a single organization (AENA) and not the entire body of ANSPs in Europe. In general, limited description of the specifications regarding the proposed A^3 operations hindered the provision of estimates regarding the potential improvements in ATFM delays and flight inefficiency and the reduction of the operating cost for the ANSPs. Moreover, issues associated with the provision of proprietary industrial data made it difficult for the corresponding partners to provide estimates for the avionics costs (forward-fit and retro-fit costs). Given the above stated limitations, a typical application of the CBA for either the Airlines or the ANSPs would yield results associated with high uncertainty, which would provide no credible findings regarding the cost-effectiveness of the A^3 ConOps for either category of organizations. Thus the focus of the analysis was placed on the application of a scenario-based CBA for assessing the A^3 ConOps impacts. The proposed analysis framework involved the application of CBA to a series of analysis scenarios built on the basis of combining various valid alternative values for uncertain variables (i.e., variables for which no data were available) associated with the costs and benefits of A^3 ConOps. Thus, given a specified B/C ratio and a combination of values for the cost (or benefit) uncertain variables, reverse CBA calculations were performed in order to determine the corresponding values of the benefit (or cost) variables for which the targeted B/C ratio was achieved. The expected outcome of this type of analysis was to determine the operational improvements and cost scenarios for which a predetermined economic performance can be achieved.

A large number of Analysis Scenarios were developed. In the airlines case, the application of the proposed approach involved analysis scenarios in which alternative combinations of benefit variables were determined for given forward-fit cost values on the basis of yielding a predetermined B/C. On the other hand, the application of the analysis approach for the ANSPs involved analysis scenarios in which the ANSPs one-off implementation cost was calculated on the basis of yielding a predetermined B/C for a given ANSPs en-route Staff Cost reduction and operating (non-staff) cost reduction. Moreover, Airlines and ANSPs combined scenarios were analysed in order to identify alternative values for the costs and benefits for both stakeholders (simultaneously) for which a predetermined B/C may be achieved. The execution of the above stated analysis scenarios led to the CBA results. The analysis results for the airlines indicate that A^3 ConOps can be economically viable even under the worst case scenario (where the forward-fit cost reaches its highest value while the expected ATFM delay reduction and flight inefficiency reduction take their lowest possible values). Moreover, the CBA for the ANSPs indicated that A^3 ConOps may contribute to the substantial reduction of the en-route service cost. The findings of the CBA seem encouraging for developing A^3 ConOps to its next maturity stage from the perspective of both the Airlines and the ANSPs economic implications.
The work performed for the CBA assessment of the A3 ConOps is provided in the following four deliverables: Deliverable D6.1 “Methodological Framework for Cost-Benefit Analysis”, Deliverable D6.3 “Report on Data Collection”, Deliverable D6.4i “Interim Report on Cost-Benefit Analysis”, and Deliverable D6.4 “Cost-Benefit Analysis Results Presentation”.

Deliverables

D6.1 Methodological Framework for Cost-Benefit Analysis by K. Zografos and K. Androutsopoulos

D6.2 Institutional and Organizational analysis for the implementation of the autonomous aircraft operations by K.G. Zografos and K.N. Androutsopoulos

D6.4 Cost-benefit results presentation

7.4 How the MTR review has influenced the work

The Mid-Term review was focused on the methodological framework developed for the assessment of the economic impacts in terms of Cost-Benefit Analysis. The approval of the proposed methodological framework by the EC external reviewers prompted the WP6 team to proceed to its implementation for the economic assessment of the A^3 ConOps.

7.5 End results, elaborating on the degree to which the objectives were reached

The work in WP6 resulted to various findings addressing the major objectives stated on the Description of Work (i.e., identification of the institutional and organizational barriers and enablers and the associated changes needed for implementing A^3 ConOps, and assessment of the economic viability of the proposed concept). Concerning the institutional and organizational issues arising from the introduction of the A^3 ConOps, the relevant analysis concluded that the implementation of the Self separation ConOps in Europe requires substantial institutional changes, including adaptation of the ATM legislation, regulative updates, and reform of the existing conventional role of the ATM stakeholders. Based on the findings of the institutional analysis, the Single European Sky framework and the regulations for the flexible use of the airspace will be mostly affected in an effort to introduce the proposed ConOps. Moreover, the changes required in the ATM systems and technologies associated with the A^3 ConOps implementation imply substantial revision of the ICAO Annexes relevant to the rules of the air, the navigation systems, and the role of the ANSPs. In addition, significant implementation regulations (guidelines and rules) will be required for the delegation of the separation task to the flight crew (which is the cornerstone of the A^3 ConOps) and the remaining elements of the A^3 ConOps supporting this task (e.g. AFR rules, ASAS and ACAS applications).

On the other hand the results from the CBA seem encouraging. A major finding from the Airlines analysis is that as B/C increases, higher en-route charges reduction are required for the same level of ATFM delay reduction and Flight Inefficiency Reduction. However, even in the most pessimistic scenario (forward-fit Cost= €73728, ATFM delay reduction=0% and Flight Efficiency Gain=0%), en-route charges reduction above 40% is sufficient to achieve a B/C above unity. Based on the findings of this analysis it was estimated that a 40% reduction of en-route ANSPs charges corresponds to 64.5% reduction of the en-route staff cost. Moreover, based on the relevant CBA calculations, viable scenarios may be identified even if the forward-fit cost was underestimated by a factor of 2.5, and % en-route ATFM delay reduction and % Horizontal Flight Efficiency Gains were equal to 0%. The ANSPs analysis indicated that even a marginal reduction of the ANSPs en-route staff cost is sufficient for achieving a B/C above 1. This finding implies that A^3 ConOps is expected to reduce substantially the en-route service cost. However, it was found that a 10% reduction of en-route staff cost, corresponds to 6.2% reduction of en-route charges implying that the airlines may achieve a B/C above unity if substantial reduction of the en-route inefficiency and the ATFM en-route delay (e.g., by 12% and 5% respectively) is attained. In general, the A^3

ConOps changes will have dramatic implications to the en-route ANSPs operations, resulting to considerable reduction of operating (staff and non-staff) cost.

As an overall conclusion it can be argued that the analysis results provided in this report seem encouraging for developing A^3 ConOps to its next maturity stage from the perspective of both the Airlines and the ANSPs economic implications.

8 Project execution for WP7: Accident risk and flight efficiency of A^3 operation

8.1 Objectives

The aim of this WP is to assess the A^3 operations developed by WP1 and WP2, through hazard identification and Monte Carlo simulation on accident risk as a function of traffic demand, to assess what traffic demand can safely be accommodated by this advanced operational concept, and to assess the efficiency of the flights. The accident risk levels assessed should be in the form of an expected value, a 95% uncertainty area, and a decomposition of the risk level over the main risk contributing sources. In order to accomplish this assessment through Monte Carlo simulation, the complementary aim of this WP is to further develop the innovative HYBRIDGE speed up approaches in rare event Monte Carlo simulation.

8.2 iFly Partners involved

WP7 has been conducted under the leadership of NLR. Within WP7, the main research has been performed by NLR, TWEN, UCAM, INRIA, DSNA and PoliMi. Critical reviews of research reports have been provided by HNWL and EEC.

8.3 Work performed and approaches employed

Description of work

The work has been organised in the following four sub-WPs:

WP7.1: Monte Carlo simulation model of A^3 operation

The development of a Monte Carlo simulation model of A^3 operation has been accomplished through a sequence of steps. First a scoping has been performed regarding the desired risk and capacity simulation study. An important aspect of this scoping was deriving the appropriate safety requirements from ICAO and ESARR4 regulation. Next a hazard identification and initial hazard analysis has been performed for the A^3 operation developed by WP1 and WP2. After these preparations the main work has been performed, i.e. the development of a Monte Carlo simulation model that captures the accident risk and the flight efficiency of the A^3 operation. The developed simulation model covers the human and technical agents, their interactions and both the nominal and non-nominal aspects of the operation.

WP7.2: Monte Carlo speed up methods

First a review of the Monte Carlo simulation based accident risk assessment situation has been performed. This review also covered the novel Monte Carlo simulation speed up techniques that had successfully been developed and applied in the iFly preceding HYBRIDGE project. Subsequently, potential directions have been identified that were expected to provide significant room for the further development of complementary speed-up and bias and uncertainty assessment techniques. These options for improvement have subsequently been elaborated and tested on their effectiveness. The potential options that have been studied within iFly WP7 are:

- To develop an effective combination of Interacting Particle System based rare event simulation with Markov Chain Monte Carlo speed up technique
- To develop a method to assess the sensitivity of multiple aircraft encounter geometries to collision risk, and develop importance sampling approaches which take advantage of these sensitivities.
- To develop novel ways how Interacting Particle System speed up techniques that apply to a pair of aircraft can effectively be extended to situations of multiple aircraft.
- To develop an efficient extension of Interacting Particle System based rare event simulation for application to hybrid systems
- To combine Monte Carlo simulation based bias and uncertainty assessment with operation design parameter optimization.

All these candidate improvements have been explored on their effectiveness and the way to integrate them with the innovative speed up approaches developed within HYBRIDGE. The resulting speed up approach has subsequently been used to conduct sensitivity analysis within sub-WP7.4.

WP7.3 Perform Monte Carlo simulations

Monte Carlo simulations have been performed to assess collision risk of the A^3 operation. At this stage of the work, the results were of point estimation type. On the basis of these point estimation results, an intermediate report has been produced which shows the assessment results obtained for A^3 operation.

WP7.4 Final report

This was the finalization of the report. The safety analysis has been extended with sensitivity analysis using novel methods from WP7.2. The results obtained have been documented in iFly report D7.4.

Deliverables

D7.1a Accident risk and flight efficiency of A^3 operation - Scoping and safety target - by H.A.P. Blom

D7.1b Hazard Identification and Initial Hazard Analysis of A^3 ConOps based operation by H.A.P. Blom, G.J. Bakker, M.B. Klompstra and F.J.L. Bussink

D7.2a Review of risk assessment status for air traffic. Editors: H.A.P. Blom, J. Krystul, P. Lezaud and M.B. Klompstra

D7.2b Trans-dimensional simulation for rare-events estimation on stochastic hybrid systems by N. Kantas and J.M. Maciejowski

D7.2d Periodic Boundary Condition in Simulating Large Scale Airborne Self Separation Airspace by A. Goswami, G.J. Bakker, H.A.P. Blom

D7.2e Rare event estimation for a large scale stochastic hybrid system with air traffic application - IPS extension to large hybrid systems - by H.A.P. Blom, G.J. Bakker and J. Krystul

D7.2f Sensitivity analysis in Monte Carlo simulation based rare event estimation by M.B. Klompstra, G.J. Bakker, H.A.P. Blom

D7.2g Final Report on Monte Carlo speed-up studies by H.A.P. Blom and G.J. Bakker

D7.4 Final report on accident risk assessment of advanced autonomous aircraft operation

8.4 How the MTR review has influenced the work

MTR identified significant delay in the various studies aiming to further improve the acceleration of the rare even MC simulations, and recommended appropriate actions. In response to this MTR recommendation, WP7 has been reorganized. The key change was that WP7.4 completion has been scheduled in parallel with the completion of the WP7.2, i.e. further improvement of MC speed-up.

8.5 End results, elaborating on the degree to which the objectives were reached

WP7 has produced two types of end results:

- Safety assessment of the A^3 ConOps under very high en-route traffic demands
- Improvement of rare event Monte Carlo simulation techniques

Safety assessment of the A^3 ConOps

In [iFly D1.3] an advanced airborne self separation operation for en-route airspace has been developed under the name A^3 ConOps (Concept of Operations). The key question posed by the iFly project is how much en-route traffic demand can this A^3 ConOps safely accommodate? In order to address this question, a multi-agent model of the A^3 ConOps has been developed, which includes human and technical agents, their interactions and both the nominal and non-nominal aspects of the operation. Subsequently this model has been used to run rare event Monte Carlo simulations for the following three encounter scenarios:

1. Two aircraft head-on encounter
2. Eight aircraft head-on encounter
3. Random traffic scenarios

The MC simulation results obtained for these scenarios show that the A^3 ConOps model works very well for all scenarios considered. More specifically, the results show that the A^3 ConOps model may safely accommodate 3x to 6x the traffic demand of a very busy en-route sector in 2005.

Parameter sensitivity analysis shows that the results are pretty insensitive to Required Navigation Performance (RNP) level, Crew response time, Medium Term separation minimum and Groundspeed. Significant sensitivity has been identified regarding Airborne Separation Assistance System (ASAS) dependability level and the tactical separation minimum. For the ASAS dependability this means that it should be 10x more dependable than what was needed for using the Autonomous Mediterranean Free Flight (AMFF) ConOps over the Mediterranean. For the Tactical separation minimum there appears no need to reduce the current value of 5 NM minimum tactical separation to the 3 NM proposed in [iFly D1.3].

Hence the answer to the fundamental question is: advanced Airborne Self Separation can safely accommodate 3x high 2005 traffic demand, under the following conditions:

- The dependability of ASAS support systems has to be of a high level. From the rare event MC simulation results safety objectives for the dependability parameters of the various sub-systems have been identified.
- The most demanding safety objective concerns the probability of ADS-B Global being down: it must be 5 times better than what has been identified as being needed for the Autonomous Mediterranean Free Flight. If the safety objectives for the ASAS system dependability cannot be realized in practice, then an alternative is to improve future TCAS such that this provides a 5 times higher factor in safety improvement than current TCAS does.

Because iFly project covers the safety evaluation of the early development phase of an advanced airborne self separation ConOps, it is recommended that these findings receive follow-up research in the next A^3 ConOps development and validation phase. Follow-up research should also cover weather influences, incorporation of vertical movements, and further validation of the A^3 model results.

In conclusion, WP7 has successfully evaluated the A^3 ConOps with respect to safety as a function of en-route traffic demand increase over high 2005 demands. The assessed risk level has been compared against ICAO and SESAR safety risk criteria that apply under corresponding higher traffic demands. This has provided a good indication of how much and in which directions a “state-of-the-art” A^3 operation has to be further improved in order to accommodate a factor 3 en-route traffic increase over Europe relative to high 2005 demand. In addition, WP7 has identified which limitations have to be mitigated in order to accommodate a three to six times increase in air traffic demand.

Improvement of rare event Monte Carlo simulation techniques

Within WP7.2 of the iFLY project, several studies have been performed on the development of various complementary methods that aim to improve the speed-up performance of rare event Monte Carlo simulation of advanced ATM concept of operations. The D7.2g report has provided an overview of these complementary speed-up results, and has shown how this has been exploited, within the iFly project, in the rare event Monte Carlo simulation of the A3 ConOps. The central method is the Interacting Particle System (IPS) method that has been developed and used for ATM in the HYBRIDGE porject. An overview of the background of this IPS approach has been given in [iFly D7.2a]. The following further extensions of the IPS methods have been studied within iFly WP7.2:

- Monte Carlo Markov Chain (MCMC) [iFly D7.2b]
- Exploiting Complexity measures
- Periodic Boundary Condition (PBC) [iFly D7.2d]
- Hierarchical Hybrid IPS (HHIPS) [iFly D7.2e]
- Regression analysis [iFly D7.2f]

All five complementary results have been carefully considered for their exploitation within the iFly project. For the MCMC, the Complexity measures and the Regression analysis approaches it has been identified that these novel approaches were promising, but at the same time were in need of further development prior to their application to the rare event evaluation of the A^3 ConOps. In combination with IPS, both the PBC and the HHIPS results have been used for the evaluation of the A^3 ConOps. The main finding is that standard MC simulation has an advantage over Sequential MC (SMC) in the sense that it provides more detailed results for events that happen regularly. However for rare events, properly tuned SMC allowed to evaluate for the ConOps up to four orders of magnitude less frequent events. This means that in practice it is best to make a combined use of standard MC simulations and SMC simulations.

9 Project execution for WP8: Further Refinement of the A^3 ConOps

9.1 Objectives

The objective of WP8 is to refine the A3 ConOps and to develop a vision how A3 equipped aircraft can be integrated with SESAR concept. The key inputs to be used for the refinement are the innovative methods and architecture implications that are delivered by WP3, WP4 and WP5. In addition, use is made of feedback from WP2, WP6 and WP7. The WP will make use of results from global work performed by AP23. The objective of WP8 also is to describe the non-airborne requirements in support of A3 equipped aircraft.

9.2 iFly Partners involved

WP8 has been conducted under the leadership of Isdefe. Within WP8, the research has been conducted by Isdefe, NLR, ETHZ, UCAM, NTUA, PoliMi, HNWL, AQUI and EEC. Critical reviews of research reports have been provided by NLR, HNWL, Isdefe, Dedale and AUEB.

9.3 Work performed and approaches employed

The WP has been organised in five sub-WPs.

- WP8.1 Integration of mathematical results.
- WP8.2 Distributed Air Traffic Flow Management Concept.
- WP8.3 A3 equipped aircraft within SESAR.
- WP8.4 Non-airborne requirements in support of A3 equipped aircraft.
- WP8.5 Potential directions for further refinement of A3 ConOps.

WP8.1 Integration of mathematical results

Within WP8.1 the results obtained in the mathematical WPs have been evaluated upon their value for being integrated within the A^3 ConOps. Options that were still open within the A^3 ConOps have been further analysed and consequentially reduced by taking advantage of the outcomes of the innovative methods developed by WP3, WP4, WP5, WP7 and WP9, i.e.

- Methods for the timely prediction of complex conflict conditions (WP3).
- Methods to systematically identify and analyse potential safety critical multi-agent situation awareness inconsistency conditions in distributed designs (WP4).
- Advanced multiple conflict resolution methods which have the potential to be formally validated on their performance (WP5).
- Advanced design aspects that have been developed within WP7 and WP9.

WP8.2 Distributed Air Traffic Flow Management Concept

Sub-WP8.2 has developed a concept for flow management which supports and emphasises the philosophy behind autonomous aircraft operations. In the current day ATM system several layers of traffic management are incorporated. Each layer has the objective to avoid overloading the subsequent layers with too much traffic load. The layer ATFM in the current ATM system has the objective to not overload any airports and sectors with too much traffic by balancing capacity and demand. In the current day ATM system capacity is limited due to a number of factors like runway separation minima, airport weather conditions, and controller workload limitations. Demand is dependent on for instance airline hub strategies and customer preferred flying times.

Although controller workload is less of an issue, with autonomous aircraft operations a number of the current bottlenecks will not dissolve automatically. If these capacity limits are not addressed well, pilots may find themselves flying circles in a stack. So there clearly was a need for a form of ATFM which works in conjunction with autonomous aircraft operations.

In an environment with autonomous aircraft operations new opportunities arise to reduce delays imposed by ATFM. Shorter feedback loops allows for better adjustment to uncertainties. Fewer bottlenecks make it easier to find solutions accommodating for real 4D ATM. Furthermore, ATFM can within limits assure through CDM and demand management that the traffic levels for autonomous aircraft operations do not exceed above set restrictions.

In this sub-WP the following activities have been performed:

- The interactions of autonomous aircraft operations and highly automated ATC with air traffic flow management have been identified;
- The problems and weak-points from air traffic flow management interacting with autonomous aircraft operations (together with their mitigations) have been identified.
- An air traffic flow management concept which emphasises the advantageous of autonomous aircraft operations has been developed.

WP8.3 A^3 equipped aircraft within SESAR

Sub-WP8.3 has developed a vision how A^3 equipped aircraft can operate within SESAR. In doing this, WP8.3 has kept all options open for which there does not exist yet a good rationale to make design decisions. Within WP8.3 the ConOps vision has been based on an analysis of how the A^3 ConOps impacts strategic ATM options identified by SESAR on issues such as:

- Mixed equipage
- 4D ATM including a systematic way of working with uncertainty
- Integrating ATFM (from WP8.2)
- CDM and demand management
- Human roles and responsibilities
- System Wide Information Management (SWIM)

Due to the nature of A^3 operation, the A^3 ConOps is purely focussed on the airborne-side and under the demanding condition that all aircraft are A^3 equipped. In practice, however, a gradual increase of equipped aircraft will be the case. Therefore WP8.3 has developed a vision how the gradual increase of A^3 equipped aircraft within the SESAR settings should fit best. This way, WP8.3 aims to contribute to the SESAR Operational Evolution regarding ATM Service Level 5 conceptualizing the implementation of 4D Trajectory and the introduction of ASAS Self-Separation in a mixed mode environment. This way, WP8.3 has addressed the question how well the A^3 thinking combines with the gradual implementation of autonomous aircraft operations, where IFR and AFR aircraft may coexist for a period of time.

WP8.4 Non-airborne Requirements in support of A^3 equipped aircraft

Sub-WP8.4 has identified the necessary non-airborne support to A^3 (e.g. FOC, ATFM, SWIM, COM, etc.). To accomplish this, the A^3 ConOps of WP8.1 has been combined with the early WP6, WP7 and WP9 results in assessing the A^3 operation. This allowed to place the A^3 ConOps in the perspective of the traffic demand levels that are supported by the A^3 operation alone and within SESAR perspective respectively. And this also allowed to identify the impact on the non-airborne requirements of A^3 operations (e.g. FOC, SWIM, ATFM, COM, etc). The rationale of addressing the requirements from a non-airborne perspective has been documented. Specific non-airborne requirements that have been looked at include:

- Communication requirements (voice, data-link)
- Data accuracy, integrity and availability
- Automated ground surveillance support requiements
- Network security
- Pre-flight requirements
- Arrival and Departure Management requirements
- Flow management requirements

WP8.5 Potential directions for further refinement of A^3 ConOps

WP8.5 has analyzed potential risks regarding key performance areas (KPA's): safety, cost/benefit and capacity. The chosen approach started with an expert based identification of potential risks requiring further attention, using results from other WP's.
On the basis of these inputs, experts working groups have been organized in order to identify potential risks of this advanced operation concept as well as potential directions for further improvement and refinement. The activities have been organized using the following systematic steps:
Step 1: Identification of technical areas. During this step the most relevant technical areas in relation to KPA's: safety, cost-benefit and capacity have been identified.
Step 2: Evaluation and filtering of results. This step has been conducted in order to filter the information provided by previous studies and the work done in previous work packages.
Step 3: Identifications of potential risks. During this step various potential risks have been identified that may apply to aircraft using the A^3 ConOps rules.
Step 4: Identification of potential directions for refinement. During this step the best possible potential directions for refinement of the ConOps have been identified.
Step 5: Study of redundancy and correspondence. During this step it has been identified whether there are any inconsistencies between the potential directions for improvement explained above.
Step 6: Finally, the main potential improvement activities have been identified.

Deliverables

D8.1	A^3 ConOps refinement
D8.2	Flow Management in Self-Separation Airspace by R. Verbeek
D8.3	A^3 equipped aircraft within SESAR's concept of operations
D8.4	Non-airborne requirements for A^3 operations
D8.5	Identification of Potential Directions for Further refinement of the A3 ConOps

9.4 How the MTR review has influenced the work

An important recommendation stemming from the MTR was to systematically maintain the options considered for possible use within the A^3 ConOps, and to be precise which versions of the A^3 ConOps were evaluated within which of the other WP's. This recommendation has been implemented in WP8. The largest impact of this decision applies to refinement of the A^3 ConOps within WP8.1. As a consequence the D8.1 report has been developed as a living document during the remainder of the iFly project. Hence the completion of the final D8.1 report shifted to the end of the iFly project.

9.5 End results, elaborating on the degree to which the objectives were reached

D8.1 identifies a number of options and possibilities in several issues. The A^3 ConOps is an innovative concept, the studies performed in the previous work packages have provided several option in the autonomous mode flight concept. These options have been evaluated, and the best options have been identified.

D8.2 identifies the interactions of A3 ConOps with the air traffic flow management, identifying the operative restrictions and finally develops the concept for flow management in Self-Separation Airspace.

D8.3 defines a soft integration of A^3 ConOps and SESAR, supporting a soft transition based in several scenarios identified.

D8.4 identifies the non-airborne requirements to support a safety autonomous aircraft operation with self-separation capability.

D8.5 identifies the bottlenecks and mitigation activities in safety and cost / benefit, providing a clear picture of the operative borders of A3 ConOps.

In conclusion, WP8 has largely realized the strategic objectives in the further refinement of the A^3 ConOps using results from other WP's. In addition, WP8 developed a vision how A^3 equipped aircraft fit best within the SESAR thinking regarding future ATM, such that the resulting operation goes beyond the A^3 en-route operation in such a way that it safely accommodates a factor three to six more traffic then at current busy traffic levels.

10 Project execution for WP9: A^3 Airborne system design requirements

10.1 Objectives

WP9 has two main objectives:

- To define preliminary Safety and Performance Requirements (SPR) for the Autonomous Aircraft Advanced (A^3) Concept of Operations developed in the iFly WP1.
- To use the results of SPR process to develop preliminary airborne system design requirements for future avionics supporting the A^3 concept.

The primary task of the iFly WP9 was to apply the SPR development process described in EUROCAE ED-78a/RTCA DO-264 to the A^3 concept. The specificity of iFly's approach lies in the fact that the above mentioned process is defined as a pre-requisite for industrial deployment of applications and as such it is usually applied considerably later in the concept development cycle. Therefore it was necessary to adapt its use and outputs to innovative and research character of the iFly project where it was applied as a concept development tool rather than as an industrialization tool.

The main objectives of the SPR development process in the iFly were thus:

- Formalize (from airborne perspective) elements of the A^3 concept in terms of operational description and requirements.
- Identify key missing elements of the A^3 concept from the industrialization/avionics point of view.
- Provide the link with existing standards and related airborne system requirements (typically associated with other ADS-B In applications).

10.2 iFly Partners involved

WP9 has been conducted under the leadership of HNWL. Within WP9, the main research has been conducted by HNWL. Critical reviews of research reports have been provided by NLR, Isdefe, UTartu, Dedale, NTUA, DSNA, ETHZ, UCAM and EEC.

10.3 Work performed and approaches employed

The work has been organised in four subWPs:

WP9.1 – Operational Services and Environment Description (OSED)

This sub-WP has developed an OSED describing the operational environment and the air traffic services required to support the 'A^3' concept described in the A^3 ConOps delivered by WP1 and refined by WP8.1. To accomplish this, use has been made of the A^3 ConOps from WP1, the output of WP2, and the innovative methods from WP3, WP4 and WP5.

The OSED development has been based on an operational services and environment information capture process that co-ordinates the information among stakeholders. The process has captured elements related to a defined CNS/ATM system, and included aspects such as aircraft equipage, ATS provider technical system, communication service provider systems, and procedural requirements. The work performed in AP23 on OSED building from ASAS operational elements and ASAS avionics support functions has been analysed and used as much as possible.

The OSED has identified the operational services and their intended operational environments and included the operational performance expectations, functions, and selected technologies of the related CNS/ATM system. Also, a high-level Functional System Description has been developed. In follow-up sub-WP's this OSED facilitated the formulation of technical and procedural requirements based on operational expectations and needs.

WP9.2 – Operational Safety Assessment (OSA)

The OSA has assessed the system safety side of the autonomous ATM concept described in the OSED produced in WP9.1. This has been accomplished through conducting two interrelated processes. First an Operational Hazard Assessment (OHA) and second an Allocation of Safety Objectives and Requirements (ASOR).

Operational Hazard Assessment (OHA)

Well in line with the purpose and scope of an OHA, operational hazards have been identified and qualitatively assessed in relation to the functionalities defined through the OSED of the advanced autonomous ATM concepts. This assessment also leads to establishing safety objectives and candidate safety requirements related to each identified hazard.

Operational services have been examined to identify and classify hazards that can adversely effect those services. Hazards have been classified according to a standardised classification scheme based on hazard severity, taking into account human factors. Overall safety objectives have been assigned to the identified hazards.

Allocation of safety objectives and requirements (ASOR)

Based on the results of the OHA, the ASOR has allocated safety objectives to organisations, has developed risk mitigation strategies that are shared by multiple organisations, and has allocated safety requirements to those organisations.

Requirements have been allocated to the CNS/ATM system elements that provide the functional capability to perform the service and the stakeholders in control of or responsible for each of the elements. Understanding the interactions of the operational services, procedures, and airspace characteristics has subsequently assisted in the identification of failures, errors, and/or combinations thereof that contribute significantly to the hazards identified in the OHA.

WP9.3 – Operational Performance Assessment (OPA)

Well in line with the purpose of an OPA, this sub-WP has developed the airborne performance requirements for A^3 operations. Thereto, the definition and setting of the performance requirements have been linked to the primary performance objectives (extracted from the OSED produced in WP9.1), as well as to safety analysis in WP9.2 and operational needs (WP1, WP8.1).

Performance requirements have been derived to ensure that the minimum operational requirements are such that end users can expect the same quality of services for the autonomous ATM concept in any airspace where the various elements of the CNS/ATM system meet these requirements.

WP9.4 – Airborne System Design Requirements
This sub-WP has used the results of the OPA and OSA processes for the development of a preliminary system design requirements for airborne systems to support the A^3 operations. Also, a first estimation of their impact on airborne requirements has been provided.

Deliverables

D9.1 Operational Services and Environment Description (OSED) of Airborne Self-Separation Procedure (SSEP) by P. Cásek, E. Gelnarová

D9.2 ED78a/DO-264 based Operational Hazard Assessment (OHA) and Allocation of Safety Objectives and Requirements (ASOR) of Airborne Self-Separation Procedure by E. Gelnarová, J. Jonák

D9.3 Operational Performance Assessment (OPA) by P. Cásek, P. Mejzlík

D9.4 Airborne System Design Requirements

10.4 How the MTR review has influenced the work

For WP9 the MTR review was placed at an ideal moment: after delivering of the OSED document (which was also presented at MTR) but within the start of performance and safety assessment tasks. This timing allowed to discuss with external reviewers the results of the operational analysis of the A^3 concept (in particular, identified gaps) and, what was the most important, of the main objectives and activities of the adapted ED-78a process proposed for WP9 tasks. In particular, a lot of attention was paid to the way how to simplify the use of obtained iFly results in subsequent ATM research, e.g., within the SESAR projects focused on airborne self separation.
The outcomes of this discussion were used to refine the proposed SPR development activities and were therefore reflected in the following WP9 deliverables.

10.5 End results, elaborating on the degree to which the objectives were reached

The iFly WP9 started with a deep analysis of the A^3 concept (D1.3) aiming to refine the existing operational description in terms of an OSED document suitable for safety and performance assessment of defined operations. Identified missing or insufficiently defined elements of the concept were documented and, when possible, their definition was refined or some alternatives were proposed. In this context, the focus was given mainly to the description of information sharing process (including support from ground systems), communications, and the functional description of airborne systems.

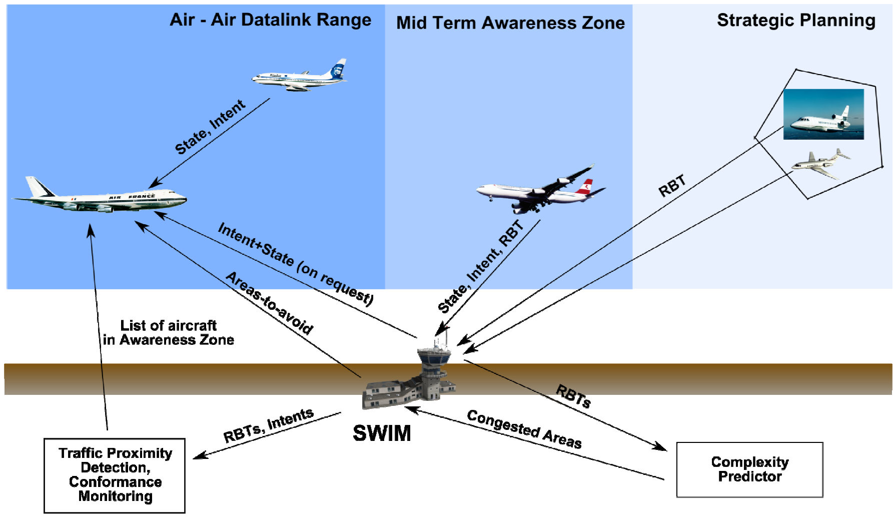

Figure 7: Information sharing in the A3 concept.

Important elements added to the A^3 concept within this process were:

- Definition of **ATM Service level** as a characteristic of airspace describing the required amount of information shared among self separating aircraft and potentially also supporting ground systems (e.g., only state reports, state + intent reports, etc.).
- Detailed description of the communication channels used during self separating operations (see Figure 7).
- Detailed definition of assumed information support from ground tools (System Wide Information Management (SWIM) system) for highest ATM service level.
- Stage-decomposition of the self separation process from the aircraft perspective.

In order to simplify the allocation of operational, safety and performance requirements within the following SPR process, the airborne system was decomposed into high-level functional blocks (taking into account the existing airborne architectures) as shown in Figure 8.

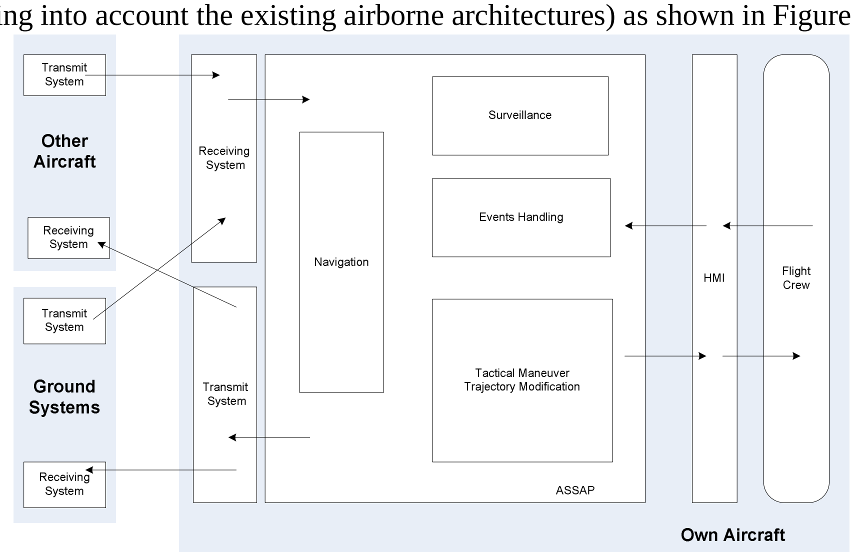

Figure 8: Functional blocks used in SPR process.

In addition, similar purposes led to definition of a generic parameterization describing airborne processing of detected potential conflicts (see Figure 9).

The above operational description was used in the development of preliminary performance requirements within the OPA process. Although a research character of the A^3 concept did not allow to quantify most of identified requirements, through the analysis of recent standards for air traffic surveillance applications (in particular, DO-312, DO-319, and DO-317) it was possible in some cases to provide the links to the values applied currently in these less complex applications.

In accordance with ED-78a process, OSA was performed in parallel with the performance assessment. The operational hazard started by identifying the operational hazards, definition of environmental conditions, external and internal mitigation means, and development of fault and event trees for each identified hazard. Three main types of operational hazards were considered in OSA:

- Aircraft is reacting on non-existing conflict (false alarm)
- Aircraft is incorrectly reacting on existing conflict
- Failure (detected) of airborne system.

Similarly to the OPA, a research character of the A^3 concept did not allow the quantification (probabilistic) of the fault and event trees and therefore the focus was given on completeness of the logic and causality structure of the identified hazards.

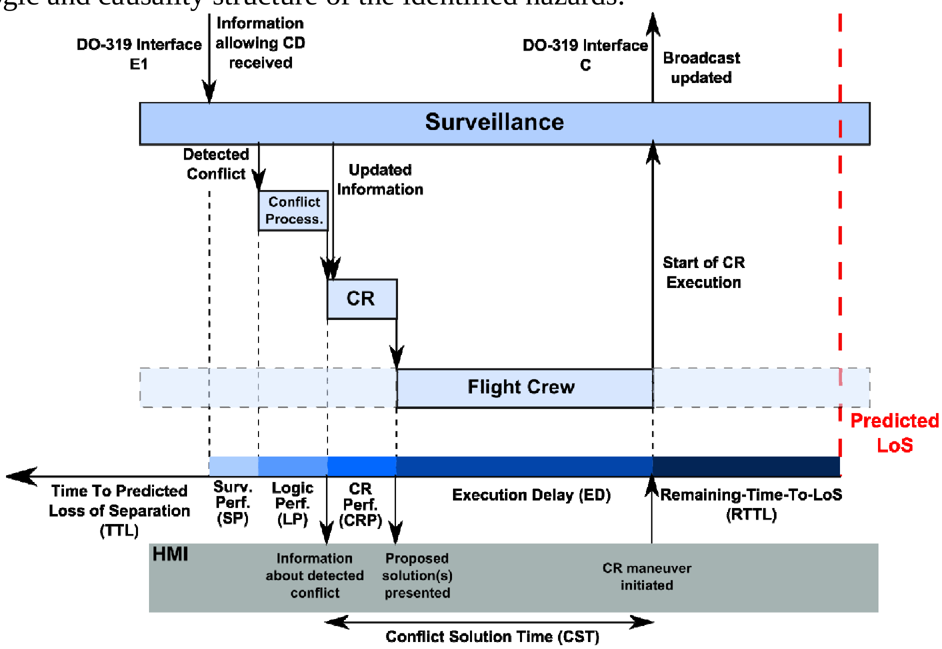

Figure 9: Overview of conflict processing.

Finally, the output of the preliminary SPR process described above was used as input to develop high-level functional system design requirements for airborne system supporting the A^3 self separation operations (D9.4). This document is based on definition of key onboard functions as shown in Figure 10.

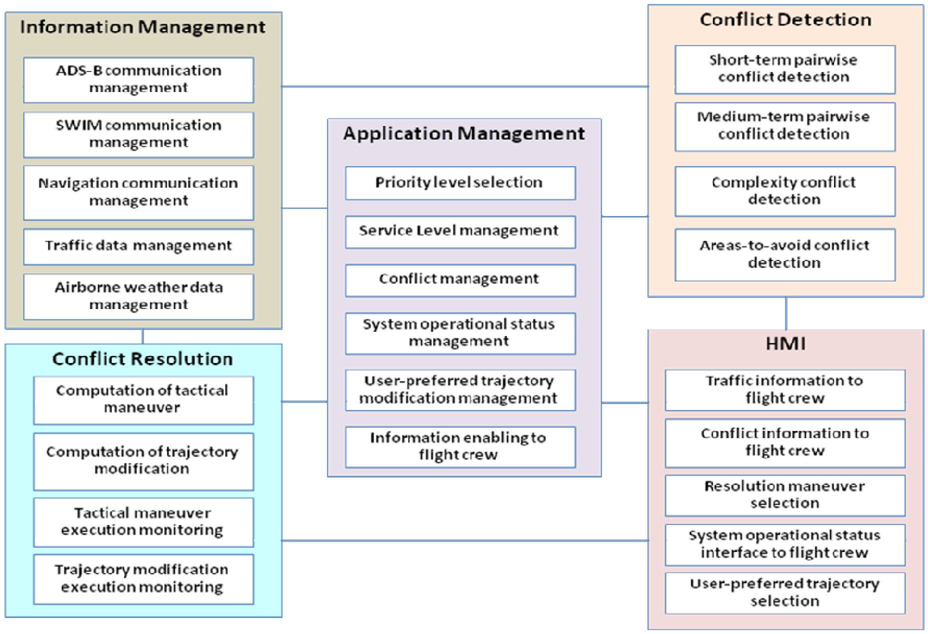

Figure 10: High-level functional definition.

For each function a detailed description is provided accompanied by the list of operational inputs (definitions) required for its implementation. In addition, when some ambiguity/gap was identified in the A^3 concept, the affected functional requirements are provided together with applied operational assumptions. This approach was adopted in order to simplify future update of the developed functional requirements associated with future evolution of the self separation concept (taking into account research character of the iFly project).

In conclusion, WP9 has fully reached the strategic objective of WP9 to perform a preliminary cycle through the EUROCAE ED78A method. This way WP9 has derived preliminary safety and performance requirements on the applicable functional elements of the A^3 operational concept focused in order to identify the required technology to make this concept a reality.

11 Project execution for WP10: Dissemination-related activities

11.1 Objectives

The objectives of WP10 are to disseminate and exploit iFly results in order to ensure the appropriate involvement of the major European stakeholders on the project activity, and to recommend the optimal use of the project results.

Dissemination and exploitation of project results is considered of primary importance for all the partners involved in the iFly project. Recommendations will be made as input to future tasks and studies.

11.2 iFly Partners involved

WP10 has been conducted under the leadership of NLR. Within WP10, key contributions have been received from NLR, HNWL, ETHZ, NTUA, UCAM, PoliMi, AQUI, AUEB, ENAC, EEC, TWEN, DSNA, INRIA and UTartu.

11.3 Work performed and approaches employed

The work has been organized in the following subWPs:

WP10.1 Studies on socio-economic aspects
This sub-WP has assessed the expected socio-economic impact of the knowledge and technology generated, as well as analysis of the factors that would influence their exploitation on the following:

- The possibility to adapt separation minima (has been included by WP7 final report, in co-ordination with the project RESET).
- An overall validation strategy/plan, addressing the recommended follow-up of the A3 ConOps.

WP10.2 Dissemination activities
The dissemination of project results has relied on the usual mechanisms for publishing scientific research. That is, the partners have placed little or no restrictions on the availability of the results (beyond respecting the usual commercial confidentiality), and have provided the documentation to relevant scientific libraries and establishments and have published papers in relevant journals and conference proceedings. The use of e-mail and Internet has been used to maximise the speed and effectiveness of the dissemination.

Key iFly partners belong to the ATM/ASAS research community and are active members of CARE ASAS, ASAS Thematic network, FAA-EUROCONTROL action plans, EUROCONTROL Programme Steering Groups on ADS, AGC, as well as industry groups such as EUROCAE, and the Requirements Focus Group (RFG). This way, dissemination of project results to these working groups has been assured and well facilitated. The list of dissemination activities that have been managed include:

- Presentations and publications and presentations to mathematical audience by WP3, WP4, WP5 and WP7 (IEEE conferences and journals).

- Presentations and publications to civil aviation audience by WP1, WP2, WP6, WP7, WP8 and WP9 (USA/Europe ATM, AIAA or IEEE-DASC conferences)
- Presentations at ASAS Thematic Network workshops.
- Workshop on the mathematics of autonomous aircraft jointly with a conference, e.g AIAA or IEEE-DASC conference.
- Summer School on autonomous aircraft concept design and validation.
- Intermediate presentations of the iFly project to the aviation community.
- Final presentation of the iFly project results to the aviation community.
- Web-based activities aiming at disseminating the knowledge and technology produced (iFly web) + Eurocontrol Experimental Centre e-letter.
- Final iFly executive project report (this report).

Deliverables

D10.1 Overall validation strategy and plan

D10.2.1 Scientific papers (see Appendix A)

D10.2.2 Workshop and presentations (see iFly web site)

D10.2.3 iFly website http://iFly.nlr.nl

D10.2.4 Final iFly executive report (this report)

11.4 How the MTR review has influenced the work

During the MTR review, Mr. Peter Hotham, Chief architect at the SESAR JU, has offered to be point of contact with SESAR JU for the iFly project. This for example has been very helpful in preparing an iFly press release regarding the A3 ConOps in relation to SESAR, and in giving a dedicated final iFly presentation to SESAR-JU experts.

11.5 End results, elaborating on the degree to which the objectives were reached

In Table 3 a listing is given of the iFly dissemination achievements. The corresponding material is available at the iFly web site.

Table 3. iFly dissemination achievements within the project period

- iFlyer + web-site http://iFly.nlr.nl
- iFly in EEC e-letter of March 2010
- Summer School at ICRAT 2010
  - 1st June 2010 in Budapest
- 4 Workshops/keynotes at conference (e.g. CDC, Formal Methods)
  - Workshop at CDC 2008, December 2008
  - 1st FMA workshop at Formal Methods week, November 2009
  - Keynote at 2nd EAAP. September 2010
  - 2nd FMA workshop at CDC2010, December 2010
- 1 presentation to RFG, FAA/Eurocontrol Action Plan 23; ICAO SASP
  - ASAS Global Network workshop in 2008
- 4 PhD Thesis
  - 1 in 2010
  - 3 in 2011
- 10 Master Thesis (in English language)
  - 1 in 2007
  - 2 in 2008
  - 1 in 2009
  - 3 in 2010
  - 3 in 2011
- 39 papers at mathematics oriented conferences
  - 3 in 2007
  - 9 in 2008
  - 12 in 2009
  - 9 in 2010
  - 6 in 2011
- 20 papers at ATM/aviation oriented conferences (INO, AIAA, ICRAT, etc.)
  - 3 in 2007
  - 6 in 2008
  - 7 in 2009
  - 5 in 2010
- 2 papers at other conferences (ICSS, Transporation Research Board)
  - 1 in 2008 (International Conference on System Safety)
  - 1 at 2010 (Transporation Research Board)
- 23 Journal papers
  - 1 in 2008
  - 8 in 2009
  - 12 in 2010
  - 2 in 2011
- 4 Book chapters
  - 2 in 2009
  - 2 in 2010

A listing og the conference papers, Journal papers and book chapters is given in Appendix A.

12 Summary of results and concluding remarks

This concluding section summarizes the achievements of the project, explains how this relates to the state-of-the-art and explains the expected impact of the project on its industry or research sector.

12.1 Achievements of the project

The achievements of the iFly project are of two types:

- Airborne Self Separation achievements
- Generic achievements

The airborne self separation achievements are as follows:

1. The A^3 ConOps has been developed for en-route traffic which goes beyond the limits posed by the airborne self separation concepts in literature [iFly D1.3].
2. Study of the conflict detection and resolution problems of the A^3 ConOps can be managed using algorithms that have modest computational requirements [iFly D5.4].
3. Study of shared situation awareness issues has stimulated the development of mitigating measures for some safety critical conditions [iFly D4.2].
4. Through conducting large scale rare event MC simulations for a model of this A^3 ConOps it has been shown that it can safely accommodate 3x the 2005 European traffic demand [iFly D7.4].
5. Through conducting a cost-benefit analysis it has been shown that the introduction of this A^3 ConOps is economically sound [iFly D6.2].
6. A vision has been developed how A^3 equipped aircraft fit best within the SESAR thinking regarding future ATM [iFly D8.3].
7. By conducting an early cycle through the EUROCAE ED78A method, for this A^3 ConOps preliminary safety and performance requirements have been derived on the applicable functional elements of the concept [iFly D9.3].
8. A human factors study has been performed, which has identified the principles for advanced cockpit design in A^3 equipped aircraft [iFly D2.4].
9. Novel directions for traffic flow control in support of the A^3 ConOps have been identified [iFly D8.2].

In addition to this the iFly project also has various more generic achievements:

1. Further extension of a powerful method in compositional modelling and analysis of complex socio-technical systems [iFly D4.1].
2. Development and initial performance evaluation of three novel complexity metrics for advanced ATM [iFly D3.2].
3. Development of four novel medium and short term conflict resolution algorithms some of which can guarantee conflict free resolutions [iFly D5.3].
4. Development of powerful extensions of the rare event Monte Carlo simulation method IPS [iFly D7.2g].
5. An inventory of options for the possible refinement of the A^3 ConOps [iFly D8.1].

All these achievements have been documented well. Moreover a steady stream of research papers has been produced in support of disseminating these achievements.

12.2 Relating the achievements of the project to the state-of-the-art

Advanced airborne self separation Conops

Development of advanced airborne separation applications is a long term process which will be strongly dependent on the practical experience from the deployment of earlier ADS-B In applications, such as In-Trail Procedure or Interval Management (airborne spacing). In this context the envisioned implementation timeframe of airborne self separation is expected to be 2025+, i.e., beyond the SESAR scope. Although several associated research activities were performed in past both in the US and in Europe (Free Flight, MFF, ASSTAR), there are several elements of the iFly project that goes considerably beyond them. For instance, the previous research was typically based on the use of a single communication channel (ADS-B broadcast) of only state information, and operations in low density traffic. On the contrary, the iFly project targeted high density traffic and a lot of effort was paid to develop a concept having communication and information backup and profiting from different types of information. Specific achievements beyond the state-of-the-art in advanced ATM development are:

i) A^3 ConOps [D1.3]
ii) Inventory of options for the refinement of an advanced ATM concept [D8.1];
iii) Innovative approaches towards traffic flow management in support of the A^3 ConOps [D8.2]; and
iv) Development of a vision to integrate A^3 –equipped aircraft with the SESAR 2020 thinking [D8.3].
v) SPR documents provide a novel level of detail and enhanced analysis (in particular, with respect to safety) of self separation operations comparing to the previous airborne self separation research [D9.1 - D9.3].
vi) Setting out the principles to be adhered in the development of an A^3 directed HMI design in the cockpit, such that this HMI provides optimal support to the crew, in support of their new tasks and responsibilities [D2.4].

Cost benefit of A^3 ConOps

Apart from using the proposed analysis approach to assess economic impacts on involved stakeholders, it can be used to identify the ConOps economic targets under which the emerging ATM system could be sustainable. A tool has been developed in order to perform the calculations required for applying the proposed CBA approach. This CBA tool could be used by policy makers as a decision support tool for estimating alternative costs and benefits targets under which the proposed ATM ConOps may lead to a desired level of economic performance. In addition, the analysis of the institutional issues arising from the introduction of the A^3 ConOps provided useful recommendations for revising the institutional framework in order to facilitate the implementation of the proposed ATM changes.

Safety of A^3 ConOps

Thanks to the rare event MC simulations of WP7, it has become clear that one school of researchers was right: those who believed that airborne self separation can safely accommodate very high en-route traffic demands. This removes large uncertainty for the aviation industry which ATM directions can safely support increasing traffic demands. Now this uncertainty is resolved, it is expected that this may trigger novel developments in advanced airborne self separation, and the integration of conventional aircraft with advanced aircraft.

Mathematical results

In air traffic complexity the state of the art is to model and predict complexity of air traffic through explicitly adopting limitations of air traffic controllers and sector boundaries. The research in WP3 has led to the development of novel complexity metrics that avoid these limitations. However, it is not yet clear whether these novel developed complexity metrics are of specific use in the further refinement of the A^3 ConOps.

The impact of situation awareness consistency in the safe evolution of ATM scenarios is high, as also demonstrated by a posteriori analyses of ATM related disasters. Early studies of situation awareness in ATM were based of psychological analysis. The integration with engineered ATM is in general a hard task because the models employed by psychologists and engineers are of different nature. The approach pursued in WP4 provides a unified formal framework that integrates psychological studies of situation awareness with mathematical models of technical devices in ATM. The approach taken in WP4 can be considered as “qualitative” in the sense that it answers yes or no to the question of whether a situation awareness inconsistency can lead to a safety-critical situation.

Finally, conflict detection and resolution research has produced the following clear improvements over state-of-the-art:

1. They provide a systematic ways to deal with the requirements of the autonomous aircraft concept of operations developed in iFly. The extensive literature review (documented in Deliverable D5.1) and the comparison of the features of the available methods with the requirements of the autonomous aircraft concept (documented in Deliverable D5.2) suggest that none of the existing methods were suitable for this task without further extensions. WP5 provided precisely such extensions for the selected short-term and mid-term conflict resolution methods.
2. They strive for theoretical guarantees on the quality of the conflict resolution manoeuvres that they produce. In literature this is not yet a consideration for most of the available conflict resolution methods. However, solid theoretical foundations and the development of formal guarantees may for example obviate the need for extensive, expensive and time-consuming validation experiments.
3. Demonstrate ways of coupling short- and mid-term conflict resolution methods. Clearly this is an important consideration since most operational concepts envision conflict resolution methods operating simultaneously at different levels. To the best of our knowledge in literature no methodology is available for determining the effect that the actions of one conflict resolution level will have on the others. Hence the novel WP5 results show a potential novel direction for introducing such cross-layer considerations in the conflict resolution process.

12.3 Impact of the project on its industry or research sector

Airborne self separation supporting very high en-route traffic demand

From a societal perspective, citizens expect air transport to be affordable and safe in the future as well as it is now. Hence, a potential stall or delay in the further investment by the air transport industry into airborne self separation, eventually may have a very negative impact on the users of the air transport system, and thus on human society. Hence it is human society that benefits significantly from a continuation of effective strategic investments of the aviation industry into advanced air traffic operations. A key condition is that researchers are able to present a joint view to the air transport industry. iFly has developed the key missing scientific pieces of knowledge that solve this puzzle.

The deployment of airborne self separation is a long-term process and the iFly WP9 provided another important step to increase the maturity of this future airborne capability. Application of a typical pre-industrial standardization process to the research A^3 concept was very useful to show what are the weak points or missing elements necessary to progress toward industrialization. This output can also represent a useful input for future research in this area, e.g., the self separation projects in SESAR.

Integration with SESAR 2020

Regarding the integration of the A3 ConOps with SESAR thinking, it is proposed that various mixed aircraft conditions are further identified and analysed on safety and economy (using rare event MC simulation and cost-benefit analysis). This way it will become clear which transition paths are best feasible and which not. In addition, in support of the A^3 ConOps, new systems must be developed and standardized by the industry. Also roles and responsibilities for pilots and controllers will change, which has to be developed in collaboration with airlines and service providers.

Economic viability of the A^3 ConOps

A major issue in implementing A^3 ConOps relates to the assessment of the relevant institutional implications. Addressing this issue relates to the specification of the gaps, enablers or barriers in the International, European, and national institutional framework (as it is derived from the existing legislation) that arise from the transition of the ATM to the A^3 ConOps context. The results from the above institutional analysis of will indicate what legislative issues should be addressed in order to facilitate the implementation of a Self Separation ConOps. Given that Self Separation ConOps is in its definition phase, the institutional issues presented in iFly are subject to the maturity level of the ATM operational and technological changes presented within the project. Additional institutional issues may arise in the future based on the specification of the details for the operations and the systems proposed within A^3 ConOps.

The assessment of the A^3 ConOps economic implications on the relevant ATM stakeholders constitutes a major prerequisite for the deployment of the proposed ATM concept. Given that the proposed concept is in its definition phase, the scope of the A^3 ConOps Cost Benefit Analysis is placed on exploring under which cost and operational improvements scenarios a Self Separation concept can be potentially cost-effective. The results from this type of analysis set the ATM performance requirements and the corresponding implementation cost levels from a Cost-Benefit Analysis perspective. This type of assessment may accompany the Self Separation ConOps development to more mature stages where refined and more concrete Cost-Benefit Analysis results will be specified.

Safety analysis of complex safety critical operations

Through the iFly study it has become clear that rare event MC simulation may form a powerful approach towards learning about the safety behavior of a large complex socio-technical system, such as ATM. During the iFly study several direction for further improvement have been studied. Of these only a few could be used within the current study. This also means, several direction are remaining for further development. What does this mean for follow-up studies of speeding-up rare event simulation of advanced ATM ConOps? Regarding this question our view is as follows:

- HHIPS [iFly D7.2e] has proven to be able to assess very infrequent rare events for two aircraft encounters. Hence, in order to do the same for random traffic scenarios, HHIPS should be extended for its application to multiple aircraft scenarios.

- In [Krystul et al., 2011] the convergence proof of IPS has been extended to the Hybrid IPS version of [Krystul&Blom, 2005]. A further extension of this convergence proof to HHIPS remains to be done. Such a proof should deliver the exact mathematical conditions under which convergence behavior is as expected, and when not.
- MCMC is a very promising approach for the further improvement of IPS [iFly D7.2b]. As has been explained in Section 3, this asks a proper handling of several ATM relevant aspects, the most critical of which is the development of an effective MCMC operator step for use in an advanced ATM directed IPS.
- Regression analysis [iFly D7.2f] is another promising approach to be properly combined with the IPS based SMC approach. Because of the huge size of ATM safety models, a prerequisite for making this feasible is that for the IPS approach an an order in magnitude extra speed-up is being developed. Otherwise regression analysis does not form a realistic alternative for the One At-a Time (AOT) approach.
- Relative to the speeding-up studies performed within iFly, follow-up studies have a better reference point (i.e. the A3 ConOps) in the design space for advanced ATM ConOps that is able to safely accommodate very high traffic demand levels.

Conflict detection and resolution algorithms

Although the conflict resolution methods developed in WP5 have been aiming at addressing the needs of the A3 ConOps, an interesting question is whether these methods can also be used as a decision support tools to help the decision making of air traffic controllers. Pending some further research, the prioritized MPC methods might be able to operate in future in an autonomous aircraft operations area, as they have shown to be able to operate in high densities. In the research sector, those methods can serve as the ground for new developments, examining some more rigorous decentralization strategies, identifying the effect of delays in the resulting aircraft trajectories and performing some human-in-the-loop experiments in order to better evaluate the methods against human factors considerations. All these issues pose challenging problems for cutting edge research for which the methods pioneered by WP5 may serve as a starting point.

Air Traffic complexity

The novel methods for complexity prediction developed represent a significant step ahead in the research on air traffic complexity prediction. Various scientific papers were published throughout the WP3 development period, both in mathematical as well as air traffic-oriented conferences and journals. This witnesses the acceptance that the work performed under WP3 received from the experts in the field and the research community.

Mathematical analysis of shared situation awareness

Formal methodologies available in the literature on analysis and control of hybrid systems were not appropriate to fully address the problem of situation-awareness inconsistencies in multi-agent ATM systems. This has spurred AQUI researchers to explore novel research directions on the analysis and control of hybrid systems, which comprise:

- Critical observability.
- Compositionality of hybrid systems.
- Algorithms for the reduction of computational complexity in the analysis of hybrid systems.

While being inspired by realistic problems in ATM systems, these research topics acquired their own identity and are promising of being applicable to different research domains than ATM systems.

13 iFly Reports

[D1.3]	Autonomous Aircraft Advanced (A^3) ConOps by G. Cuevas, I. Echegoyen, J.G. García, P. Cásek, C. Keinrath, R. Weber, P. Gotthard, F. Bussink, A. Luuk
[D2.1]	Description of airborne human responsibilities in autonomous aircraft operations by A. Luuk, J.A. Wise, F. Pouw and V.Gauthereau
[D2.2]	Situation Awareness, Information, Communication and Pilot Tasks of under autonomous aircraft operations by J. Wise, C. Keinrath, F. Pouw, A. Sedaoui, V. Gauthereau and A. Luuk
[D2.3]	Identification of human factors for improvement of the A^3 ConOps by C. Keinrath, J. Wise, A. Sédaoui, A. Luuk
[D2.4]	Potential human factors improvements for A^3 ConOps by A. Luuk and C. Keinrath
[D3.1]	Complexity metrics applicable to autonomous aircraft by M. Prandini, L. Piroddi, S. Puechmorel, S.L. Brázdilová
[D3.2]	Final report on timely prediction of complex conditions for en-route aircraft
[D4.1]	Report on hybrid models and critical observer synthesis for multi-agent situation awareness by M. Colageo, M.D. Di Benedetto, A. D'Innocenzo
[D4.2]	Report on Observability Properties of Hybrid-System Composition by M.D. Di Benedetto, A. Petriccone, G. Pola
[D5.1]	Comparative Study of Conflict Resolution Methods by G. Chaloulos, J. Lygeros, I. Roussos, K. Kyriakopoulos, E. Siva, A. Lecchini-Visintini and P. Cásek
[D5.2]	Analysis of conflict resolution needs of the A^3 operational concept by N. Kantas, J. Maciejowski, A. Lecchini-Visintini, G. Chaloulos, J. Lygeros, I. Roussos, K. Kyriakopoulos, P. Cásek
[D5.3]	Report on advanced conflict resolution mechanisms for A^3 ConOps, by E. Siva, J.M. Maciejowski, G. Chaloulos, J. Lygeros, G. Roussos, K. Kyriakopoulos
[D5.4]	Final WP5 report including validation, by E. Siva,, J.M. Maciejowski, G. Chaloulos, J. Lygeros, G. Roussos, K. Kyriakopoulos.
[D6.1]	Methodological Framework for Cost-Benefit Analysis by K. Zografos and K. Androutsopoulos
[D6.2]	Institutional and Organizational analysis for the implementation of the autonomous aircraft operations by K.G. Zografos and K.N. Androutsopoulos

[D6.4]	Cost-benefit analysis results presentation, by K. Zografos and K. Androutsopoulos
[D7.1a]	Accident risk and flight efficiency of A^3 operation - Scoping and safety target - by H.A.P. Blom
[D7.1b]	Hazard Identification and Initial Hazard Analysis of A^3 ConOps based operation by H.A.P. Blom, G.J. Bakker, M.B. Klompstra and F.J.L. Bussink
[D7.2a]	Review of risk assessment status for air traffic. Editors: H.A.P. Blom, J. Krystul, P. Lezaud and M.B. Klompstra
[D7.2b]	Trans-dimensional simulation for rare-events estimation on stochastic hybrid systems by N. Kantas and J.M. Maciejowski
[D7.2d]	Periodic Boundary Condition in Simulating Large Scale Airborne Self Separation Airspace by A. Goswami, G.J. Bakker, H.A.P. Blom
[D7.2e]	Rare event estimation for a large scale stochastic hybrid system with air traffic application - IPS extension to large hybrid systems - by H.A.P. Blom, G.J. Bakker and J. Krystul
[D7.2f]	Sensitivity analysis in Monte Carlo simulation based rare event estimation by M.B. Klompstra, G.J. Bakker, H.A.P. Blom
[D7.2g]	Final Report on Monte Carlo speed-up studies, by H.A.P. Blom and G.J. Bakker
[D7.4]	Final report on accident risk assessment of the A^3 operation, by H.A.P. Blom and G.J. Bakker
[D8.1]	Integration of mathematical results, Eds: L. Biescas and H. Blom
[D8.2]	Flow Management in Self-Separation Airspace, by R. Verbeek
[D8.3]	A^3 equipped aircraft within SESAR's concept of operations, by S. Peces and L. Biescas
[D8.4]	Non-airborne requirements in support of A^3 equipped aircraft, by V. Bordón and J. Bueno
[D8.5]	Identification of Potential Directions for Further refinement of the A3 ConOps by V. Bordón
[D9.1]	Operational Services and Environment Description (OSED) of Airborne Self-Separation Procedure (SSEP) by P. Cásek, E. Gelnarová
[D9.2]	ED78a/DO-264 based Operational Hazard Assessment (OHA) and Allocation of Safety Objectives and Requirements (ASOR) of Airborne Self-Separation Procedure by E. Gelnarová, J. Jonák

[D9.3]	Operational Performance Assessment (OPA) by P. Cásek, P. Mejzlík
[D9.4]	Airborne System Design Requirements of Airborne Self-Separation Procedure, by P. Casek and I. Romani de Oliveira
[D10.1]	Overall validation strategy and plan, by H. Blom

Appendix A Scientific papers

A.1 Journal publications for Transportation/Aerospace/ATM/civil aviation oriented audience

Id. no.	PAPERS - PUBLIC	WP no.	Respons. Partner	Date	Version
P2.2	Luuk, K., Luuk, A., and Aluoja, A. (2009). Predicting Professional Success of ATC Personnel from Their Personality Profile at Admission to *ab Initio* Training. International Journal of Aviation Psychology, Vol 19, issue 3, 235-251.	2.2	UTartu	July 2009	Final, published in the IJAP
P5.9	E. Crisostomi, A. Lecchini-Visintini and J.M. Maciejowski, "Combining Monte Carlo and worst-case methods for trajectory prediction in air traffic control: a case study". Published in Automatic Control in Aerospace (online journal). vol.2, no.1, June 2009. (http://www.aerospace.unibo.it/, ISSN 1974-5168.)	5.2	UCAM/ULES	Jun 2009	Final
P7.6	H.A.P. Blom, B. Klein Obbink and G.J. Bakker, Simulated collision risk of an uncoordinated airborne self separation concept of operation, ATC Quarterly, March 2009.	7	NLR	Dec 2008	Published March 2009
P6.1	"Assessing the Economic and Institutional Impacts Resulting from the Introduction of a Self Separation Operational Concept in Air Traffic Management" This paper was published in the Proceedings (CD-ROM) of the 90th Annual Meeting of the Transportation Research Board (23-27 January 2011 at Washington D.C.). The paper was also accepted for publication in the Transportation Research Record: Journal of the Transportation Research Board. This paper was based on the work performed in WP6 of iFly project.	6	AUEB	15/03/2011	Accepted for Publication in TRR: Journal of the Transportatio n Research Board
P9.1	Silvie Luisa Brázdilová, Petr Cásek and Jan Kubalčík: Air Traffic Complexity for a Distributed ATM, submitted to the Journal of Aerospace Engineering, Proceedings of the IMechE Part G.	9.3	HNWL	27.4.2010 – submitted, June 2011, published, Vol. 225, issue 6	
P10.6	I.R. De Oliveira, L.F. Vismari, P.S. Cugnasca, J.B. Camargo Jr., G.J. Bakker and H.A.P. Blom, A case study of advanced airborne technology impacting air traffic management, Eds: Li Weigang et al., Computational models, software engineering and advanced technologies in air transportation, Engineering Science Reference, Hershey, 2010, pp. 177-214	10	NLR	Oct 2009	Preprint

A.2 Journal publications for mathematical oriented audience

Id. no.	PAPERS - PUBLIC	WP no.	Respons. Partner	Date	Version
P3.2	Application of Reachability Analysis for Stochastic Hybrid Systems to Aircraft Conflict Prediction by Maria Prandini and Jianghai Hu. Published in the IEEE Transactions on Automatic Control, vol. 54 (4), pp. 913-917, 2009	3.2	PoliMi	April 2009	Final
P3.14	A probabilistic measure of air traffic complexity in three-dimensional airspace by M. Prandini, V. Putta, J. Hu. Published in the International Journal of Adaptive Control and Signal Processing, special issue on Air Traffic Management: Challenges and opportunities for advanced control, vol. 24(10): 813–829, 2010	3.2	PoliMi	April 2010	Final
P3.17	Toward air traffic complexity assessment in new generation air traffic management systems by M. Prandini, L. Piroddi, S. Puechmorel, S.L. Brázdilová Published in the IEEE Transactions on Intelligent Transportation Systems, Vol. 12, No. 3, pp. 809-818.	3.1	PoliMi, ENAC, HNWL	January 2011	Final
P4.4	A.A. Julius, A. D'Innocenzo, G.J. Pappas, M.D. Di Benedetto (2007). Approximate equivalence and synchronization of metric transition systems. SCL = Systems and Control Letters	4	AQUI	September 2008	SCL, 58(2): 94-101, Feb 2009
P4.5	E. De Santis, Invariant dual cones for hybrid systems SCL = Systems and Control Letters	4	AQUI	September 2008	SLC, 57(12): 971-977, Dec 2008
P4.7	E. De Santis, M.D. Di Benedetto, G. Pola, A structural approach to detectability for a class of hybrid systems.	4	AQUI	May 2009	Automatica, 45(5):1202-1206, May 2009
P4.8	P. Caravani, E. De Santis, Observer based stabilization of linear switching systems IJRNC = International Journal of Robust and Nonlinear Control	5	AQUI	September 2008	In: IJRNC, 19(14):1541-1563, Sep 2009
P4.10	M.D. Di Benedetto, S. Di Gennaro, A. D'Innocenzo, Discrete State Observability of Hybrid Systems. IJRNC = International Journal of Robust and Nonlinear Control	4	AQUI	September 2009	IJRNC, 19(14): 1564-1580 Sept. 2009
P4.11	M.D. Di Benedetto, S. Di Gennaro, A. D'Innocenzo, Verification of Hybrid Automata Diagnosability. IEEE TAC = IEEE Transactions on Automatic Control	4	AQUI	October 2010	IEEE TAC. To appear
P4.12	A. Abate, A. D'Innocenzo, M.D. Di Benedetto, S. Sastry. Understanding Deadlock and Livelock Behaviors in Hybrid Control Systems.	4	AQUI	May 2009	NAHS: 3(2):150-162

	NAHS = Nonlinear Analysis: Hybrid System				May 2009 Available on website
P4.17	E. De Santis, M.D. Di Benedetto, G. Pola, A complexity reduction approach to detectability of switching systems IJC = International Journal of Control	4	AQUI	September 2010	IJC, 83(9): 1930-1938, Sept. 2010
P5.4	N. Kantas, J.M. Maciejowski and A. Lecchini-Visintini, "*Sequential Monte Carlo for Model Predictive Control*". Appeared in proceedings of the 2008 International Workshop on Assessment and Future Directions of Nonlinear Model Predictive Control. To appear in : L. Magni, D.M. Raimondo and F. Allgower (eds), Nonlinear Model Predictive Control: Towards New Challenging Applications, Lecture Notes in Control and Information Sciences, vol.384, Springer, 2009.	5.3	UCAM/ULES	Sep 2008	Final available at the iFly website
P5.17	I. Lymperopoulos and J. Lygeros, "Improved Multi-Aircraft Ground Trajectory Prediction for Air Traffic Control". Appeared in the March 2010 issue of the AIAA Journal of Guidance, Control, and Dynamics, vol.33 no.2 pp. 347-362.	5.3	ETHZ	Jan 2010	Final
P5.18	I. Lymperopoulos and J. Lygeros, "Sequential Monte Carlo methods for multi-aircraft trajectory prediction in Air Traffic Management". Published in the International Journal of Adaptive Control and Signal Processing, Vol. 24, No. 10, pp. 830-849.	5.3	ETHZ	Oct 2010	Final
P5.23	N. Kantas, A. Lecchini-Visintini and J. Maciejowski, "Simulation Based Optimal Design of Aircraft Trajectories for Air Traffic Management". Published in the International Journal on Adaptive Control and Signal Processing, Vol. 24, No. 10, pp. 882-899.	WP5 .3	UCAM/ULES	Oct 2010	Final
P5.24	A. Lecchini-Visintini, J. Lygeros and J. Maciejowski, "Stochastic optimization on continuous domains with finite-time guarantees by Markov chain Monte Carlo methods". Published in the IEEE Transactions on Automatic Control, Vol. 55, No. 12, pp. 2858-2863.	5.3	UCAM/ULES-ETHZ	Dec 2010	Final
P5.26	G. Roussos, D.V. Dimarogonas and K.J. Kyriakopoulos, "3D Navigation and Collision Avoidance for Nonholonomic aircraft-like vehicles". Published in the International Journal of Adaptive Control and Signal Processing, Vol. 24, No. 10, pp. 900-920.	5.3	NTUA	Oct 2010	Final
P5.30	J. Lygeros and M. Prandini, "Stochastic hybrid systems: a powerful framework for complex, large scale applications". Published in the European Journal of Control 2010, vol. 16, No. 6, pp. 583-594.	5.3	ETHZ/PoliMi	Nov 2010	Final
P5.31	A. Abate, J.P. Katoen, J. Lygeros and M. Prandini, "Approximate model checking of stochastic hybrid	5.3	ETHZ/PoliMi	Nov 2010	Final

	systems”. Published in the European Journal of Control 2010, vol. 16, No. 6, pp. 624-641.				
P5.37	A. Lecchini-Visintini and J. Lygeros. Editorial for the Special Issue "Air Traffic Management: Challenges and opportunities for advanced Control" Int. Journal on Adaptive Control and Signal Processing, 24(10):811-812, 2010.	5.3	ETHZ/ULES	Oct 2010	
P5.40	G. Roussos, and K. J. Kyriakopoulos, “Decentralised Navigation and Conflict Avoidance for Aircraft in 3D Space”. Accepted for publication in the IEEE Transactions on Control Systems and Technology.	5.3	NTUA	August 2011	
P5.41	G. Roussos, K. J. Kyriakopoulos, “Decentralized and prioritized Navigation and Collision Avoidance for Multiple Mobile Robots”. [Longer version of P5.27]. Accepted for publication in a Springer Tracts in Advanced Robotics (STAR) series volume.	5.3	NTUA	June 2011	
P7.12	Sampling-per-mode rare event simulation for switching diffusions, by Jaroslav Krystul, Francois Le Gland and Pascal Lezaud The preprint version is available at http://hal.inria.fr/inria-00550716/en/	7	TWEN/INRIA /DSNA	Dec 2010	Accepted paper for publication in journal “Stochastic Processes and their Applications” Preprint available at website

A.3 Book chapters

Id. no.	PAPERS - PUBLIC	WP no.	Respons. Partner	Date	Version
P7.4	Book chapter "Splitting Techniques" by Pierre L'Ecuyer, Pascal Lezaud, Francois Le Gland and Bruno Tuffin. Appeared in the monograph "Rare Event Simulation using Monte Carlo Methods" edited by Gerardo Rubino and Bruno Tuffin and to be published by John Wiley & Sons (expected publication date March 2009).	7	INRIA & DSNA	Sep 2008	Book has been published March 2009
P7.5	Book chapter "Rare event estimation for a large scale stochastic hybrid system with air traffic application" by Henk Blom, Bert Bakker and Jaroslav Krystul. Appeared in the monograph "Rare Event Simulation using Monte Carlo Methods" edited by Gerardo Rubino and Bruno Tuffin and to be published by John Wiley & Sons.	7	NLR & TWEN	Sep 2008	Book has been published March 2009
P7.10	Hybrid state Petri nets which have the analysis power of stochastic hybrid systems and the formal verification power of automata by M.H.C. Everdij and H.A.P. Blom. In: Petri Nets Applications, Ed: P. Pawlewski, Chapter 12, ISBN: 978-953-307-047-6, Publisher: INTECH, Publishing date: February 2010	7	NLR	Feb 2010	Book has been published Feb 2010
P10.6	I.R. De Oliveira, L.F. Vismari, P.S. Cugnasca, J.B. Camargo Jr., G.J. Bakker and H.A.P. Blom, A case study of advanced airborne technology impacting air traffic management, Eds: Li Weigang et al., Computational models, software engineering and advanced technologies in air transportation, Engineering Science Reference, Hershey, 2010, pp. 177-214	10	NLR	Oct 2009	Preprint

A.4 Conferences with civil aviation oriented audience

Id. no.	PAPERS - PUBLIC	WP no.	Respons. Partner	Date	Version

AIAA ATIO 2007 and 2009

P10.1	Safety risk simulation of an airborne self separation concept of operation, H. Blom , B. Klein Obbink, G. Bakker, Proc. AIAA ATIO Conference 2007, Belfast, Ireland	10	NLR	18-20 September 2007	Preprint of paper at the iFLY website
P10.5	E. Itoh, M. Everdij, B. Bakker and H. Blom, Speed control for airborne separation assistance in continuous descent arrivals, Proc. 9th AIAA ATIO conference, 21-23 September 2009, Hilton Head, South Carolina, USA, paper number AIAA 2009-6909	10	NLR	Sep 2009	Preprint Available at iFly website

APISAT 2008

P10.4	E. Itoh, P.J. van der Geest and H. Blom, Improved airborne spacing control for trailing aircraft, Proc. 2009 Asia-Pacific International Symposium on Aerospace Technology (APISAT 2009)	10	NLR	Nov 2009	Preprint

ASAS-GN 2008

P1.2	iFly: ASAS Self Separation – Airborne Perspective by Petr Cásek and Rosa Weber Presentation at ASAS-GN workshop, 12-13 November 2008 in Rome	1	Honeywell	Nov 2008	Slides available on webiste Presented at ASAS-GN 2008

ATOS 2010

P5.25	Petr Cásek and Silvie Luisa Brázdilová: Priority Rules in a Distributed ATM, 1st International Air Transport and Operations Symposium (ATOS 2010), Delft.	5	HNWL	14.4.2010	Final available at the iFly website

ATM Seminar 2009

P3.7	Distributed Trajectory Flexibility preservation helps mitigate traffic complexity by H. Idris, D. Wing, D. Delahaye, S. Puechmorel Presented at ATM Seminar 2009	3.2	ENAC	29 June - 2 July 2009	Final

CEAS 2009

P3.10	Airspace Complexity for Airborne Self Separation by S.L. Brázdilová, P. Cásek, and J. Kubalčík. Presented at the CEAS 2009 European Air and Space Conference, 26-29 Oct 2009, Manchester, UK	3.2	HNWL	October 2009	Final Available on website

EAAP 2008

P2.1	Claudia Keinrath, Fleur Pouw, John Wise, Aavo Luuk, Amel Sedaoui, and Vincent Gauthereau (2008). iFly Human Factors in Autonomous Aircraft Operations (Airborne Self Separation Environment). *Proceedings of the 28th Conference of the European Association for Aviation Psychology, 27-31 October 2008, Valencia, Spain*, *290-295.*	2	HNWL	July 2008	Final Paper presented on the 28th EAAP Available on website

EIWAC 2009

P3.9	New trends in air traffic complexity by S. Puechmorel and D. Delahaye Presented at ENRI International Workshop on ATM/CNS (EIWAC 2009), Tokyo, Japan, March 5 and 6, 2009	3.2	ENAC	March 2009	Final Available on website

Eurocontrol Safety Seminar 2007

P7.2	Simulated safety risk of airborne self separation, H. Blom , B. Klein Obbink, G. Bakker, Proc. Eurocontrol Safety Seminar 2007, Rome	10	NLR	24-26 October 2007	Available at iFly website

ICRAT 2008

P4.3	M. Colageo, A. Di Francesco, Hybrid System Framework for the Safety Modelling of the In Trail Procedure.	4 10	AQUI	April 2008	ICRAT08 Available on web site

ICRAT 2010

P4.15	Maria D. Di Benedetto, G. Di Matteo and A. D'Innocenzo, Stochastic validation of ATM procedures by abstraction algorithms.	4	AQUI	March 2010	ICRAT10
P5.19	I. Lymperopoulos, G. Chaloulos and J. Lygeros, “An Advanced Particle Filtering Algorithm for Improving Conflict Detection in Air Traffic Control”. Presented at the 4th International Conference on Research in Air Transportation (ICRAT2010).	5.3	ETHZ	Jun 2010	Final available at the iFly website
P5.32	A new method for generating optimal conflict free 4D trajectory by N. Dougui, D. Delahaye, S. Puechmorel and M. Mongeau ICRAT 2010	WP5	ENAC	June 2010	Final available at the iFly website

INO workshop 2007

P5.5	E. Crisostomi, A. Lecchini-Visintini and J.M. Maciejowski, "Combining Monte Carlo and worst-case methods for trajectory prediction in air traffic control: a case study". Paper 23, EUROCONTROL Innovative Research Workshop, EUROCONTROL Experimental Centre, Bretigny sur Orge	5.2	UCAM/ULES	Dec 2007	Final available at the iFly website

INO workshop 2008

P1.1	P. Cásek, and C. Keinrath “Airborne System for Self Separation in a Trajectory-Based Airspace” Presentation of paper at 7th Eurocontrol Innovative ATM Research Workshop, EEC Bretigny, December	1	Honeywell	Nov 2008	Paper available on website Presented at

	2008				INO workshop
P4.9	M.D Di Benedetto, A. D'Innocenzo, A.Petriccone, Automatic Verification of Temporal Properties of Air Traffic Management Procedures Using Hybrid Systems.	4	AQUI	November 2008	INO 2008 Available on website
P7.3	Simulated collision risk of an uncoordinated airborne self separation concept of operation by Henk A.P. Blom , Bart Klein Obbink, G.J. (Bert) Bakker	7	NLR	Nov 2008	Version for INO 2008 Available at iFly website

INO workshop 2009

P4.14	E. De Santis, M.D. Di Benedetto, A. Petriccone, G.Pola, A Compositional Hybrid System Approach to the Analysis of Air Traffic Management Systems.	4	AQUI	December 2009	INO 2009 Available on website
P5.16	G. Chaloulos, G. Roussos, J. Lygeros and K. J. Kyriakopoulos, "Mid and Short Term Conflict Resolution in Autonomous Aircraft Operations". Presented at the 8th Innovative Research Workshop & Exhibition (INO2009).	5.3	ETHZ-NTUA	Dec 2009	Final available at the iFly website
P8.1	Comparison of pairwise priority-based resolution schemes through fast-time simulation by Richard Irvine	8	EEC	September 2009	Final INO 2009 Preprint on iFly website

INO workshop 2010

P3.18	Air traffic complexity in advanced automated Air Traffic Management systems by M. Prandini, V. Putta, J. Hu. Presented at INO2010	3.2	PoliMi	Sept 2010	Final Available on website

ISSC 2008

P10.3	Safe, airborne self-separation operators in tomorrow's airpsace? by R.Weber, H.A.P. Blom, P. Cásek Paper presented at the ISSC 2008	10			Available at iFly website

SESAR Innovation days 2011

P7.13	Safety of advanced airborne self separation under very high en-route traffic demand by Henk Blom and Bert Bakker	7	NLR	Sep 2011	Accepted for presentation at the SESAR Innovation Days 2011

TRB 2011 (Transportation Research Board)
(also reported in Appendix B.1)

P6.1	"Assessing the Economic and Institutional Impacts Resulting from the Introduction of a Self Separation Operational Concept in Air Traffic Management" This paper was published in the Proceedings (CD-ROM) of the 90th Annual Meeting of the	6	AUEB	15/03/2011	Accepted for Publication in TRR: Journal of the Transportation Research Board

	Transportation Research Board (23-27 January 2011 at Washington D.C.). The paper was also accepted for publication in the Transportation Research Record: Journal of the Transportation Research Board. This paper was based on the work performed in WP6 of iFly project.				

A.5 Conferences with mathematical oriented audience

Id. no.	PAPERS - PUBLIC	WP no.	Respons. Partner	Date	Version
ACC 2008					
P5.2	Giannis P. Roussos, Dimos V. Dimarogonas and Kostas J. Kyriakopoulos, *"3D Navigation and Collision Avoidance for a Non-Holonomic Vehicle".* Presented at the American Control Conference 2008.	5.2	NTUA	Jun 2008	Final available at the iFly website
ACC2010					
P5.20	G. Roussos and K. J. Kyriakopoulos, "Decentralised Navigation and Collision Avoidance for Aircraft in 3D Space". Presented at the 2010 American Control Conference (ACC2010).	5.3	NTUA	Jun 2010	Final available at the iFly website
P5.21	G. Chaloulos, P. Hokayem and J. Lygeros, "Distributed Hierarchical MPC for Conflict Resolution in Air Traffic Control". Presented at the 2010 American Control Conference (ACC2010).	5.3	ETHZ	Jun 2010	Final available at the iFly website
ACC2011					
P7.11	Air traffic complexity and the interacting particle system method: An integrated approach for collision risk estimation by Maria Prandini, Henk A.P. Blom, Bert G.J. Bakker. Accepted paper for ACC 2011	7	PoliMi	April 2011	Presented at ACC 2011
AIAA GNC 2008					
P5.3	Georgios Chaloulos, Giannis P. Roussos, John Lygeros, Kostas J. Kyriakopoulos, *"Ground Assisted Conflict Resolution in Self-Separation Airspace"*. Presented at the 2008 AIAA Guidance, Navigation, and Control Conference.	5.2	ETHZ-NTUA	Aug 2008	Final available at the iFly website
AIAA GNC 2009					
P3.8	Describing air traffic flows using stochastic programming by K. Lee, D. Delahaye, S. Puechmorel. Presented at AIAA GNC 2009	3.2	ENAC	August 2009	Final
CDC 2007					
P7.1	Probabilistic Reachability Analysis for Large Scale Stochastic Hybrid Systems, H. Blom, G. Bakker and J. Krystul, IEEE Conference on Decision and Control 2007, New Orleans.	7	NLR & TWEN	12-14 December 2007	Preprint available at the iFLY website
CDC 2008					
P3.3	Application of Reachability Analysis for Stochastic Hybrid Systems to Aircraft Conflict Prediction by Maria Prandini and Jianghai Hu. Presented at CDC 2008.	3.2	PoliMi	Sept 2008	Preprint for CDC 2008 Available on website

P3.4	An approximate dynamic programming approach to probabilistic reachability for stochastic hybrid systems by Alessandro Abate, Maria Prandini, John Lygeros, and Shankar Sastry. Presented at CDC 2008.	3.2	PoliMi	Sept 2008	Preprint for CDC 2008 Available on website
P4.6	M.D. Di Benedetto, S. Di Gennaro, A. D'Innocenzo, Diagnosability of hybrid automata with measurement uncertainty	4	AQUI	December 2008	CDC 08
P5.6	G. Roussos, G. Chaloulos, K. Kyriakopoulos, J. Lygeros, "*Control of Multiple Non-Holonomic Air Vehicles under Wind Uncertainty Using Model Predictive Control and Decentralized Navigation Functions*". Presented at the 2008 IEEE Conference on Decision and Control.	5.3	ETHZ-NTUA	Dec 2008	Final available at the iFly website
P5.7	A. Oikonomopoulos, S. Loizou, K. Kyriakopoulos, "*Hybrid Control of a Constrained Velocity Unicycle with Local Sensing*". Presented at the 2008 IEEE Conference on Decision and Control.	5.3	NTUA	Dec 2008	Final available at the iFly website
P5.8	A. Lecchini-Visintini, J. Lygeros, J.M. Maciejowski, "*On the Approximate Domain Optimization of Deterministic and Expected Value Criteria*". Presented at the 2008 IEEE Conference on Decision and Control.	5.3	UCAM/ULES-ETHZ	Dec 2008	Final available at the iFly website

CDC 2009

P3.11	A probabilistic approach to air traffic complexity evaluation by Maria Prandini and Jianghai Hu. Presented at CDC 09.	3.2	PoliMi	Sept 2009	Final Available on website
P3.12	Dynamical Systems Complexity with a view towards air traffic management applications by S. Puechmorel and D. Delahaye. Accepted at CDC 09.	3.2	ENAC	Sept 2009	Final
P4.13	P. Caravani, E. De Santis, On observer based stabilization of networked systems.	4	AQUI	December 2009	CDC09 Available on website
P5.15	G. Roussos and K. J. Kyriakopoulos, "Towards Constant Velocity Navigation and Collision Avoidance for Autonomous Nonholonomic Aircraft-like Vehicles". Presented at the IEEE Conference on Decision and Control 2009.	5.3	NTUA	Dec 2009	Final available at the iFly website

CDC 2010

P3.15	A geometric approach to air traffic complexity evaluation for strategic trajectory management by L. Piroddi and M. Prandini Presented at CDC 2010	3.2	PoliMi	Sept 2010	Final Available on website
P3.16	Air Traffic Complexity Based on Dynamical Systems by D. Delahaye and S. Puechmorel Presented at CDC 2010	3.2	ENAC	Sept 2010	Final
P4.16	A. Petriccone, G. Pola, M.D. Di Benedetto, E. De Santis, A Complexity Reduction Approach to the Detection of Safety Critical Situations in Air Traffic Management Systems	4	AQUI	July 2010	CDC10
P5.28	G. Roussos and K.J. Kyriakopoulos, "Completely	5.3	NTUA	Dec 2010	Final

	Decentralised Navigation of Multiple Unicycle Agents with Prioritization and Fault Tolerance". Presented at the 49th IEEE Conference on Decision and Control 2010 (CDC2010).				available at the iFly website
P5.29	E. Siva, J. M. Maciejowski and K.V. Ling, "Robust Multiplexed Model Predictive Control for Agent-based Conflict Resolution". Presented at the 49th IEEE Conference on Decision Control (CDC2010).	5.3	UCAM	Dec 2010	Final

CDC 2011

P5.39	G. Roussos, and K. J. Kyriakopoulos, "Completely Decentralised Navigation Functions for Aircraft Conflict Resolution in 3D Space". Accepted for presentation at the 50th IEEE Conference on Decision Control (CDC2011).	5.3	NTUA	July 2011	

DARS 2010

P5.27	G. Roussos, K. J. Kyriakopoulos, "Decentralised and prioritized Navigation and Collision Avoidance for Multiple Mobile Robots". Presented at the 10th International Symposium on Distributed Autonomous Robotics Systems, Lausanne, Switzerland.	5.3	NTUA	Nov 2010	Final available at the iFly website

EPTCS 2010

P7.9	Bisimulation relations between automata, stochastic differential equations and Petri Nets, M.H.C. Everdij and Henk A.P. Blom, Electronic Proceedings in Theoretical Computer Science (EPTCS), March 2010	7	NLR	March 2010	Proceedings March 2010

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P5.10	Stability of Model Predictive Control Using Markov Chain Monte Carlo Optimisation, by E. Siva, P.J. Goulart, J.M. Maciejowski, and N. Kantas. Presented at the ECC09.	5.3	UCAM/ULES	Aug 2009	Final available at the iFly website
P5.12	G. Roussos, D. Dimarogonas, K. Kyriakopoulos, "*Distributed 3D Navigation and Collision Avoidance for Multiple Nonholonomic Agents*". Presented by G. Roussos on 25/8/2009 at the 2009 European Control Conference (ECC2009).	5.3	NTUA	Aug 2009	Final available at the iFly website
P5.14	M. Prandini, L. Piroddi, J. Lygeros "A two-step approach to aircraft conflict resolution combining optimal deterministic design with Monte Carlo stochastic optimization". Presented at the 2009 European Control Conference.	5.3	PoliMi-ETHZ	Aug 2009	Final available at the iFly website

HCSS2008

P4.2	A. Abate, A. D'Innocenzo, M.D. Di Benedetto, S. Sastry. Markov Set-Chains as abstractions of Stochastic Hybrid Systems.	4	AQUI	March 2008	HSCC 2008 Available on web site

HSCC2011

P5.34	S. Summers, M. Kamgarpour, C. Tomlin, and J. Lygeros, "A stochastic reach-avoid problem with	5.3	ETHZ	April 2011	

	random obstacles". Presented at the Hybrid Systems: Computation and Control 2011.				

ICRA 2009

P5.11	A. Oikonomopoulos, S. Loizou, K. Kyriakopoulos, "*Coordination of Multiple Non-Holonomic Agents with Input Constraints*". Presented at the 2009 IEEE International Conference on Robotics and Automation (ICRA09).	5.3	NTUA	May 2009	Final available at the iFly website

IEEE MED 2009

P7.7	Stochastic reachability as an exit problem, by M.L. Bujorianu and H.A.P. Blom, Proceedings of the 17th Mediterranean Conference on Control and Automation, IEEE MED'09, June 24-26, 2009 in Thessaloniki, Greece.	7	NLR	June 2009	Published in Proc IEEE MED 2009 Available at iFly website

IFAC Symposium on System Identification 2009

P7.8	N. Kantas, A. Doucet, S.S. Singh and J.M. Maciejowski, "An overview of Monte Carlo methods for parameter estimation on general state space models", has been presented at the IFAC Symposium on System Identification}, St.Malo, France, July 2009.	7	UCAM	March 2009	Preprint Available at iFly website

IFAC World Congress 2011

P4.18	G. Pola, M.D. Di Benedetto and E. De Santis, A Compositional Approach to Bisimulation of Arenas of Finite State Machines	4	AQUI	March 2011	IFAC WC 2011
P5.33	M. Kamgarpour, M. Soler, C.J. Tomlin, A. Olivares, and J. Lygeros, "Hybrid Optimal Control for Aircraft Trajectory Design with a Variable Sequence of Modes". Presented at the IFAC World Congress 2011.	5.3	ETHZ	August 2011	
P5.35	G. Chaloulos, P. Hokayem, and J. Lygeros, "Hierarchical MPC with Priorities for Conflict Resolution in Air Traffic Control". Presented at the IFAC World Congress 2011.	5.3	ETHZ	August 2011	
P5.36	E. Siva and J.M. Maciejowski, "Robust Multiplexed MPC for Distributed Multi-Agent Systems". Presented at the 18th IFAC World Congress 2011.	5.3	UCAM	March 2011	
P5.38	K.V. Ling, J.M. Maciejowski, J. Guo and E. Siva, "Channel-hopping model predictive control". Presented at the IFAC World Congress 2011.	5.3	UCAM	August 2011	

MTNS2010

P5.22	Z. Yang, N. Kantas, A. Lecchini Visintini and J M Maciejowski, "Stable Markov Decision Processes Using Simulation Based Predictive Control". Presented at the 2010 Symposium on Mathematical Theory of Networks and Systems (MTNS2010).	5.3	UCAM/ULES	Jul 2010	Final

NIPS 2007(also poster presentation)

P5.1	A. Lecchini-Visintini, J. Lygeros and J. Maciejowski, "Simulated Annealing: Rigorous finite-time guarantees for optimization on continuous domains". Accepted for a Poster Spotlight presentation at Advances in Neural Information Processing Systems (NIPS) 20, MIT Press. Preprint: arXiv:0709.2989.	5.2	UCAM/ULES-ETHZ	Nov 2007	Final available at the iFly website

SIAM CT 2009

P3.5	Complexity in Air Traffic Management by S. Puechmorel, D. Delahaye and N. Dougui Presented at SIAM CT 2009	3.2	ENAC	July 2009	Final
P3.6	A New Algorithm for Automated Aircraft Conflict Resolution by S. Puechmorel, D. Delahaye and N. Dougui Presented at SIAM CT 2009	3.2	ENAC	July 2009	Final

SSSC 2007

P4.1	E. De Santis, M.D. Di Benedetto, Observer design for discrete-time linear switching systems. *3rd IFAC Symposium on System, Structure and Control, October 17-19, 2007, Foz de Iguassu, Brazil*	4	AQUI	October 2007	SSSC07 Available on web site

A.6 (Masters / PhD) Thesis

P3.1	Master thesis "Methods for reachability analysis of stochastic hybrid systems" Student: D. Schito Advisor: M. Prandini Politecnico di Milano (in Italian)	3.2	Polimi	Dec 2007	Final
P3.13	Laurea thesis "Analysis of a probabilistic approach to air traffic complexity evaluation" A. Ornago and R. Roselli (in Italian)	3.2	PoliMi	Sept 2009	Final
P5.13	A. Lauriello, Master thesis "Conflict resolution in air traffic control", Advisor: M. Prandini, Politecnico di Milano (in Italian)	5.2	PoliMi		Final

A.7 Abbreviations

ACC	*American Control Conference*
ACC2011	*American Control Conference 2011, San Francisco, California, USA, June 29 - July 1, 2011*
AIAA	*American Institute of Aeronautics and Astronautics*
AIAA GNC 2009	*AIAA Guidance, Navigation and Control (GNC) Conference 2009* *Chicago, Illinois, USA, August 10-13, 2009*
ASAS-GN 2008	*Towards ASAS-GN Seminar 2008: "Towards an ASAS-Global Network: Next Steps!"* *Rome, Italy, November 12-13 November, 2008*
ATM Seminar 2009	*8th USA/Europe Air Traffic Management Research & Development Seminar Napa, California, USA, June 29-July 2, 2009*
CDC	*Conference on Decision Control*
CDC 2008	*47th IEEE Conference on Decision and Control, Cancun, Mexico, December 9-11, 2008*
CDC 2009	*Joint 48th IEEE Conference on Decision and Control and 28th Chinese Control Conference, December 16-18, 2009, Shanghai, P.R. China*
CDC 2010	*49th IEEE Conference on Decision and Control, Atlanta, Georgia, USA, December 15-17, 2010*
CEAS 2009	*European Air and Space Conference, 26-29 Oct 2009, Manchester, UK*
EAAP	*28th EAAP Conference, European Association for Aviation Psychology (EAAP), 27-31 Oct 2008, Valencia, Spain*
ECC	*European Control Conference*
HSCC08	*Hybrid Systems: Computation and Control 2008, Lecture Notes in Computer Science*
ICRAT	*International Conference on Research in Air Transportation*
ICRAT08	*3rd International Conference on Research in Air Transportation, June 1-4, 2008, Fairfax, Virginia, USA*
ICRAT10	*4th International Conference on Research in Air Transportation, June, 2010, Budapest, Hungary.*
IEEE	*Institute of Electrical & Electronics Engineers*
IEEE MED 2009	*17th Mediterranean Conference on Control and Automation, IEEE MED'09* *Thessaloniki, Greece, June 24-26, 2009*
IEEE TAC	*IEEE Transactions on Automatic Control*
IFAC	*18th IFAC World Congress, Milan, Italy, 2011*
IJAP	*International Journal of Aviation Psychology*
IJC	*International Journal of Control*
IJRNC	*International Journal of Robust and Nonlinear Control*
INO	*EUROCONTROL Innovative ATM Research Workshop & Exhibition*
INO 2008 / *INO Workshop*	*7th EUROCONTROL Innovative Research Workshop and Exhibition, At the EUROCONTROL Experimental Centre, December 2nd-4th 2008.*
INO 2009	*8th Innovative Research Workshop & Exhibition, EUROCONTROL Experimental Center, Brétigny-sur-Orge, France, 1-3 Dec. 2009.*
INO 2010	*9th Innovative Research Workshop & Exhibition, EUROCONTROL Experimental Center, Brétigny-sur-Orge, France, 7-9 Dec. 2010*
ISSC 2008	*26th International System Safety Conference, Vancouver, B.C., Canada, August 25-29, 2008*
MTNS	*Mathematical Theory of Networks and Systems*
NAHS	*Nonlinear Analysis: Hybrid System*
SCL	*Systems and Control Letters*
SIAM CT 2009	*Siam Conference on Control Theory, July 6-8, 2009, Denver, Colorado.*
SSSC07	*3rd IFAC Symposium on System, Structure and Control, October 17-19, 2007, Foz de Iguassu, Brazil*
TRB 90th Annual Meeting	*90th Annual Meeting of the Transportation Research Board (23-27 January 2011 at Washington D.C.*

Appendix B Acronyms

Acronym	Definition
A^3	Autonomous Aircraft Advanced
ACAS	Airborne Collision Avoidance System
ADS	Automatic Dependant Surveillance
ADS-B	Automatic Dependant Surveillance - Broadcast
AFR	Autonomous Flight Rules
AMFF	Autonomous Mediterranean Free Flight
ANSP	Air Navigation Services Provider
AOC	Airline Operational Centre
AOT	One At-a Time
AP23	Action Plan 23
ASAS	Airborne Separation Assistance System
ASEP	Airborne Separation
ASEP-ITP	Airborne Separation-In Trail Procedure
ASOR	Allocation of Safety Objectives and Requirements
ASSTAR	Advanced Safe Separation Technologies and Algorithm(s)
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Traffic Services
ATSA	Airborne Traffic Situational Awareness
ATSA-ITP	Airborne Traffic Situational Awareness In-Trail Procedure
CARE-ASAS	Co-operative Action of R&D in Eurocontrol on Airborne Separation Assurance Systems
CBA	Cost Benefit Analysis
CD	Conflict Detection
CD&R	Conflict Detection and Resolution
CDM	Collaborative Decision Making
CFM	Central Flow Management
CNS	Communication, Navigation and Surveillance
ConOps	Concept of Operations
CPDLC	Controller to Pilot Data Link Communication
CR	Conflict Resolution
EMOSIA	European Model for Strategic ATM Investment Analysis
E-OCVM	European Operational Concept Validation Methodology
ESARR	Eurocontrol Safety Regulatory Requirement
FAA	Federal Aviation Administration
FMS	Flight Management System
FOC	Flight Operations Centre
GNSS	Global Navigation Surveillance System
HHIPS	Hierarchical Hybrid IPS
HMI	Human Machine Interface
HYBRIDGE	Distributed Control and Stochastic Analysis of Hybrid Systems Supporting Safety Critical Real-Time Systems Design (EC 5th Framework Programme)

Acronym	Definition
ICAO	International Civil Aircraft Association
IFR	Instrumental Flight Rules
IPS	Interacting Particle System
LoC	Lines of Change
LoS	Loss of Separation
MCMC	Monte Carlo Markov Chain
MILP	Mixed Integer Linear Program
MPC	Model Predictive Control
MTR	Mid Term Review
NF	Navigation Functions
NM	Nautical Mile
OHA	Operational Hazard Assessment
OPA	Operational Performance Assessment
OSA	Operational Safety Assessment
OSED	Operational Services and Environment Description
PBC	Periodic Boundary Condition
RBT	Reference Business Trajectory
RESET	Reduced Separation Minima
RFG	Requirements Focus Group
RNP	Required Navigation Performance
RTD	Research, Technology and Development
SA	Situational Awareness
SASP	Separation and Airspace Safety Panel
SES	Single European Sky
SESAR	SES Advanced Research
SESAR-JU	SES Advanced Research Joint Undertaking
SMC	Sequential Monte Carlo
SPR	Safety and Performance Requirements
SSEP	Airborne Self Separation
SWIM	System Wide Information Management System
TCAS	Tactical Collision Avoidance System
WP	Work Package