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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

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Abstract

Within the iFly project an advanced airborne self separation concept of operation is under development in a sequence of two subsequent design cycles. During the first design cycle the Autonomous Aircraft Advanced Concept of Operations (A^3 ConOps) has been developed, with as aim to safely and efficiently accommodate three to six times as much en-route traffic as in 2005. This A^3 ConOps envisages a net-centric environment in which all aircraft are responsible for airborne self separation, without support from Air Traffic Control (ATC).
This report addresses the second cycle, and studies various mathematical methods regarding their integration within the A^3 ConOps. The options still open within the A^3 ConOps are further analysed and consequently reduced by taking advantage of the outcomes of the innovative methods under development by other iFly WP's, i.e. WP3 (Prediction of complex traffic conditions), WP4 (Multi-agent Situation Awareness consistency analysis), WP5 (Pushing the limits of conflict resolution algorithms), WP7 (Safety/capacity analysis of A^3 ConOps) and WP9 (Safety requirements analysis). This results into recommendations regarding the best possible algorithm options for the further refinement of the A^3 ConOps.

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1 Introduction

1.1 iFly project

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

iFly will perform 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 will be used to define a "baseline" operational concept. For the assessment cycle and second design cycle, innovative methods for the design of safety critical systems will be used to refine the operational concept with the goal of **safely managing a three to six times increase in traffic demand of 2005**. These innovative methods find their roots in robotics, financial mathematics and telecommunications.

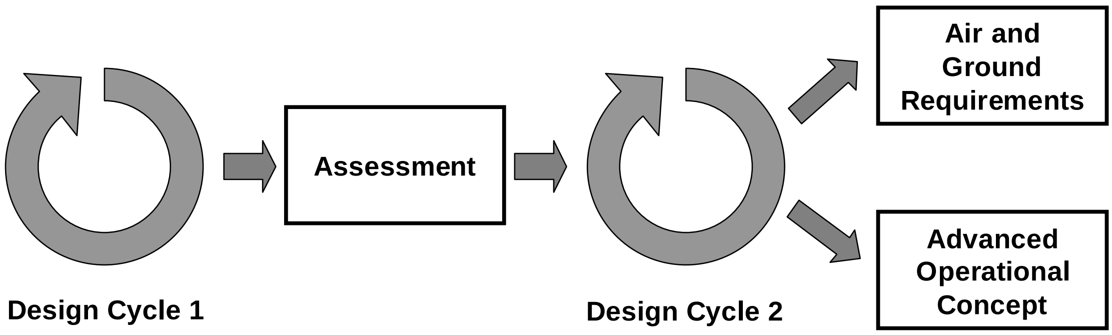

FIGURE 1. iFly Work Structure.

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 is 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 is developed within WP1. An important starting and reference point for this A^3 ConOps development is formed by the human responsibility analysis in WP2.

<u>Innovative methods</u>
Develop innovative architecture free methods towards key issues that have to be 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 is 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 develops preliminary safety and performance requirements on the applicable functional elements of the A^3 ConOps, focused on identifying the required technology.

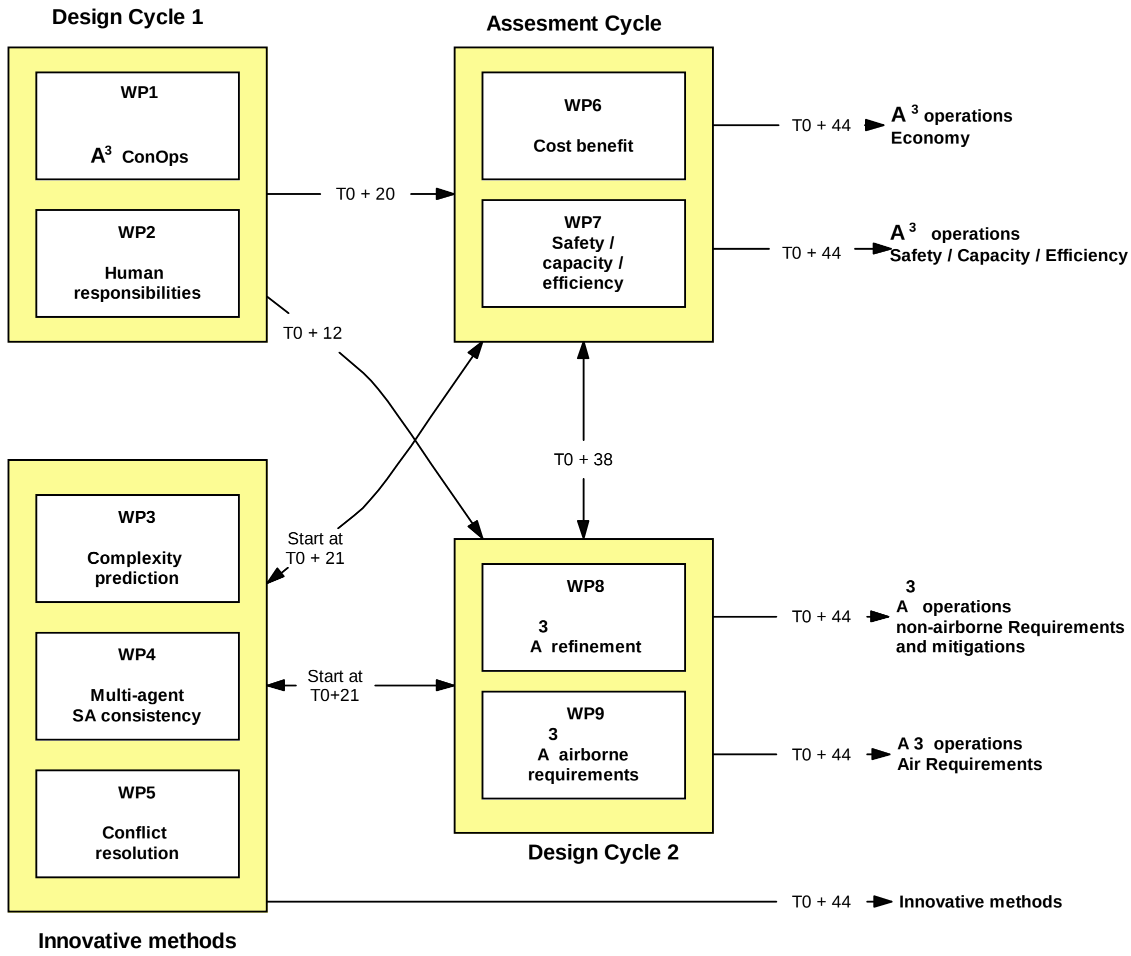

FIGURE 2. Organisation of iFly research.

1.2 *Objective of iFly Work Package 8*

During the first design cycle an advanced airborne self separation Concept of Operations (ConOps) has been developed and documented [1] under the name A^3 ConOps. Work Packages 8 and 9 together are in charge of conducting the 2^{nd} design cycle for this A^3 ConOps design. Whereas the aim of WP9 is to perform an early operational safety requirements evaluation of the A^3 ConOps according to ED78a (= DO264), the aim of WP8 is to study further refinements of the A^3 ConOps. These refinement studies are organised in five sub-WPs:

- WP8.1: Integration of mathematical results;
- WP8.2: Distributed Air Traffic Flow Management Concept;
- WP8.3: A^3 equipped aircraft within SESAR 2020;
- WP8.4: Non-airborne Requirements in support of A^3 equipped aircraft;
- WP8.5: Further refinement of the A^3 ConOps during EOCVM phase V2

The current report documents the outcomes of the study conducted within WP8.1.

1.3 *Organisation of WP8.1 and this report*

WP8.1 studies various mathematical methods regarding their integration within the A^3 ConOps. The options still open within the A^3 ConOps are further analysed and consequently reduced by taking advantage of the outcomes of the innovative methods under development by WP3 Prediction of complex traffic conditions, WP4 Multi-agent Situation Awareness consistency analysis and WP5 Pushing the limits of conflict resolution algorithms.

This D8.1 report is organised as follows. Section 2 identifies the options for potential refinement of the the A^3 ConOp. Section 3 analyses the options described in Section 2 and identifies their advantages and disadvantages**.** Section 4 provides an overview of the results obtained and the possible ways to continue. Section 5 presents concluding remarks.

2 Options for refinement of A^3 ConOps

In this section a series of options are identified which aim to refine the A^3 ConOps of [1]. These options are identified for the following six functionalities within the A^3 ConOps:

- Surveillance;
- Short Term Conflict Detection & Resolution;
- Medium Term Conflict Detection & Resolution;
- Long Term Approaches;
- Cockpit/airborne functional architecture;
- Mult Agent Situation Awareness.

For each of these six functionalities, candidate options for refinement of the A^3 ConOps have been identified in the following six sub-sections.

2.1 Surveillance

The Surveillance System (SS) is the entity responsible to share with the Flight Management System among others, the information of the position, altitude and movements of the nearby air traffic obtained from the observation of the surrounding airspace.

Surveillance tasks involve repeated or continuous observation intended to maintain awareness of some entity or geographical area. The main terms in the surveillance domain are presented in Table 1.

The surveillance data domain contains

Data	Description
System Track	The best knowledge of the position of an aircraft at a fixed time. Includes (when available) 2D/3D position, past history information, velocity vectors, aircraft identification info (SSR code, 24bit ICAO code), and aircraft derived data (e.g. intent, air speed, etc)
Sensor Descriptions	Defines the various sensors (radar stations, ADS-B ground stations etc), their geographies, configurations and operational status
Aircraft Track	Represents a track for a proximate aircraft detected by on-board ADS-B (or where available TIS-B). The tracks are used to augment the Traffic Display and also by trajectory determination for the handling of an ASAS clearance. (Probably outside the scope of SWIM)

Table 1 A^3 Surveillance Data Domain

2.1.1 Surveillance/Awareness zones

Self separation operations are critically dependent on the availability of information about surrounding traffic. Therefore, different levels of surveillance information are defined to provide an accurate prediction of the aircraft state and future positions.

Three timeframes are defined in relation to the predominant type of data employed:

- **Short term timeframe –** typically up to 3-5 minutes, represents the time horizon up to which the trajectory obtained by a state-based extrapolation may still represent a reasonable approximation.

- **Medium term timeframe –** typically up to 10-20 minutes, represents the time horizon up to which the trajectory can be reconstructed from intent data.

- **Long term timeframe –** typically more than 30 minutes, represents the time horizon used for dynamic on-board trajectory optimization. Only RBT-based data may provide useful information about flights in this timeframe.

According to the previous timeframes, three additional operational characteristics are defined:

- **Mid Term Time Horizon (MTTH) –** defines the required amount of broadcasted intent information. The parameter specifies the minimum length (in time) of trajectory that will be possible to rebuild from the broadcasted intent information. An alternative solution is to consider the number of broadcasted Trajectory Change Points (TCP’s).

- **Mid Term Awareness Zone (MTAZ) –** defines a dynamic area around each autonomous aircraft encompassing the traffic which could potentially cause an intent-based (detectable through broadcasted intent information) conflict with the aircraft. SWIM-based services will support an autonomous aircraft by providing the information about the traffic in MTAZ.

- **Long Term Awareness Zone (LTAZ) –** defines a dynamic area around the RBT of each autonomous aircraft (within SSA) which is considered for potential trajectory changes. SWIM-based services will support an autonomous aircraft by providing the strategic information about LTAZ (meteo information, areas-to-avoid, areas-recommended-to-avoid, etc).

2.1.2 Options

2.1.2.1 Surveillance Alternative 1: Space-based ADS-B

For the source of this option and more detailed information about it we refer to [24].

Satellites are able to receive ADS-B signals and can relate this information to a ground station or other aircraft. This way you may provide over-the-horizon surveillance for aircraft that are outside ADS-B range.

2.1.2.2 Surveillance Alternative 2: Datalink for surveillance

For the source of this option and more detailed information about it we refer to [21] and [22].

The ConOps describes that the aircraft operate in an environment where their RBT is down linked to the ground. This information could be up-linked to other aircraft for surveillance purposes.

2.1.2.3 Surveillance Alternative 3: Airborne Information Data-link Network

For the source of this option and more detailed information about it we refer to [22], [23] and [26].

Aircraft may connect to an airborne information network between aircraft similar to a computer network. Each aircraft could send its available information to other peers in the network, which on their turn can send it to other aircraft.

2.1.2.4 Surveillance Alternative 4: Non Cooperative Sensors

For the source of this option and more detailed information about it we refer to [25].

The surveillance systems include reporting / messaging systems, which rely on the aircraft to provide information, such as non-automatic reporting systems and regimes; and sensor systems such as radars that collect information about aircraft without their cooperation.

Airborne equipment uses non cooperative sensor technologies to locate other aircraft and hazards and they don’t demand any help from the target. Surveillance methods that sense non transponding targets indirectly are considered non cooperative sensing methods.

A target is sensed and tracked, either (1) through passively acquiring information about the target or (2) by actively deploying energy to seek out the target (e.g., radar which emits an electronic pulse and determine range and bearing by the angle of sensor and timing of the response, or laser range finder which emits infrared coherent light and detects reflections).

Active sensors, such as a laser range finder, require more energy, so they tend to be bigger and heavier. These sensors typically can provide more accurate range information, though they are not good at angle resolution because their field of regard is either very small (laser range finder point) or very large (radar or acoustic omni-directional ping).

2.2 Short Term Conflict Detection & Resolution

The Short Term Conflict Detection and Resolution module considers the best traffic information available up to the 3 to 5 minutes range, as well as area information. The traffic information may include the first level of intent (i.e., turn point or level-off altitude within 3 to 5 minutes). It is assumed that under normal operations the ownship aircraft will always be able to consider at least its own first level of intent.

- Target State information, which is providing information on the horizontal and vertical targets (heading, speed and altitude) for the active flight segment, can be used as first level of intent.

- Short Term CR will enable a quick execution of the conflict resolution; this will involve:

  - Fast automated assessment and calculations
  - Presentation of simple manoeuvre options to the flight crew
  - Primary focus will be on CR execution instead of trajectory management

- Implicitly coordinated Short Term traffic CR requires that all aircraft use compatible resolution algorithms with a cooperative set of resolution manoeuvres. As the coordination among these manoeuvres will be implicit, there will be no direct communication between aircraft for manoeuvre coordination.

- Short Term traffic CR algorithms will have to be able to resolve conflicts which involve several other aircraft ('1 on N' capability), and not create new conflicts.

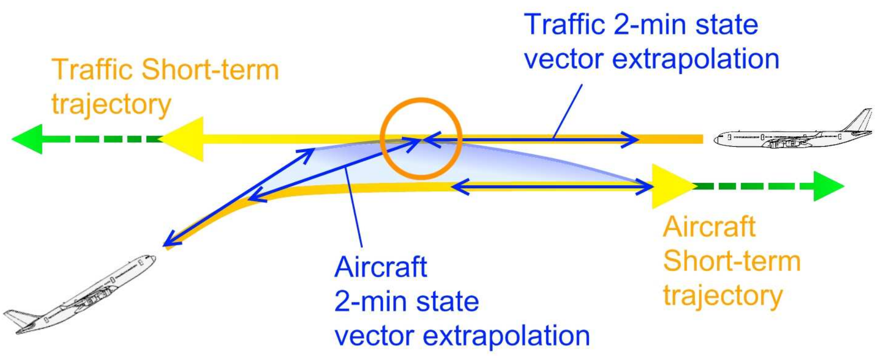

Figure 3 Two-minutes short term state vector conflict (level-off attitude example) If the 2 min state vector predicted distance is less than the separation minimum (i.e. 3 Nm / 900 ft.) a conflict is detected. In this example the predicted vertical distance is zero feet; as a result a conflict is detected.

2.2.1 Algorithm Options

2.2.1.1 Short Term CD&R Algorithm Alternative 1: Decentralized Navigation Functions

For the source of this option and more detailed information about it we refer to ([19], subsection 4.4).

Decentralised Navigation functions enable each aircraft to navigate while avoiding conflicts with its neighbours by moving downhill on an artificial potential that comprises repelling forces between aircraft and attractive forces towards their destinations. Decentralized Navigation function approach uses a feedback control scheme that provides fast response and is computationally efficient. A comparison between the algorithm's characteristics and the concept requirements is given below.

		ConOps Requirements	Proposed Algorithm	Comments
Inputs	Ownship	State, Intent	State, Intent	
	Traffic	State, Intent (opt.)	State	
Outputs		Resolution Manoeuvre	Requirement met; specifically: **Speed** **Climb-descent rate** **Rate of heading turn**	Manoeuvre defined implicitly **Constant Speed, bounded climb-descent angle**
Lookahead Time		Up to 3 to 5 min	**Requirement met, only local sensing for Conflict Detection**	
Priority Rules		No	Requirement met, with option of priority rules	
Assumptions		Implicit Coordination '1 to N' resolution No new conflicts	No direct coordination All possible conflicts avoided	

Table 2 Comparison of ConOps requirements for short-term CD&R and Decentralized Navigation Functions

2.2.1.2 Short Term CD&R Algorithm Alternative 2: Explicit coordination

For the source of this option and more detailed information about it we refer to ([18], p. 39). The ConOps proposes the use of implicit coordination for Short Term Conflict Detection and Resolution. One may also consider to use explicit coordination (inter aircraft communication to determine resolution manoeuvre).

2.2.1.3 Short Term CD&R Algorithm Alternative 3: Cooperative manoeuvre

For the source of this option and more detailed information about it we refer to ([18], p. 38). Instead of creating resolutions that fully resolve the conflict, it may be an option to generate resolutions that solve only 50% of the conflict (e.g. an aircraft maneuver creates only 50% of the minimum separation minimum). The other aircraft would then have to resolve the other 50%. This way the burden is shared among both aircraft and the manoeuvres might be limited in size. This however would need a good coordination. This is a lot like the way Navigation Functions operate, as both aircraft are repelled by each other. This aspect can also be related to priority rules, e.g. in each encounter only the lower priority aircraft manoeuvres unless both aircraft have the same priority and cooperative manoeuvring is used.

2.2.1.4 Short Term CD&R Algorithm Alternative 4: Short term Conflict Prevention

For the source of this option and more detailed information about it we refer to ([18], pp. 82-85).

The ConOps does not describe a system for Short Term Conflict Prevention (CP). A CP system can be developed that uses so called NO-GO bands. These are coloured bands on the primary flight display which indicate which groundspeed, altitude and vertical-speed values should be avoided from a short term conflict resolution perspective.

2.2.1.5 Short Term CD&R Algorithm Alternative 5: Undershooting Minimum Separation Criteria.

For the source of this option and more detailed information about it we refer to [2].

In the A3 ConOps an STCR advisory applies to conflicts with any other aircraft within Short-Term time horizon. Implicitly it is assumed that a resolution advisory resolves a conflict such that minimum separation criteria are satisfied. However, in specific cases it may be difficult (or impossible) to find a resolution which realizes these criteria. In such case it is an option to use a resolution advisory which increases the separation as much as is possible, but not up to the minimum separation criteria. In [iFly D7.1c, Subsection 4.2] this approach has been adopted regarding short term turn advisories: it is determined as the minimum turning angle (to the left or to the right) such that there are no predicted conflicts left with any aircraft and which is within reach of the Short-Term time horizon. If there is no minimum turning angle possible below a certain value (Maximum-Angle-Short-Term), then the turning angle below this maximum value is identified which provides the lowest underscoring of the minimum separation criteria. In [iFly D7.1c] there are no priorities at all applicable under STCR.

2.2.1.6 *Short Term CD&R Algorithm Alternative 6: Optimisation techniques*

For the source of this option and more detailed information about it we refer to [10], [11], [12], [13], [14], [15], [16], and [17].

Optimisation methods provide a natural framework for handling constraints and can offer increased performance with respect to various criteria.

A wide variety of approaches to Short Term CD&R utilize optimization techniques in order to incorporate requirements such as minimum fuel consumption or deviation from planned course, and passenger comfort. Optimization offers a natural framework for dealing with such matters and has been adapted to various operational models. Conflict avoidance is expressed as an inequality constraint, usually of quadratic form, while a cost function representing delay, deviation from track or other fitness criteria is minimized.

More specifically:

- In [10] a worst case approach for two aircraft is presented, where each one calculates the maximal set of initial conditions that guarantee a safe trajectory for the system for all possible maneuvers of the conflicting neighbour. This algorithm is inherently non-cooperative and decentralized and is mostly suited for off-line prediction of safe and unsafe escape maneuvers.
- In [11] a less conservative, cooperative approach is developed. Each aircraft is considered to have information on the state and goals of all other ones closer than a maximum “alert” distance and based on this knowledge designs its trajectory so that

the sum of the delays of all neighboring aircraft is minimized, while avoiding conflicts.

- Durand et al. [12] describe another distributed algorithm for short term conflict resolution, where prioritized planning is considered, planning new trajectories for aircraft after first establishing a priority order. Establishing an order of priority could also enable the distributed use of a “one against many” algorithm, like in [13].
- A similar formulation of the problem described above is used in [14] and [15], in an even more decentralized form where each aircraft’s cost function depends solely on its own trajectory. The authors assume a global system comprising of multiple local subsystems which interact through local constraints that are imposed on their states. A solution is then calculated by an algorithm involving Lagrange multipliers and penalty function methods which offers global convergence in a finite number of steps.
- A class of CD&R methods using a different form of optimization includes those proposed by Bilimoria [17] and Dowek, Munoz and Geser [16]. In these approaches the relative speed between conflicting aircraft is used to calculate the relative trajectory of the intruding aircraft. Note that no intent information is used, only position and velocity vector information are considered to be available. Once a loss of separation is detected, a family of new trajectories is produced that are tangential to the protected zone of the intruding aircraft, thus providing a separation equal to the minimum allowed. Specifically the new trajectories are designed by assuming a discrete maneuver (i.e. instantaneous change in heading, ground speed or both) strictly with geometric means and in a closed form. As there are infinite maneuvers that produce tangential trajectories, 3 types of solutions are considered as candidates: the ones given only by a heading or ground speed change, and those that require the least possible change in the velocity vector.

2.3 Medium Term Conflict Detection & Resolution

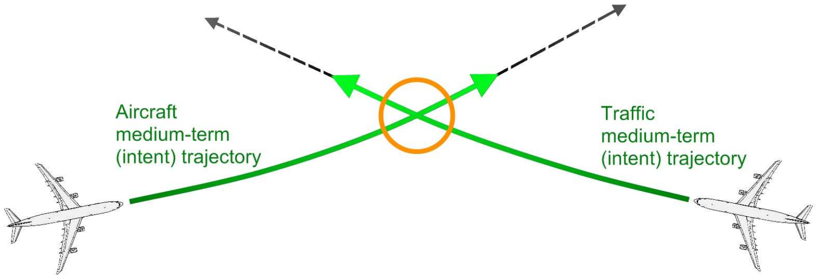

Figure 4 Medium Term Conflict

The Medium Term Conflict Detection and Resolution module takes into account own trajectory intent information and that of surrounding traffic, up to 15 – 20 minutes (up to the time that it is possible to obtain reliable information) and area information.

- Traffic Conflict Resolution uses priority rules to determine which aircraft has the right of way and which aircraft has to manoeuvre (see section 4.2)

- The aircraft which has to manoeuvre is required to do so, as stated in the AFR Rules, so that the conflict resolution is not delayed up until the point the conflict has to be resolved by both aircraft.

- Resolutions will be displayed in the form of a modified route which can be implemented automatically or manually through the Flight Management System.

- The flight crew should be able to consider the appropriate conflict resolution manoeuvre, evaluate several options, and execute any given manoeuvre, with the only constraints being:

    - The manoeuvre has to solve all conflicts.

    - The manoeuvre shall not create new conflicts and be conflict free up to a TBD time (e.g., 10min) beyond the medium term look ahead time.

- Medium term CR will, under normal circumstances represent the most cost-effective traffic separation assurance option, since comparatively small changes in the trajectory will be sufficient to ensure aircraft separation.

- The resolution algorithms will have to ensure that at no time during the flight, the aircraft trajectory will place the aircraft in a 2 minute state vector conflict.

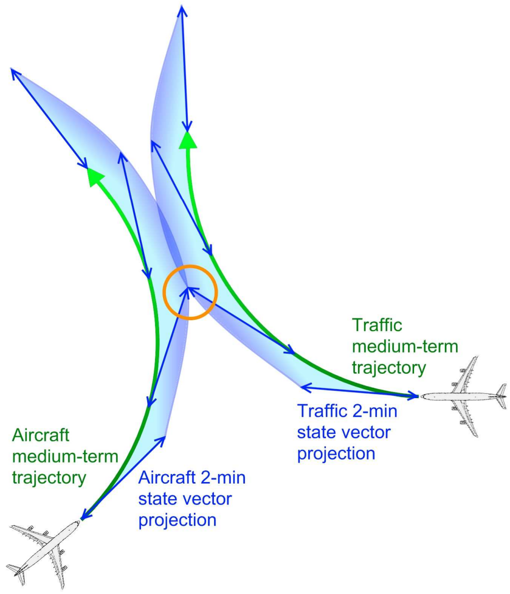

Figure 5 Cross-checking of state vector conflicts along the intent track. If the 2 min state vector predicted distance is less than the separation minimum (i.e. 3 Nm / 900 ft.) a conflict is detected. In this example the predicted lateral distance is zero Nm; as a result a conflict is detected.

2.3.1 Operational assumptions for Mid-Term Conflict Resolution

- Operational assumptions for Mid-term Conflict Resolution: Aircraft have knowledge of all other aircraft involved in their region of interest. Additionally, the boundaries of the region of interest and target regions corresponding to exit gateways onto the RBT are identified and pre-specified by the conflict detection algorithm.

- The transmission of aircraft positions, wind disturbance measurements, future plans to neighbouring aircraft is enabled by SWIM, as discussed in the A^3 concept.

- A conflict free set of actions exists for any new aircraft, without the need for existing aircraft to re-plan their sequences of actions.

- We assume there are no time delays associated with SWIM. In the event of communications failure, aircraft can execute their previously calculated control policies based on the last time they planned their trajectories.

2.3.2 Algorithm options

2.3.2.1 Mid Term CD&R Algorithm Alternative 1 Model Predictive Control

For the source of this option and more detailed information about it we refer to ([19], Sections 3, 4 and 5)

Model Predictive Control is a closed loop control formulation which is proposed in several alternatives of the CD&R algorithms proposed in the Mid Term, because of its similarity to air traffic situations. MPC algorithms run in a periodic fashion, allowing to incorporate new data and information as the conflict scenarios evolve.
In the standard form of MPC, a model of the system is parameterised with a sequence of manipulated variables (control inputs) over a finite time horizon. This model is used to form an optimisation problem whose decision variables comprise this sequence of control inputs. The objective to be minimised is an appropriately chosen function of the future output and state trajectories over this horizon starting from the current state. The optimisation problem is solved and the first step of the resulting input sequence is applied. At the next time step, this process is repeated, based on the new measured state. The horizon length is kept fixed, giving rise to the term ‘receding horizon control’. Whilst the predictions made within the optimisation problem are ‘open-loop’, the recomputation of the optimal finite-horizon trajectory based on the new measurements obtained renders this a ‘closed loop’ control formulation, countering the effect of uncertainty.

2.3.2.2 Mid Term CD&R Algorithm Alternative 1.1: MMPC (Multiplexed Model Predictive Control)

For the source of this option and more detailed information about it we refer to ([19], Section 4).

The underlying protocol is that aircraft plan their future trajectories in a predefined cyclic sequence, taking into account others’ received plans. Each aircraft involved in an encounter plans its own future trajectory, then transmits its future plan to the other aircraft. The next aircraft in the sequence does the same. Each aircraft executes the first step in the plan it has announced, until it is its next turn to recompute its plan. SWIM in this case is used in order to provide an initial centralized solution to the situation. The algorithm can be robust to communication failure with SWIM, provided its duration is not longer than the Mid Term CD&R horizon.

2.3.2.3 Mid Term CD&R Algorithm Alternative 1.2: MMPC with disturbance feedback

For the source of this option and more detailed information about it we refer to ([19], Section 4.3).

This is a refinement of the previous algorithm, where this time affine disturbance feedback is used between policy updates. Thus changes in speed and heading can be applied in every time step. The scheme involves a single aircraft re-optimizing its policy at any one time. In between optimization updates, aircraft apply a fixed feedback policy according to the disturbance they encounter. This modified scheme permits longer prediction horizon lengths than the original MMPC. SWIM in this case is used in order to provide an initial centralized solution to the situation. The algorithm can be robust to communication failure with SWIM, provided its duration is not longer than the Mid Term CD&R horizon.
We proceed by outlining two variants of the algorithm.

2.3.2.4 Mid Term CD&R Algorithm Alternative 1.2.1: Fixed Order MMPC with disturbance feedback

For the source of this option and more detailed information about it we refer to ([19], Section 4.3.1)

Aircraft take it in turns to broadcast their intent and re-optimise their flight plans. Each aircraft can construct accurate predicted plans of the other aircraft when it plans its own set of moves. This can be implemented either according to a fixed or variable timing sequence. A variable order of update permits incorporation of priority rules, but using a more restrictive fixed update order enables a higher frequency of policy update. SWIM in this case is used in order to provide an initial centralized solution to the situation. The algorithm can be robust to communication failure with SWIM, provided its duration is not longer than the Mid Term CD&R horizon.

2.3.2.5 Mid Term CD&R Algorithm Alternative 1.2.2: Variable Order MMPC with disturbance feedback

For the source of this option and more detailed information about it we refer to ([19], Section 4.3.2)
In the earlier formulations, aircraft optimise sequentially, one per time step, to ensure feasibility. In this formulation, each aircraft optimises in parallel for a new plan, conditioned on the other aircraft executing one of their candidate conflict free plans. Aircraft still update their policies in a round-robin fashion, but a variable order of update is employed. The choice of updating aircraft at any given time step is based on satisfaction of some global objective, for instance that which would minimise some total cost of all aircraft. The motivation for performing parallel optimisation is to make most use of time between updates, and to allow aircraft with ‘greatest need’ to re-optimise their policy sooner, for instance in order to respond to strong wind disturbances. SWIM in this case is used in order to provide an initial centralized solution to the situation. The algorithm can be robust to communication failure with SWIM, provided its duration is not longer than the Mid Term CD&R horizon.

The algorithms we have just detailed are subsumed by the general multiplexed MPC framework, whereby aircraft update their policies in a sequential Round Robin[1] fashion. All variants require an initial centralized solution enabled by SWIM.

The original multiplexed algorithm, outlined in 2.3.2.2, is modified in 2.3.2.3-2.3.2.5, wherein aircraft apply corrections to their plans (disturbance feedback) in between updates according to wind disturbances they experience, to counter the effect of wind. This is done to facilitate feasibility, and permits longer prediction horizons to be utilized. Multiplexing is not restricted to employing a specific order of update, and this flexibility can be exploited to achieve system wide objectives by adopting a variable order formulation, as outlined in 2.3.2.5.

[1] Round Robin: Arrangement of choosing all aircraft in a group equally in some rational order, this order defines which aircraft is the responsible of calculates and evaluates its priority in comparison to other aircraft’s priorities.

Feature	ConOps Requirement	Robust decentralized MPC
Look-ahead time	15–20 minutes	Requirement met
Coordination	Not required	Not required
Principle of use	Intent	Requirement met
Priority rules	Yes	Used for the cyclic ordering and in case of comms. failure
Secondary conflict creation	Do not	None created
2-minute state vector conflict	Avoid	Not addressed yet No problem in principle
Type of resolution algorithm	Intent-based	Intent-based
Alternative resolutions	Should provide	Not provided yet

Table 3 Comparison of ConOps requirements and properties of the robust decentralised MPC algorithm for mid-term conflict resolution

2.3.2.6 Mid Term CD&R Algorithm Alternative 1.3: Decentralized MPC with a simplified AC model

For the source of this option and more detailed information about it we refer to ([19], Section 5)
In this approach, Decentralized MPC is used to find the optimal trajectories for aircraft involved in the situation. For the model of the aircraft, a simplified model is used in order to guarantee less computation needs and possibly some guarantees for this abstraction of the aircraft. This is an ongoing work and the pros/cons are only based on indications.

2.3.2.7 Mid Term CD&R Algorithm Alternative 2: Combined MPC and Short Term CD&R approach

For the source of this option and more detailed information about it we refer to ([19], Section 3)

This algorithm works in a similar fashion as the previous ones, in the sense that it still uses MPC for the Mid-Term CD&R, but also takes into account the presence of the Short Term CD&R level.

Each aircraft computes its own trajectory and broadcasts to the others, which then take it into account in their calculations. The process is repeated periodically (e.g. every 3-5 minutes). “Priorities” are implicit in the decision of which aircraft computes its solution first in each round. We have considered two schemes:

1) Fixed priorities: Each aircraft has a unique priority; as for example discussed in the priority alternatives later on the document. In an encounter the aircraft with the highest priority computes its trajectory first and broadcasts, then the one with the second highest

does the same, etc. Aircraft with lower priority take the trajectories broadcast by the higher priority ones as constraints in their calculations.

2) Random priorities: At every round the aircraft draw a random number between 0 and 1 and broadcast it. The aircraft with the lowest number gets the highest priority for the round, computes its trajectory and broadcasts, then the one with the second lowest number does the same, etc. Again lower priority aircraft treat the trajectories broadcast by higher priority aircraft as constraints when calculating their own trajectories.

So far, it seems that both schemes lead to resolution. Fixed priorities tend to penalize some aircraft excessively. High priority aircraft get straight paths and low priority ones basically have to go around everyone else, whereas a small deviation from a higher priority aircraft may lead to much better trajectories for the low priority ones. On the other hand, random priorities tend to lead to more "meandering" trajectories. When an aircraft has high priority it heads straight for its destination but in the next round it may have to deviate. What seems to work best is using fixed priorities but penalizing (in the cost function they use in their optimization) high priority aircraft if their chosen trajectories force low priority aircraft to deviate excessively. SWIM in this case can be used to provide a globally optimal solution to the situation. The algorithm can be robust to communication failure with SWIM, as it can perform in a completely decentralized fashion.

2.3.2.8 Mid Term CD&R Algorithm Alternative 2.1: Combined MPC and Navigation Functions

For the source of this option and more detailed information about it we refer to ([19], Section 3)

As Navigation Functions have been used for the Short Term CD&R, the previously described algorithm has been tested with the use of Navigation Functions in the Short Term.

Feature	ConOps Requirement	MPC & NF
Look-ahead time	15–20 minutes	15–20
Coordination	Not required	None
Principle of use	Intent	Requirement met
Priority rules	Yes	Can be implemented
Secondary conflict creation	Do not	Not created
2-minute state vector conflict	Avoid	Not addressed yet
Type of resolution algorithm	Intent-based	Intent-based
Alternative resolutions	Should provide	Can provide

Table 4 Comparison of ConOps requirements and properties of the combined MPC&NF algorithm for mid-term conflict resolution

2.3.2.9 Mid Term CD&R Algorithm Alternative 3: Merge and follow

For the source of this option and more detailed information about it we refer to [RFG, 2010].

Use of Interval Management: Aircraft may choose to merge behind and follow a lead aircraft that flies in the same direction. The interval between the aircraft will be managed as not to create conflicts.
This alternative assumes a very specific pattern of the RBTs, designed by Long Term CD&R and TFM modules. Thus, in cases that this is not available, it doesn't seem that there will be a way to guarantee that conflicts will be possible to resolve. Even though it might be able to solve some cases, it is rather restrictive in terms of the manoeuvres that aircraft are allowed to do.

2.3.2.10 Mid Term CD&R Algorithm Alternative 4: Undershooting minimum separation minima

For the source of this option and more detailed information about it we refer to ([2], pp. 18-19)

An MTCR Advisory applies to conflicts with any other aircraft within Medium Term Time horizon. It is determined as the minimum turning angle (to the left or to the right) such that there are no predicted conflicts left with any aircraft which has higher priority than aircraft i and which is within reach of the MTT horizon. If there is no minimum turning angle possible below a certain value (maximum-Medium-Turn-Angle), then the turning angle below this is identified which provides the lowest underscoring of the minimum spacing criteria of 5Nm and 1000 ft between centerlines. In that case aircraft i names itself handicapped. As soon as the advised MTCR advisory and handicap have been accepted by the crew of aircraft i, then both are implemented as a RBT in the FMS of aircraft i. Subsequently the RBT and the handicap information in the FMS is broadcasted through ADS-B. If aircraft A is closer to its destination than aircraft B is, then aircraft A has MTCR priority over aircraft B. i.e. aircraft B should modify its RBT first. This way of working repeats until the RBT is complete

2.3.2.11 Mid Term CD&R Algorithm Alternative 5: Pairwise conflict resolution algorithms found in literature

For the source of this option and more detailed information about it we refer to [31], [32], [33], [42], [43]. The scope of these studies was limited to resolving pairwise conflicts, thus ignoring possible problems that are created by or to other neighbouring aircraft. Important examples of this approach are:

- A. Reference [31]. In this approach, an improvement of the A* algorithm is proposed for avoiding obstacles and trajectory planning in ATM. The approach is iterative and is only presented for avoiding static obstacles in this paper.
- B. Reference [32]. This approach forms a Mixed Integer Linear Program to tackle the conflict resolution problem, minimizing the fuel burnt. The results are very promising, being able to handle big conflicting instances.
- C. Reference [33]. In this approach, a simple time-stepping algorithm is presented that will detect potential conflicts and resolve them by computing the globally optimal steering programs for both aircraft in real time. Its main limitation is that manoeuvres are executed at constant airspeed, reducing the resolution alternatives.
- D. Reference [42]. This work considers an algorithmic approach to tackle the conflict resolution problem, using iterative algorithms to calculate a resolution. The proposed resolutions are 4D (3D and time manoeuvres). Unlike other approaches, this is mainly heuristic.

- E. Reference [43]. In this approach, conflicts are solved using single-step decisions on velocity changes, as well as altitude changes (no heading angle changes). Its main limitations are that it is not easily extensible to cases where uncertainties are present, as well as the fact that heading angle changes are excluded from the potential manoeuvres.

2.3.3 Medium Term Priority Rules options

The term ‘priority scheme’ is used to describe the way in which priorities are used for the purposes of providing an orderly resolution of a situation involving potentially conflicting aircraft. Priority schemes can be used, together with algorithms for finding conflict-free trajectories, as part of an overall resolution scheme.

The determination or allocation of the relative priorities of flights could take into account many factors, such as the costs which are associated with perturbing the trajectories of aircraft, but these considerations are not described in this section. Some possibilities are described in iFly deliverable D1.3 “Autonomous Aircraft Advanced (A3) ConOps” (see below).

2.3.3.1 Medium Term Priority Rules Alternative 1: Simple pairwise priority scheme, initial iFly concept of operations

For the source of this option and more detailed information about it we refer to [1].

The priority scheme described in the initial iFly concept of operations applies to potential conflicts involving two aircraft. The aircraft with the lower priority must manoeuvre to prevent loss of separation with the aircraft with the higher priority.

2.3.3.2 Medium Term Priority Rules Alternative 2: Pairwise priority scheme with priority reversal

For the source of this option and more detailed information about it we refer to [34].

[34] illustrates situations in dense traffic in which an aircraft, designated by a priority scheme as being the aircraft which must manoeuvre to avoid a potential conflict, is “boxed-in” and cannot find a resolution of the potential conflict. In such circumstances a priority-reversal procedure would give a second chance to resolve the potential conflict.

2.3.3.3 Medium Term Priority Rules Alternative 3: Pairwise priority scheme with priority reversal – the handicapped method

For the source of this option and more detailed information about it we refer to [35].

[35] addresses the following situation. Suppose that two aircraft predict a loss of separation between them and that as the result of the application of a priority rule the low priority aircraft must manoeuvre to avoid the higher priority aircraft. If the manoeuvring aircraft is “boxed-in”

by surrounding aircraft, i.e. it cannot find a resolution which would provide the minimum required separation, it instead selects a resolution trajectory which maximises its separation with the higher priority aircraft (without losing separation with third party aircraft). It then marks itself as being handicapped (presumably until it has passed the aircraft with which it has the smallest separation) and broadcasts this fact. While it is handicapped other aircraft treat the handicapped aircraft as the highest priority aircraft, i.e. it is unable to manoeuvre. Consequently, the other aircraft in the initial conflict will manoeuvre to provide the full minimum required separation (if possible).

This approach is rather similar to straightforward priority reversal, with the difference that the first aircraft tries to maximise its separation from a conflicting aircraft before reversing priority. Also, third party aircraft will give priority to the handicapped (constrained) aircraft in subsequent conflicts.

2.3.3.4 Medium Term Priority Rules Alternative 4: FACES

For the source of this option and more detailed information about it we refer to [36].

In [36] a decentralised strategy is described for resolving potential conflicts amongst arbitrary groups of aircraft. The authors take account of the fact that, due to finite surveillance range, aircraft do not share the same information about their neighbours. A token allocation strategy is used such that on any time step no two aircraft within detection range of one another manoeuvre simultaneously (i.e. no concurrent resolution), nor does deadlock occur. Over successive time-steps aircraft manoeuvre to resolve the situation.

2.3.3.5 Medium Term Priority Rules Alternative 5: Implicit coordination

For the source of this option and more detailed information about it we refer to [37].

[37] proposes a priority scheme for self-separating aircraft. It deliberately avoids the use of explicit coordination between aircraft, which is potentially fragile. The scheme aims to cope with more complicated situations than simple pairs of potentially conflicting aircraft.

The scheme is reasonably complicated but has not yet been evaluated through simulation or by considering a set of scenarios. It is not clear whether the scheme results in a total order for sequencing manoeuvres amongst a group of aircraft.

2.3.3.6 Medium Term Priority Rules Alternative 6: Global priorities in MPC

For the source of this option and more detailed information about it we refer to [27].

On any resolution step the MPC level determines a set of goals for the aircraft involved in the situation. Each aircraft then calculates a navigation function taking into account its own goal and the positions of the other aircraft which are within its sensing range. A global set of priorities can be taken into account by changing the order in which aircraft calculate their navigation functions.

2.3.3.7 Medium Term Priority Rules Alternative 7: Dynamic priorities

For the source of this option we refer to [2].

In order to make the priorities dynamic, they are proposed to be dependent on the distances of all aircraft to their destinations. The aircraft with the shortest distance has highest priority, and the aircraft with the longest distance has lowest priority. Because the destination of each aircraft is broadcasted as part of the planned trajectory, each ASAS onboard an aircraft knows the destinations of all aircraft for which it may there might be a medium term conflict. This allows each ASAS to calculate the priority sequence for all these aircraft, and without need for any coordination. Each aircraft is always allowed to improve its 4D planned trajectory as long as this does not infringe with 4D trajectory plans received from aircraft with a higher priority. But each aircraft also is required to make its 4D trajectory plan conflict free (15 min ahead) with all aircraft having a higher priority.

2.4 Long Term Approaches

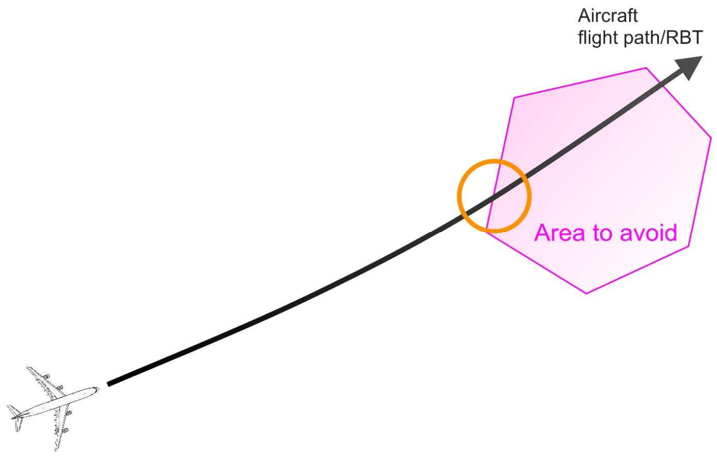

Figure 6 Area Conflict

In the A3 ConOps described in [D3.1], Long Term Area Conflict Detection (LTACD) is conceived as an airborne function in charge of detecting those situations where an aircraft may enter an “area to avoid” within the LTAZ. Areas-to-avoid include weather hazards and congested/high complexity areas, and are made available to aircraft by the automated ground surveillance support as part of the strategic information about the LTAZ. The pilot will be informed of the detected *area-conflicts* so that an appropriate action can be taken to avoid their actual occurrence. More precisely, the LTACD function triggers the onboard Trajectory Management (TM) module, which, as soon as some area-conflict is detected, suggests to the pilot a trajectory modification to solve the conflict.
An alternative solution is to implement the LTACD function on the ground, as a centralized support tool, and transmit the relevant information onboard only when an area-conflict is detected. This information may also include a trajectory modification to solve the conflict.
In the sequel, we shall present and discuss possible alternatives for the resolution of the area-conflicts and for the identification of the areas-to-avoid.

2.4.1 Algorithm options

2.4.1.1 Area-conflict resolution

2.4.1.1.1 Alternative 1: Ground-holding

For the source of this option and more detailed information about it we refer to ([D5.1], Section 3.1).

Ground-holding is one of the most commonly used method in current ATM systems for Traffic Flow Management (TFM) operations. The idea is that aircraft that are scheduled to fly through some congested airspace region should be kept on ground until that region is not

congested anymore. The underlying philosophy is that ground-holding is safer and more cost-efficient than resorting to alternative actions during the airborne phase of the flight.
Effective algorithms are available in the literature for the implementation of the ground-holding method within a centralized strategic flow management tool. The main limitation of the method itself is that it cannot be applied to solve a congestion issue that an aircraft might encounter during its flight. Hence, it cannot be used for onboard TM but only for the pre-flight trajectory management operations, which aim at providing a strategically de-conflicted airspace prior to the actual flights taking place.

2.4.1.1.2 Alternative 2: Generalized traffic flow management

For the source of this option and more detailed information about it we refer to ([D5.1], Section 3.2).

A significant research effort has been devoted in the literature to the development of generalized TFM techniques (see Section 3.2 of [D5.1]). Differently from the ground-holding approach, in generalized TFM aircraft can be delayed also during the airborne phase of the flight, at specific points along their planned path, and not only before departure. These delays can be absorbed in different ways, through either airborne-holding or speed control. The idea is that this solution leads to a more effective use of the airspace capacity and potentially reduces the overall delay.
Interestingly, generalized TFM techniques can deal with area-conflicts that arise at some point during the aircraft flight, hence, in principle; they could be used also for onboard TM operations. At the current stage, however, the available algorithms seem to be able to work only on the ground, in a centralized fashion. The main reason is that airborne systems have limited computational power as compared to ground systems and the generalized TFM algorithms are computationally too demanding to be distributed onboard of the aircraft.

2.4.1.1.3 Alternative 3: Mid term conflict resolution with areas-to-avoid as constraints

For the source of this option and more detailed information about it we refer to [D5.2]

Long term area-conflict resolution could be addressed by using the algorithms conceived for mid term conflict resolution to solve the area-conflicts instead of mid term aircraft conflicts. As updated information on the areas-to-avoid becomes available onboard, suitable constraints could be enforced into the optimisation program solved by the mid term conflict resolution algorithm so that long-term area conflicts are avoided.
This method is briefly discussed in [D5.2] and appears quite interesting. However, no study is currently available to assess the feasibility of the approach. As in mid term conflict resolution, problems related to the convergence of a distributed implementation of the method may arise. Some – possibly implicit – coordination is needed to avoid situations where, for instance, all aircraft leave some congested area and end up generating and passing through another congested area.

2.4.1.1.4 Alternative 4: Flexible airspace cells with flow restrictions

For the source of this option and more detailed information about it we refer to ([D8.2], Section 4.2).

The flexible airspace cells with flow restrictions approach has been proposed in [D8.2] as a strategic flow measure to limit the need for short and mid term conflict resolution manoeuvres in a confined area in between closely spaced restricted volumes of airspace. The idea is that a set of triangular cells with specific flow restrictions and direction rules should be designed in order to avoid that traffic flows passing through the confined area cross each other.
Although the conceptual way of working has been developed, several aspects remain to be defined and assessed. In particular, flow restriction thresholds and rules need to be specified. Also, the possibility of dynamically redesigning the cells should be evaluated.

2.4.1.1.5 Alternative 5: Flexible schedules for flow restrictions

For the source of this option and more detailed information about it we refer to ([D8.2], Section 4.4).

The flexible schedules for flow restrictions approach has been proposed in [D8.2] as a mean for strategically deconflicting the confined areas in between closely spaced restricted volumes of airspace. Based on the RBTs of all aircraft, flexible schedules are determined so as to dynamically balance the demand with the available capacity in areas subject to flow restrictions. Further away from the flow restriction, aircraft are left a higher flexibility in their manoeuvring options. Only when needed, the flexible schedule becomes restrictive by prescribing specific arrival times at the flow restriction.
The approach has been proposed only at a conceptual level. Specific scheduling algorithms has to be developed and their performance in terms of safety, flexibility and fairness remains to be evaluated.

2.4.1.2 Area-to-avoid computation

As part of the strategic information about LTAZ, the automated ground surveillance support makes available to the aircraft the information about the area-to-avoid, which include areas with high air traffic complexity. This involves evaluating a suitable complexity metric across the airspace based on the RBTs of all aircraft stored in SWIM and applying some threshold to detect critical areas. Different complexity measures have been developed within WP3 and are briefly described next. For all of them, thresholds still need to be defined.

2.4.1.2.1 Alternative 6: Geometric characterization of complexity

For the source of this option and more detailed information about it we refer to ([D3.2], subsection 5.2)

Complexity is evaluated at each position and time instant along some look-ahead time horizon in terms of local airspace density within an ellipsoidal buffer region centred at that position, weighted nonlinearly with the direction of the aircraft motions at that time instant. The aircraft future positions are predicted based on their RBTs, neglecting the uncertainty affecting the

prediction. 4D (space cross time) maps are generated on a 3D spatial grid at discrete sampling times. Complexity maps along each single aircraft RBT can be extracted for TM purposes.
The metric is easy to compute. A key property is that it is additive, which makes computations scale linearly with the number of aircraft and simplifies the update of the complexity map when, e.g., a single aircraft RBT changes since one has only to subtract the original contribution of the aircraft and add the new one based on the updated RBT. Some design parameters (the size of the ellipsoidal region and the weights) have to be tuned.

2.4.1.2.2 Alternative 7: Complexity evaluated in terms of Lyapunov exponents

For the source of this option and more detailed information about it we refer to ([D3.2], Section 4)

Complexity is evaluated in terms of maximum local Lyapunov exponents of the dynamical system modelling the traffic over the considered look-ahead time horizon. The resulting measure expresses the local level of order/disorder of the traffic. 3D maps are generated on a 3D spatial grid. Timing information is lost when identifying the vector field defining the dynamical system based on the predicted position/velocity samples along the aircraft RBTs. Uncertainty affecting the future aircraft positions is not considered. The metric is computationally intensive to calculate and is not additive.

2.4.1.2.3 Alternative 8: Complexity evaluated in terms of local flexibility of a trajectory

For the source of this option and more detailed information about it we refer to [40]

Complexity is evaluated in terms of the extent to which the aircraft RBT can be modified locally without causing any interference with other aircraft. 4D (space cross time) maps can be generated as well as 1D maps representing the complexity values along the aircraft RBTs as a function of time.
The metric can be computed by borrowing tools from computational geometry; it is additive. Some design parameters related to the maximum admissible amount of local deviation need to be tuned. The uncertainty affecting the aircraft future position is not explicitly accounted for in the metric, since reference is made to the nominal RBTs.

2.4.1.2.4 Alternative 9: Probabilistic conflict-related measure of complexity

For the source of this option and more detailed information about it we refer to ([D3.2], subsection 5.1)

Complexity is evaluated in terms of probability that multiple aircraft occupy the same ellipsoidal buffer region in the same timeframe (probabilistic occupancy). Uncertainty affecting the prediction of the aircraft future position is explicitly accounted for. When the size of the buffer region resembles that of the protection zone surrounding an aircraft, the complexity measure can be used for multi-aircraft conflict prediction. 4D (space cross time) maps can be generated, as well as 1D complexity maps along the aircraft nominal RBT.
In the current implementation, analytical formulas are available for piecewise linear nominal trajectories, when the correlation between the future positions of different aircraft is neglected. The contribution of each aircraft to the complexity measure can be computed in

isolation and then combined with that of the other aircraft. This causes the computation effort to scale linearly with the number of aircraft and makes it easier updating the complexity map when just a few RBTs are modified. Some parameters related to the along-track and cross-track dispersion with respect to the nominal trajectory need to be tuned.

2.5 Cockpit/Airborne Functional Architecture

This section describes several options of airborne functional architecture supporting the self separation operations defined in A3 ConOps (iFly D1.3). For each of them a short description accompanied by a discussion of advantages/disadvantages is provided.

2.5.1 Options

2.5.1.1 *Cockpit/Airborne Functional Architecture Alternative 1*

For the source of this option and more detailed information about it we refer to [1].

This option (shown in Figure 7 below) is based on the functional architecture described in A3 ConOps. ASAS system encompasses Conflict Detection and Conflict Resolution processes, which are functionally separated from each other. Any resolution advisory from ASAS first goes to the flight crew: either in the form of a proposed RBT change (provided by Medium Term Conflict Resolution), or as a flight manoeuvre (from Short Term Conflict Resolution). An accepted MTCR advisory goes to FMS as a new RBT, while an approved STCR advisory is directly provided to flight guidance (autopilot). Only an RBT that is in the FMS will be broadcast. Hence, any RBT relevant (intent) information that is not yet within FMS will not be sent to surrounding aircraft.

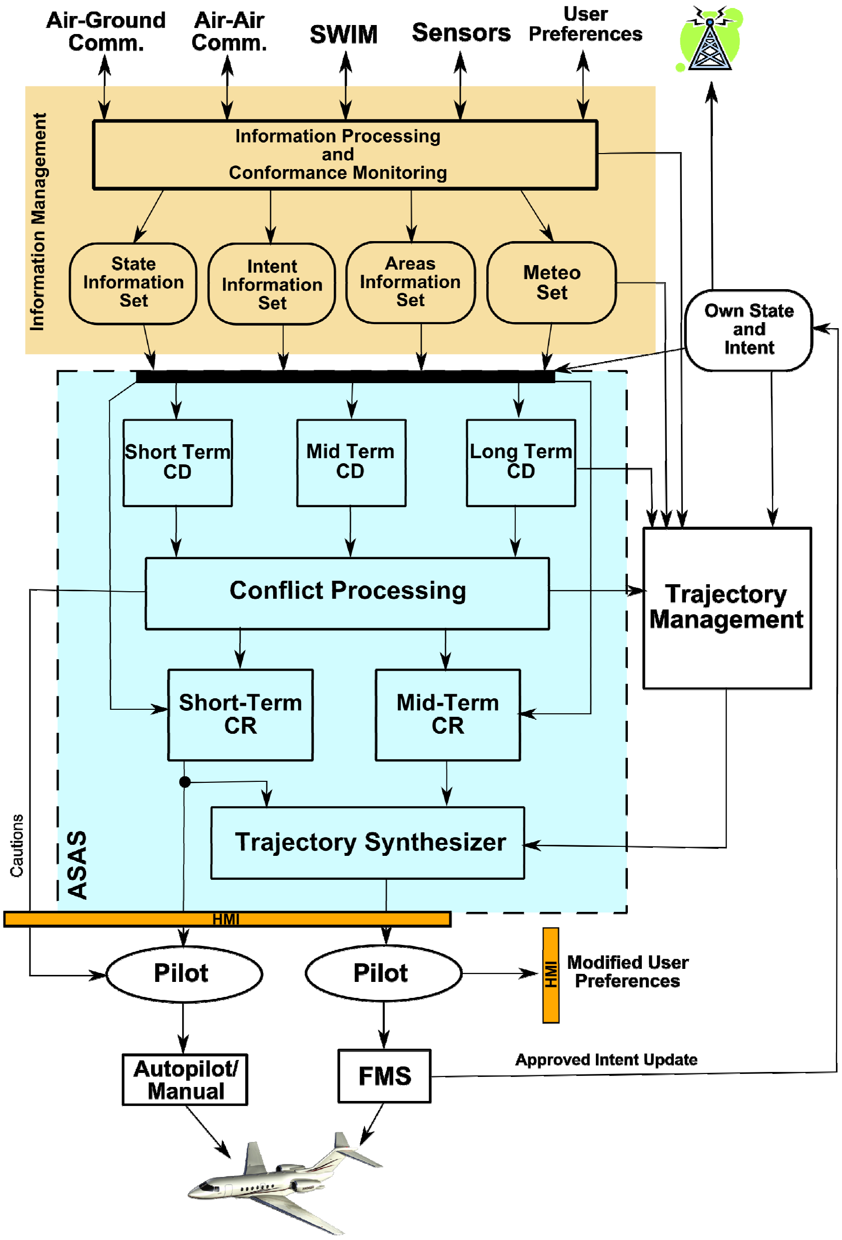

Figure 7 Airborne System functional architecture [iFly D1.3]

2.5.1.2 Cockpit/Airborne Functional Architecture Alternative 2

For the source of this option and more detailed information about it we refer to [27].

This option (shown in Figure 8) aims to combine the features of some specific conflict resolution methods developed in frame of the iFly WP5: Decentralized Navigation Functions (NF) used for short term CR, and Model Predictive Control (MPC) targeted to medium term timeframe. For this purpose, the conflict resolution process is reformulated as a hierarchical control problem where Model Predictive Control uses the intent information received from surrounding aircraft to set up (periodically) the optimal parameters for the Navigation Functions. The short term CR, based on these NFs, then ensures a conflict-free trajectory (through a direct coupling to autopilot/flight guidance) taking into account the actual state of surrounding aircraft.

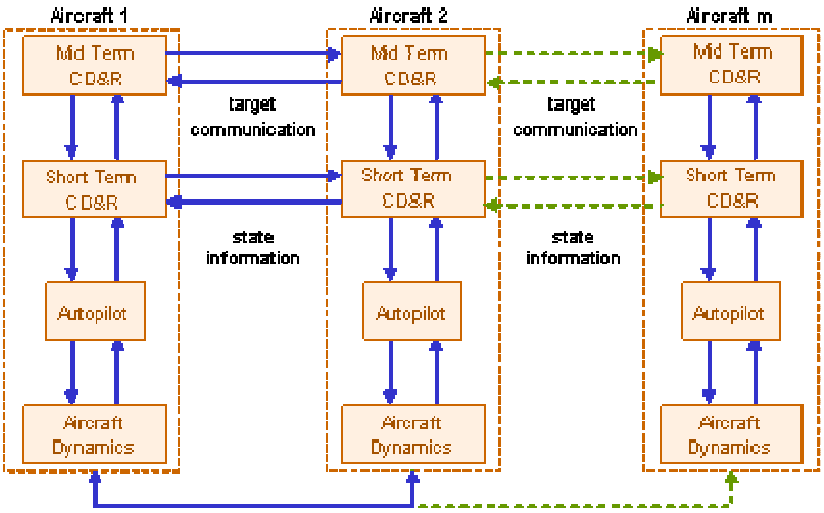

Figure 8 Airborne System Functional Architecture (iFly D5.3, p. 9)

2.5.1.3 *Cockpit/Airborne Functional Architecture Alternative 3*

For the source of this option and more detailed information about it we refer to [28] and [29].

This option (shown in Figure 9) represents a possible modification of the functional architecture presented in [1] (see Alternative 1). In this alternative, the pilot is directly in-the-loop making decisions (approving/accepting the trajectory changes proposed by onboard system) and taking action to manoeuvre the aircraft for mid-term and long-term conflicts, while the aircraft operates in an autonomous mode for short-term conflicts as CD&R information goes directly to the autopilot. The flight crew has also control over the communication with SWIM, i.e. to upload actual RBT as well as other relevant information for the flight that needs to be uploaded in SWIM to enable an efficient collaborative decision making process.

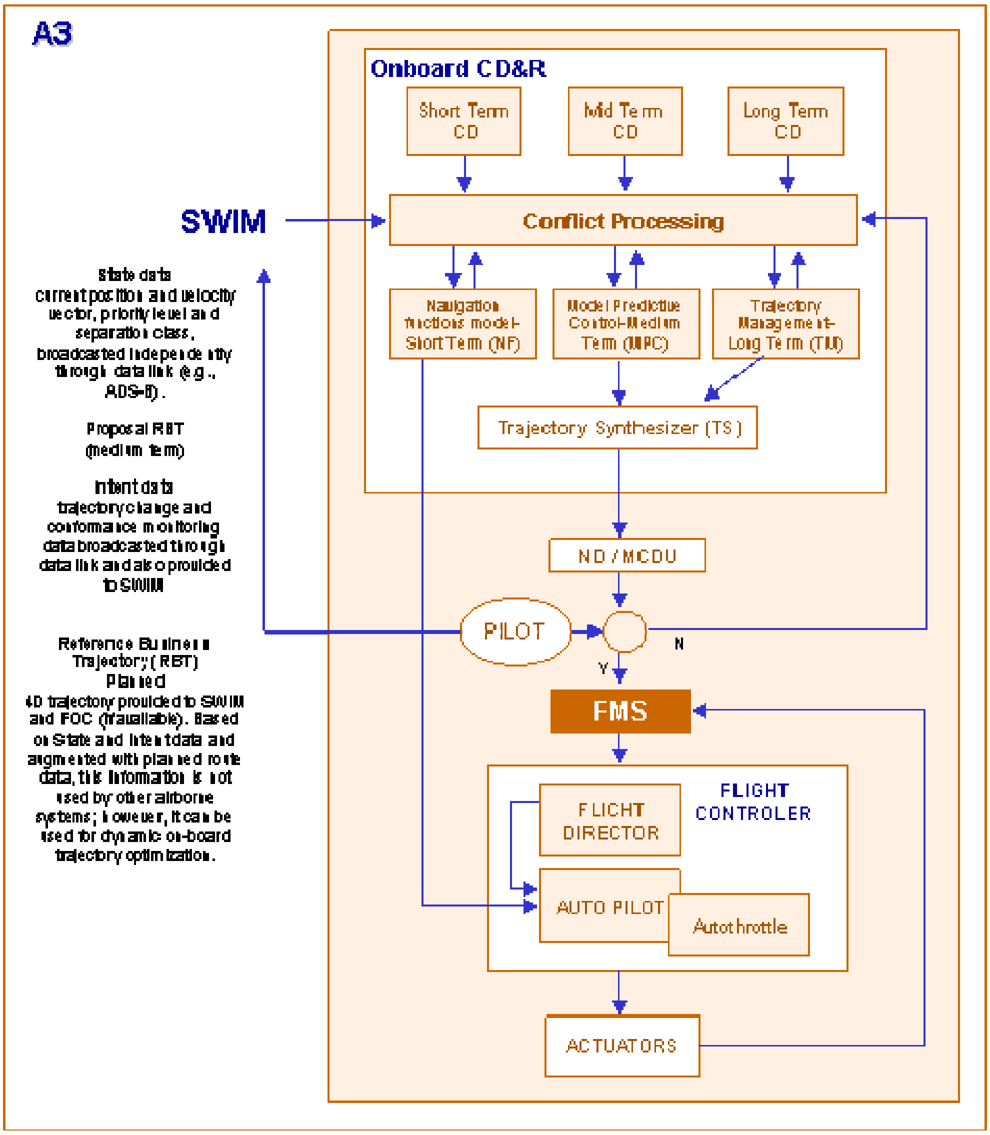

Figure 9 Airborne System Functional Architecture (Alternative 1 Evolution)

2.6 Multi Agent Situation Awareness

"Humans will be central in the future European ATM system as managers and decision-makers; In the ATM Target Concept it is recognized that humans (with appropriate skills and competences, duly authorized) will constitute the core of the future European ATM System's operations. However, to accommodate the expected traffic increase, an advanced level of automation support for the humans will be required.»(cf. SESAR, 2007).

The A^3 concept takes up the above mentioned statement and introduce the **aircrew as managers and decision-makers**, supported by onboard tools which will enable them to accomplish their new/ changed tasks. Having this in mind, the Human-Automation Interaction has been identified as a key issue to be looked at the stage of the development process. Besides, the ambitious goal of increasing efficiency of air traffic control requires distribution of tasks among autonomous agents. It is therefore necessary to guarantee that all the agents who participate in the decision have a similar if not identical perception of what the situation is. Because under strange non-nominal conditions loosing SA similarity is a risk, several SA mitigating measure options have been identified in the next subsection.

2.6.1 Options

2.6.1.1 *Multi Agent Situation Awareness Alternative 1: Acting upon disconformance identified between flightpath and intent of another aircraft.*

For the source of this option we refer to ([2], p. 19).

For each aircraft i there is an ASAS Conformance Monitoring support system which compares for each other aircraft j (i.e. for j unequal to i), whether the state information that i has about j agrees with the intent information that i has about j. In case aircraft i identifies a significant difference for aircraft j (e.g. when aircraft i has an intent for aircraft j to make a left turn but aircraft i has state information about aircraft j which shows that the turn is not being made by j) then the ASAS support system of aircraft i assumes that it does not has a reliable intent for aircraft j, and both Medium Term and Short Term CD&R of aircraft i stops using the intent information it has for aircraft j. From that moment on the ASAS CD&R of aircraft i works for aircraft j purely state based. This way of working continues until aircraft i has received state and/or intent information from aircraft j that agree with each other.

2.6.1.2 Multi Agent Situation Awareness Alternative 2: Mitigating critical states related to the absence of transmission.

For the source of this option and more detailed information about it we refer to ([39], p. 9).

[iFly D4.2] identified three critical states related to the absence of transmission. This type of failure is relatively simply detectable for onboard system. According to ([iFly D9.3], PR 16, PR19), specific update rates are required both for state and intent ADS-B messages. If information is not refreshed within the specified time period, information is marked as degraded and alternative information sources (SWIM, point-to-point data links) are used to get recent data. Furthermore, for the degraded intent information the trajectory prediction used in CD is reduced to a shorter look-ahead time [iFly D9.3PR.19). Also there is onboard conformance monitoring function, continuously comparing the received state data with the available intent information [iFly D9.3, PR.20) and again reducing the look-ahead time when a deviation is detected. Furthermore, an independent CD function working only with state data [iFly D9.3, PR.23) is required within ASAS equipment.

2.6.1.3 Multi Agent Situation Awareness Alternative 3: Mitigating critical states related to a failure of onboard (ASAS) equipment.

For the source of this option and more detailed information about it we refer to ([9], pp. 34-36) and [39].
The main mitigation mean for this type of failure are built-in test functions which inform flight crew about a failure of the system. Another backup is the situation awareness of the flight crew maintained through CDTI (OSA). However, this type of mitigation may be feasible only for short term time horizon (e.g., ATCo today considers about 5 minutes look ahead time only). The potential needs for further mitigation means should be identified within the concept validation.

2.6.1.4 Multi Agent Situation Awareness Alternative 4: Mitigating critical states related to the general failure of CD function.

For the source of this option and more detailed information about it we refer to ([9], pp. 43-46 & 57-59).
The main mitigation of the impact (effect**)** for this type of problems is the short-term CR with implicit coordination ensuring that the other conflicting aircraft will solve potential conflict even without the manoeuvring of own aircraft. Considering the prevention of this hazard, the flight crew situation awareness and training remain the main mitigation means. However, the same statement about the validation as in item 2 applies here.

2.6.1.5 Multi Agent Situation Awareness Alternative 5: Mitigating critical states that do not affect own onboard functions.

For the source of this option and more detailed information about it we refer to ([39], p. 15).

According to [D4.2, p.66], critical states that do not affect own onboard functions, are very difficult to detect onboard own aircraft. This has subsequently been addressed in [39]. In addition to built-in test function in transponder, it is assumed that within the SWIM there will be a conformance monitoring function (ASSUMP-OPA.4) detecting if there is no deviation between the known RBT and actual state information and will potentially inform surrounding aircraft. However these aspects are not yet quite developed in A^3 ConOps and remain to be refined based on the validation results.

3 Critical Analysis of all options

This Section provides an analysis of the Pros and Cons of all options identified in Section 2. Subsection 3.1 evaluates the surveillance options. Subsection 3.2 evaluates the Short Term Conflict Resolution options. Subsection 3.3 evaluates the Medium Term Conflict Resolution options. Subsection 3.4 evaluates the Medium Term Priority Rules. Subsection 3.5 evaluates the Long Term Approaches. Subsection 3.6 evaluates the Cockpit/Airborne Architecture options. Subsection 3.7 evaluates the Multi Agent Situation Awareness options.

3.1 Surveillance Alternatives

Surveillance Alternatives	
Advantages	**Disadvantages**
Surveillance Alternative 1: Space-based ADS-B	
• Over-the-horizon surveillance • There is a gain of independence from ground, so there is less dependency on SWIM • Due to the possible redundancy of data, improve the data reliability.	• Need of a great equipment investment (expensive constellation of satellites). • Possible gaps in coverage. • It would cause a delay in the information sharing. • Possible loss of robustness of signal because of the transmission between different equipments (satellite/ADS-B) and changes in the bandwidth. • Due to the possible redundancy of data, increase the amount of data and their processing.
Surveillance Alternative 2: Datalink for surveillance	
• The technology has already been proven. • It is possible the share of information.	• Possible changes in the bandwidth, possible latency • Expensive implementation and ground dependency. • Possible delay in the data reception.
Surveillance Alternative 3: Airborne Information Data-link Network	
• The technology has already been proven and it is being used in the military field (Link-16). • Cheap systems • It is possible the share of information. • Direct communications between aircrafts.	• Possible saturation of bandwidth and possible latency. • Delay in the information sharing • Dependency on other aircraft • At the moment the technology has been only used in the military field.
Surveillance Alternative 4: non Cooperative Sensors	
• The technology is proven and operative. • Due to the possible redundancy of data, improve the data reliability. • There is a fusion of information obtained though the sensors • Increase of the safety level • Decrease the processing time.	• There is a weight increase even though it doesn't seem very relevant. • Changes in the equipment location into the aircraft structure could be necessary in some cases. • Some devices would be limited to Short Term operations (short range). • High quality coordination is required from the number and quality of the message point of view. • Decrease of the safe level. • The role and responsibilities are not completely defined.

3.2 Short Term Conflict Resolution Alternatives.

Short Term Conflict Resolution Alternatives	
Advantages	**Disadvantages**
Short term CD&R Algorithm Alternative 1: Decentralized Navigation Functions	
• Formal conflict avoidance guarantee • Completely decentralised, Fast response and computationally efficient. • No implicit coordination (no direct coordination, all possible conflicts avoided) • No need for encounter definition – clustering, implicetely defined through sensing. • Bounded velocity, rate of climb, descent	• Integration of performance constraints not trivial • Performance optimization not considered (fuel consumption, time etc)
Short term CD&R Algorithm Alternative 2: Explicit coordination	
• Increase in the level of coordination – more efficient solutions may be possible. • Multiple algorithms for candidate solutions may be used.	• Conflict avoidance relies a lot on the performance, reliability and security of the communication systems. Susceptible to communication errors, attacks. • Explicit coordination is a complex and slow process – separate encounters/clusters must be defined beforehand and agreement must be reached • Require significantly more communication, while implicit coordination is possible just with surveillance data. •
Short term CD&R Algorithm Alternative 3: Cooperative maneuver	
• Deviations may be reduced, at least for simple conflicts • Efficiency improvements (time, fuel consumption etc)	• High quality and reliable coordination is required. • Each aircraft relies on the actions of its neighbors to ensure conflict avoidance. • The concept is not applicable to complex conflicts involving many aircraft. • The role and responsibilities are not completely defined.
Short term CD&R Algorithm Alternative 4: Short term Conflict Prevention	
• Preventive instead of reactive • Increase of the situation awareness • Can be used complementary to any short-term CDR algorithm	• Does not mitigate the need for conflict resolution once a conflict is detected • Clutter on display • Does not give information about the complete maneuver, only for current allowed heading/speed/ground speed • Decrease of the space available for

Short Term Conflict Resolution Alternatives	
Advantages	**Disadvantages**
	flying.
Short term CD&R Algorithm Alternative 5: Undershooting Minimum Separation Criteria.	
• May represent a viable option if a completely conflict-free solution cannot be found	• Unclear how, when and by who the effective separation minima will be (temporarily) reduced • May require recalculation for the STCR algorithm to use the reduced separation minima.
Short term CD&R Algorithm Alternative 6: Optimization techniques	
• Can provide optimal solution, if one exists within the space searched by the optimization algorithm.	• However, conflict avoidance yields non-convex optimization problems, which are computationally expensive (especially considering the fast response required in the short-term CD&R) and cannot guarantee that a solution will be found. • Worst case optimization approaches can guarantee safety once a solution is found, but are too conservative and encounters can quickly become infeasible for more than 2 aircraft.

3.3 Mid Term Conflict Resolution Alternatives.

<table>
<tr><th colspan="2">Medium Term Conflict Resolution</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td colspan="2">Mid term CD&R Algorithm Alternative 1.1: MMPC (Multiplexed Model Predictive Control)</td></tr>
<tr><td>• Explicit coordination results in conflict free flight plan adjustments.
• The algorithm can be robust to communication failure with SWIM.
• Coordination is maintained between all the aircrafts involved.
• It is supported by ground (SWIM) but without considering any controller.
• It is an approach to a multi-aircraft scenario.</td><td>• Method is not flexible enough to allow variable update order and intermediate changes of plans which might be desirable, in order to counter unanticipated disturbances arising from high wind velocities, or changes in conflict status from new aircraft entering the scenario.
• As changes in control are not performed between updates, the prediction horizon length is limited by having to find an initial plan to take into account future unknown disturbances.
• Synchronization implies efficient communication is required
• This approach assumes that multi-aircraft scenarios can be identified, but the way in which this is done has not been described.
• The priority rules defined by the ConOps are not use in the algorithm.</td></tr>
<tr><td colspan="2">Mid term CD&R Algorithm Alternative 1.2: MMPC with disturbance feedback</td></tr>
<tr><td>• More flexible scheme: changes in speed and heading can be applied every time step.
• The constraint that aircraft update their plan of actions according to a fixed pre-specified order is relaxed.
• Framework is more flexible than standard MMPC solutions when considering new aircraft entering and leaving the conflict region.</td><td>• Higher communication load is required since intermediate policy changes have to be updated.
• This approach assumes that multi-aircraft scenarios can be identified, but the way in which this is done has not been described.
• The algorithm is based on an initial input from SWIM.
• The priority rules defined by the ConOps are not use in the algorithm.
• The algorithm doesn’t provide any conflict resolution.</td></tr>
</table>

<table>
<tr><th colspan="2">Medium Term Conflict Resolution</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Mid term CD&R Algorithm Alternative 1.2.1: Fixed order MMPC with disturbance feedback</td></tr>
<tr><td>

More flexible scheme: changes in speed and heading can be applied every time step.
The constraint that aircraft update their plan of actions according to a fixed pre-specified order is relaxed.
Framework is more flexible than standard MMPC solutions when considering new aircraft entering and leaving the conflict region.
More restrictive fixed update is used.
Priority rules can be incorporated in the formulation.

</td><td>

Higher communication load is required since intermediate policy changes have to be updated.
This approach assumes that multi-aircraft scenarios can be identified, but the way in which this is done has not been described.
The algorithm is based on an initial input from SWIM.
The priority rules defined by the ConOps are not use in the algorithm.

</td></tr>
<tr><td colspan="2">Mid term CD&R Algorithm Alternative 1.2.2: Variable Update Order MMPC with disturbance feedback</td></tr>
<tr><td>

More flexible scheme: changes in speed and heading can be applied every time step.
The constraint that aircraft update their plan of actions according to a fixed pre-specified order is relaxed.
The framework is more flexible than standard MMPC solutions when considering new aircraft entering and leaving the conflict region.
The updating order does not have to be defined in advance.

</td><td>

Higher communication load is required since intermediate policy changes have to be updated.
This approach assumes that multi-aircraft scenarios can be identified, but the way in which this is done has not been described.
The algorithm is based on an initial input from SWIM.
The priority rules defined by the ConOps are not use in the algorithm. However, priorities are present, defined in an alternative way.

</td></tr>
<tr><td colspan="2">Mid term CD&R Algorithm Alternative 1.3: Decentralized MPC with a simplified AC model</td></tr>
<tr><td>

Straightforward to implement any priority rule.
Possibly the computation time is

</td><td>

Algorithm is still in progress.
It is not yet clear whether any guarantees on the performance of the algorithm can

</td></tr>
</table>

Medium Term Conflict Resolution	
Advantages	**Disadvantages**
expected to be less than the centralised algorithms.	be provided. • This approach assumes that multi-aircraft scenarios can be identified, but the way in which this is done has not been described.
Mid term CD&R Algorithm Alternative 2: Combined MPC and Short Term CD&R approach	
• It produces solutions that are compatible with the Short Term. In such a way, aircraft will not be placed in a situation that the Short Term CD&R algorithm will produce a solution contradicting with the already implemented solution of Mid Term CD&R. • It seems to scale better with the number of aircraft than the previously mentioned alternatives. • Taking into account the Short-Term, it may decide to resolve the conflict at the optimal level, minimizing the desired cost. • Introducing priority rules is straightforward in this formulation.	• Theoretical guarantees cannot be provided in terms of recursive feasibility as in alternatives 1.2, 1.2.1, 1.2.2... • The problem being solved in general is not guaranteed to be solved in reasonable time, as it can be its non-convex and this may be very inefficient in terms of computation. • This approach assumes that multi-aircraft scenarios can be identified, but the way in which this is done has not been described.
Mid term CD&R Algorithm Alternative 2.1: Combined MPC and Navigation Functions	
• It produces solutions that are compatible with the Short Term. In such a way, unnecessary actions from the Short-Term can be avoided, producing a solution compatible with the Navigation Functions. • Taking into account the Navigation Functions, it may decide to resolve the conflict at the optimal level, minimizing the desired cost. • Introducing priority rules is straightforward in this formulation. • This approach can be decentralized using heuristics, without violating the priority structure or the feasibility.	• Theoretical guarantees cannot be provided in terms of recursive feasibility as in alternatives 1.2, 1.2.1, 1.2.2. • The problem being solved in non-convex, i.e. analytically intractable. Therefore, the use of randomized optimization algorithms has been deployed, which sometimes is inefficient in terms of computation. • This approach assumes that multi-aircraft scenarios can be identified, but the way in which this is done has not been described.
Mid term CD&R Algorithm Alternative 3: Merge and Follow	

<table>
<tr><th colspan="2">Medium Term Conflict Resolution</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>The approach produces rather simple, intuitive maneuvers.</td><td>This approach prespecifies a very specific pattern for the resolutions, thus reducing the freedom of the maneuvering for aircraft.
No guarantees can be provided.</td></tr>
<tr><th colspan="2">Mid term CD&R Algorithm Alternative 4: Undershooting of planning separation minimum</th></tr>
<tr><td>Priorities can be implemented in a natural way.
In the event that a resolution cannot be found, this approach allows an aircraft to search for resolutions which give a separation less than the minimum required resolution. This is probably beneficial for the level of safety which is achieved. This technique could be used with most other resolution schemes.</td><td>There is no guarantee that this algorithm will resolve a certain situation.
It is not possible to know a priori (using this algorithm) the cases that the algorithm is able to resolve from the ones that it cannot.
It only allows one turn, the solution will be suboptimal, as maneuvers with more turns might be able to resolve conflicts more efficiently.
This approach assumes that multi-aircraft scenarios can be identified, but the way in which this is done has not been described.</td></tr>
<tr><th colspan="2">Mid term CD&R Algorithm Alternative 5: Pairwise conflict resolution algorithms found in literature</th></tr>
<tr><td>Algorithms already developed.
It could provide an optimal solution in single pairwise conflict.</td><td>Pairwise conflicts may create problems to other neighboring aircraft
It might not be able to handle a situation with more aircraft involved.
It unlikely seems that algorithms described in literature could be compatible with the A3 ConOps.
Most of the algorithms ignore the existence of the wind uncertainty, which may lead to unidentified conflicts or ineffective resolutions.
Not all methods can be solved efficiently in terms of computation when more than 2 aircraft are present.</td></tr>
</table>

3.4 Medium Term Priority Rules.

Medium Term Priority Rules	
Advantages	**Disadvantages**
Mid term Priority rules Alternative 1 : Simple pairwise priority scheme, initial iFly Concept of Operations	
• Only one aircraft must manoeuvre to resolve the potential conflict	• In situations which are more complicated than potential conflicts involving only two aircraft, e.g. 4 aircraft converging on a point, a pairwise priority scheme (if used as part of a distributed resolution scheme) can be expected to give rise to concurrent resolutions, resulting in incompatible trajectories. Such situations could be surprising and confusing for aircrews, and could prevent a target level of safety from being reached • Pairwise allocation of priority can sometimes designate an aircraft to manoeuvre which is “boxed-in” by surrounding aircraft. It is likely that this would prevent a real target level of safety from being reached
Mid term Priority rules Alternative 2: Pairwise priority scheme with priority reversal	
• A priority-reversal procedure could provide a second chance to resolve potential conflicts in which the aircraft which is initially designated as the lower priority aircraft cannot find a resolution. This could ameliorate the level of safety attained by a pariwise priority scheme	• This remains a pairwise priority scheme which (if used in a distributed resolution scheme) can be expected to create concurrent resolutions in situations which are more complicated than simple conflicting pairs of aircraft (see the earlier section “Simple pairwise priority scheme”) • Priority reversal would probably involve some kind of explicit coordination. Explicit coordination brings with it scope for further failures which might prevent a target level of safety from being reached
Mid term Priority rules Alternative 3: Pairwise priority scheme with priority reversal – The handicapped method	
• A low priority aircraft which cannot provide the full minimum required separation nonetheless provides the greatest separation which it can provide, before reversing priority. The (initially) higher priority aircraft in a two-aircraft	• This remains a pairwise priority scheme which (if used in a distributed resolution scheme) can be expected to create concurrent resolutions in situations which are more complicated than simple conflicting pairs of aircraft (see the

<table>
<tr><th colspan="2">Medium Term Priority Rules</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>conflict provides the remainder of the required separation. Providing the greatest possible separation before reversing priority probably has the safety benefit of reducing collision-risk in the event that the priority reversal fails</td><td>earlier section “Simple pairwise priority scheme”)</td></tr>
<tr><th colspan="2">Mid term Priority rules Alternative 4: FACES</th></tr>
<tr><td>Applicable to arbitrary groups of aircraft
No explicit coordination
Provable properties</td><td>This scheme could be described as decentralised ‘prioritised planning’ [38]. A weakness of ‘prioritised planning’ is that the choice of manoeuvring sequence can have dramatic effects on the feasibility and efficiency of the resolution. A centralised scheme can investigate many manoeuvring sequences, but attempting to do this in a decentralised way could require a great deal of explicit coordination. This criticism applies to all schemes which assume a particular manoeuvring sequence, and may well be a very strong argument for centralised resolution
There is an assumption of discrete time steps, so that all aircraft would need to share the same timebase</td></tr>
<tr><th colspan="2">Mid term Priority rules Alternative 5: Implicit Coordination</th></tr>
<tr><td>An approach to the distributed resolution of situations which are more complex than pairs of potentially conflicting aircraft
Avoids the use of explicit coordination</td><td>A proposal - no evaluation yet
The degree of generality of the approach is not clear. [37] describes a situation involving three aircraft. How well does this scheme work with situations involving four, five or more aircraft?</td></tr>
<tr><th colspan="2">Mid term Priority rules Alternative 6: Global Priority in MPC</th></tr>
<tr><td>Compared with the use of navigation functions on their own, the addition of the MPC layer allows dynamic constraints (i.e. real aircraft speeds) to be respected</td><td>The technique for identifying the set of aircraft involved in a situation has not yet been described
This approach has not yet been evaluated with realistic traffic</td></tr>
<tr><th colspan="2">Mid term Priority rules Alternative 7: Dynamic Priorities</th></tr>
<tr><td>This approach makes the priority determination process dynamic, and it is aligned with the principle that a detour for an aircraft which is near its destination tends to increase the distance to be flown more than for an aircraft that</td><td>In case 4D trajectory plans of one or more other aircraft are not received by an aircraft, then its calculated priority sequence may differ from the priority sequence that is calculated by other aircraft. In such case it may happen that</td></tr>
</table>

Medium Term Priority Rules	
Advantages	**Disadvantages**
is further away from its destination • The calculation of the priorities can be performed onboard each aircraft without the need of any coordination between aircraft.	medium term conflicts in 4D trajectory plans are not resolved, and remain to be resolved during short term conflict resolution.

3.5 Long Term Approaches.

Long Term Approaches	
Advantages	**Disadvantages**
Long term Alternative 1: Ground holding	
• Algorithms readily available in the literature	• Use confined to pre-flight management operations • Not extendable to en-route operations • Not applicable onboard
Long term Alternative 2: Generalized traffic flow management	
• Algorithms readily available in the literature • Suitable also for en-route TM operations	• Not applicable onboard for TM operations, due to the computational load
Long term Alternative 3: Mid-term conflict resolution with areas-to avoid as constraints	
• Mid term aircraft conflicts could also be accounted for while solving the area-conflicts • Both on the ground and onboard solutions are possible	• No algorithm is currently available. • Some form of coordination is needed to avoid convergence problems in the distributed implementation
Long term Alternative 4: Flexible airspace cells with flow restrictions:	
• Strategically de-conflicting action that should reduce the need for short and mid term conflict resolution maneuvers in confined airspace regions • Possible use of simple geometric rules to design the airspace cells and define the direction rules that apply to those cells	• No algorithm is currently available • ground support function that reduces the aircraft autonomy, though only in confined airspace regions in between restricted areas
Long term Alternative 5: Flexible schedules for flow restrictions	
• Strategically de-conflicting action that should reduce the need for short and mid term conflict resolution maneuvers in confined airspace regions • Aircraft arrival times at flow restrictions subject to a strict schedule only if this is absolutely necessary • Flexible schedules can be applied from days before the aircraft is planned to reach the flow restriction to a few minutes before. In the former case, the schedule will typically have a large flexibility. When getting closer to the actual arrival time, flexibility will be reduced when appropriate.	• Flexible scheduling algorithms are currently not available • Fairness remains to be verified • Ground support function that reduces the aircraft autonomy only when needed and only in confined airspace regions in between restricted areas
Long term Alternative 6: Geometric characterization of complexity	

Long Term Approaches	
Advantages	**Disadvantages**
• Easy to compute • Additive metric	• Thresholds for defining the critical areas-to-avoid need to be set • Some design parameters have to be tuned • Uncertainty on the future aircraft positions is neglected
Long term Alternative 7: Lyaponuv exponents	
• Studies available in the literature on the complexity metric performance, though only within the actual ATM system	• Thresholds for defining the critical areas-to-avoid need to be set • Computationally demanding • Not additive measure • Timing information is lost • Uncertainty on the future aircraft positions is neglected
Long term Alternative 8: Local trajectory flexibility	
• Easy to compute through computational geometry tools, especially in the 2D case (level flight) • Additive metric	• Thresholds for defining the critical areas-to-avoid need to be set • Some design parameters have to be tuned • Computational procedure in 3D airspace should be refined • Uncertainty on the future aircraft positions is neglected
Long term Alternative 9: Conflict probability	
• Analytical formulas available for an efficient computation of the complexity measure • Uncertainty on the future aircraft positions is explicitly accounted for • The measure is strictly related with the probability of conflict • The contribution to complexity of each aircraft can be computed in isolation and then combined with that of the other aircraft	• Thresholds for defining the critical areas-to-avoid need to be set • Some design parameters have to be tuned • Correlation between the future positions of different aircraft is neglected in the current implementation

3.6 Cockpit/Airborne System Functional Architecture Alternatives.

Cockpit/Airborne System Functional Architecture Alternatives	
Advantages	**Disadvantages**
Cockpit/Airborne System Functional Architecture Alternative 1 (follows A3 ConOps in D1.3)	
• Functional architecture meets targeted to A3 ConOps (meets operational requirements) • Pilot is in the loop	• Potential limitations of the optional CD&R algorithms is not yet known
Cockpit/Airborne System Functional Architecture Alternative 2(proposed in WP5)	
• Functional architecture targeted to specific CD&R algorithms. • Flight performance constraints taken into account	• Pilot is out of the loop • Many CD&R algorithms do not match this architecture
Cockpit/Airborne System Functional Architecture: Alternative 3 (proposed in WP8 based on A3 ConOps in D1.3 evolution)	
• Functional architecture combined with specific CD&R algorithms. • Pilot in the loop	• Complex requirements on the Conflict Processing block resulting from algorithms needs • Many CD&R algorithms do not match this architecture

3.7 Multi Agent Situation Awareness Alternatives.

Multi Agent Situation Awareness Alternatives	
Advantages	**Disadvantages**
Multi Agent Situation Awareness Alternative 1: Acting upon disconformance identified between flightpath and intent of another aircraft	
• This approach does not require new technical devices for the application of the mitigation mean. • Avoiding the use of an intent that is likely to be unreliable.	• Own aircraft implicitly reduces its RBT based prediction horizon for all aircraft of which own aircraft identifies a significant devation between RBT and actual flightpath. • In case of many surrounding aircraft, information received by ASAS may hamper maintaining an undelayed situation awareness, and then the mitigating measure also starts working.
Multi Agent Situation Awareness Alternative 2: Mitigating critical states related to the absence of transmission.	
• This approach does not require new technical devices to cope with absence of transmission and is therefore based on built-in functions (it is expected that the existing/planned (SESAR) communication means can be used for additional communications). • Minor or none degradation of the situation awareness • Data back-up through additional sources of information.	• There may be higher latency of additional communication means (lower update rate). • Handling of potential discrepancy between data from different sources shall be carefully designed (recent data obtained from other information sources may significantly differ from the actual one, thus causing a remarkable reduction of situation awareness).
Multi Agent Situation Awareness Alternative 3: Mitigating critical states related to the failure of onboard (ASAS) equipment	
• This approach does not require new technical devices to cope with failure of onboard (ASAS) equipment, because the built-in functions already are common in the avionics	• Satisfactoriness of the mitigation means needs to be verified. • This type of situation assessment is feasible only for short term time horizon.
Multi Agent Situation Awareness Alternative 4: Mitigating critical states related to the general failure of CD functions	
• This approach does not require new technical devices.	• Satisfactoriness of the mitigation means needs to be verified • If a failure of CD functions occurs to more than one conflicting aircraft the mitigation mean does not work properly. •
Multi Agent Situation Awareness Alternative 5: Mitigating critical states that do not affect own onboard functions	

Multi Agent Situation Awareness Alternatives	
Advantages	**Disadvantages**
• This approach would introduce new important functionality for situation awareness inconsistencies detection	• Actual technical instrumentation does not support this mitigation mean (however, it is expected that the current or already planned (SESAR) communication means could be used for this purpose).

4 Findings of iFly simulation results for various options

This Section discusses evaluation results obtained in iFly work packages WP3, WP4, WP5 and WP7 for the various options identified and evaluated in Section 2 and Section 3 respectively. Subsection 4.1 addresses the surveillance options. Subsection 4.2 addresses the Short Term Conflict Resolution options. Subsection 4.3 addresses the Medium Term Conflict Resolution options. Subsection 4.4 addresses the Medium Term Priority Rules. Subsection 4.5 addresses the Long Term Approaches. Subsection 4.6 addresses the Cockpit/Airborne Architecture options. Subsection 4.7 addresses the Multi Agent Situation Awareness options.

4.1 Surveillance

The options proposed are:
Surveillance Alternative 1: Space-based ADS-B
Surveillance Alternative 2: Datalink for surveillance
Surveillance Alternative 3: Airborne Information Data-link Network
Surveillance Alternative 4: non Cooperative Sensors

None of these four surveillance options have explicitly been simulated in any of the WP's. However, results obtained in WP7, implicitly support the value of considering these options.

Options 1, 2 and 3 all are potentially valuable contributions to the development of a highly dependable SWIM system. And such a highly dependable SWIM system is needed in order to relay ADS-B information to aircraft for which the line-of-sight is over the horizon. Results obtained within the rare event MC simulations of WP7 confirm that this is an important need.

Regarding Option 4, the rare event MC simulation results obtained in WP7 show that for very high traffic demands, there is a need to improve current GNSS regarding its global dependability performance. Option 4 definitively forms a valuable alternative to avoid this need in improving the global dependability of GNSS.

This leads us to the conclusion that each of the four proposed surveillance alternatives are expected to be of potential value in the further development of the A3 ConOps.

4.2 Short Term Conflict Resolution

The options proposed are:
SCD&R Option 0: Velocity Obstacles based conflict resolution
SCD&R Option 1: Decentralized Navigation Functions
SCD&R Option 2: Explicit coordination
SCD&R Option 3: Cooperative maneuver
SCD&R Option 4: Short term Conflict Prevention
SCD&R Option 5: Undershooting Minimum Separation Criteria.
SCD&R Option 6: Optimization techniques

Of these seven SCD&R options, no simulation results have been obtained for options 2 and 6. The reason is that integration of these options 2 and 6 has been judged to be computationally too demanding (both within WP5 and within WP7). For the other four options explicit or implicit simulation results have been obtained for planar flight conditions only (i.e. all aircraft stay at the same flight level).

SCD&R option 1 (which implicitly includes options 3, 4 and 5) has been simulated within WP5 SCD&R under the assumption that the output of the decentralized NF algorithm is directly used for control of the aircraft (i.e. without any interference of the crew), and all systems are assumed to work perfectly. In [iFly D5.3] simulation results are given for a five aircraft encounter example. This encounter was resolved well, and without underscoring minimum separation criteria. However, one of the aircraft made very large accelerations in air speed (more than $2.5\, m/s^2$). These are unrealistically large values for en-route flying commercial aircraft. In [iFly D5.4] large scale simulations have been conducted, with traffic demand 3x as high as central Europe in 2006. Also here NF resolved all conflicts well, and without underscoring the minimum separation minimum. Moreover, the extra distance to be flown was between 0.75% and 1.5%. In view of the many unrealistic assumptions (e.g. aircraft performance, no crew interference, no system failures) these simulation results only show that the theoretical principle of NF based SCD&R works. However it is not yet clear whether an NF based algorithm works as well in a more realistic simulation set-up.

Within [iFly D7.4], SCD&R Options 0, 4 and 5 have jointly been evaluated through running large scale simulations. The simulations were of rare event Monte Carlo simulation type and covered practical issues such as crew decision-making, implementation of their decision, and the various possibilities for system failures. The rare event MC simulation results obtained are very good, also under very high en-route traffic demand. This shows that it is feasible to have a very well working SCD&R by combining:

- Velocity Obstacles based conflict resolution (option 0) and prevention (option 4)
- If needed to allow (option 5) an aircraft to implement and transmit a course change which requires (an)other aircraft to help realizing the minimum separation criteria.

In conclusion, the combination of Options 0, 4 and 5 has proven to fit well within the A3 ConOps design. Regarding option 1 (NF), the question remains what the value would be of replacing Velocity Obstacles based SCD&R by a realistic implementation of decentralized NF (Option 1) in the rare event MC simulations.

Because all simulations performed within iFly assume that aircraft keep on flying at the same flight level, a remaining issue is to include height effects into the SCD&R algorithm and to evaluate the performance on safety, capacity and efficiency using large scale simulations.

4.3 Medium Term Conflict Resolution

The specific options proposed are:
MCD&R Option 0: Velocity Obstacles based conflict resolution
MCD&R Option 1.1: MMPC (Multiplexed Model Predictive Control)
MCD&R Option 1.2.1: Fixed order MMPC with disturbance feedback
MCD&R Option 1.2.2: Variable Update Order MMPC with disturbance feedback
MCD&R Option 1.3: Decentralized MPC with a simplified AC model
MCD&R Option 2.1: Combined MPC and Navigation Functions

MCD&R Option 3: Merge and Follow
MCD&R Option 4: Undershooting minimum separation between plans
MCD&R Option 5: Pairwise conflict resolution algorithms found in literature

Of these nine MCD&R options, no simulation results have been obtained for options 1.1, 3 and 5. For the other MCD&R options planar flight conditions only have been simulated (i.e. all aircraft stay at their flight level), and the results are documented in [iFly D5.3], [iFly D5.4] and [iFly D7.4].

In [iFly D5.3], specific encounters between 3-5 aircraft have been studied for MCD&R options 1.1, 1.2.1, 1.2.2, 1.3 and 2.1. In all these simulations the flight crew was assumed to be out of the loop, and there were no failures. The simulations conducted for Option 2.1 included varying wind effects. The simulation results were positive for all options.

In [iFly D5.4], large scale traffic (3x European traffic in 2006) has been simulated for MCD&R options 1.2.1, 1.2.2 and 1.3, the flight crew was assumed to be out of the loop, and there were no failures. For options 1.2.1 and 1.2.2 reduced sets of this large scale data has been simulated only. The simulations results obtained show that options 1.2.1 and 1.2.2 have significant difficulties in handling very large traffic scenarios in an effective way. The simulation results obtained for option 1.3 are more promising. Nevertheless also here there was no 100% escape from the curse of complexity; as a result of which some 20% of the cases were put aside. Moreover, optimization regarding flight level allocation is not considered. For option 1.3, the extra distance flown under 3x 2006 traffic demand has been measured to vary between 1.5 and 2.2 %.

Within [iFly D7.4], MCD&R Option 0 has been evaluated in combination with Option 4, using large scale MC simulations including human in the loop and capturing various hazards. The main reason for adopting Option 4 is to have a simple approach in solving box-in situations, i.e. a lower priority aircraft is boxed in between 4D planned trajectories of higher priority aircraft. The rare event MC simulations obtained show that using this Option 4 in combination with Velocity Obstacles based MCD&R works very well under very high traffic demands. The simulated traffic demand was 3x busiest area in 2005, which leads to an average aircraft density that is twice as high as considered in [iFly D5.4].

In conclusion, MCD&R Options 0, 1.3 and 4 are the most promising candidates for integration in the A^3 ConOps. Options 0 and 4 have the advantage that their proper working has been shown under realistic conditions regarding pilots in the loop and potential failures. Option 1.3 has the advantage that it aims to minimize the extra distance jointly flown in a combinatorial way. The open question is how this compares to the extra distance flown under MCD&R options 0 and 4. In order to find this out, the approach simulated within [iFly D7.4] should also be run for the large scale traffic scenario and the results obtained should be compared to those obtained with the combinatorial optimization approach of Option 1.3.

For all Options applies that they remain to be extended to include height. Subsequently additional MC simulations have to be performed in order to validate their proper working.

4.4 Medium Term Priority Rules

The options proposed are:

Priority Option 1: Simple pairwise priority scheme, initial iFly Concept of Operations
Priority Option 2: Pairwise priority scheme with priority reversal
Priority Option 3: Pairwise priority scheme with priority reversal – The handicapped method
Priority Option 4: FACES
Priority Option 5: Implicit Coordination
Priority Option 6: Global priority in MPC
Priority Option 7: Dynamic Priorities

Of these seven Priority options, no simulation results have been obtained for options 2, 4 and 5. For the other Priority options planar flight conditions only have been simulated (i.e. all aircraft stay at their flight level), and the results are documented in [iFly D5.3], [iFly D5.4] and [iFly D7.4].

In [iFly D5.3] priority Options 1 and 6 have been tested in simulation. The results obtained show that existence of these priority schemes allows the algorithms to quickly identify the aircraft that need to maneuver, and that this leads to a relative small loss in flight efficiency only.

In [iFly D5.4] priority Option 1 has been combined with MCD&R Option 1.3 and tested in simulations for 3x 2006 European traffic scenarios. This has shown to work very well. However, one should be aware that, generally speaking, assigning priorities restricts the resolution algorithm and therefore affects the resolution cost (e.g. total extra fuel burnt, extra distance flown, etc).

Within [iFly D7.4], Priority Options 3 and 7 have been evaluated. Option 7 has been developed in order to adhere to the principle that the further an aircraft is away from its destination the less costly it is to deviate from its plan in resolving a conflict. Option 3 (the handicapped method) is needed in case a lower priority aircraft that has no alternative then to go for a 4D plan that is in conflict with the 4D trajectory plan of a higher priority aircraft. Thanks to the handicap broadcast, the higher priority aircraft knows it looses its higher priority and should help resolving any remaining conflict in 4D trajectories. The rare event MC simulations obtained show that both Option 3 and Option 7 work very well.

In conclusion, the advantage of adopting priority and handicap rules has proven to be quite helpful in mitigating the complexity of the combinatorial problem. From this perspective it is recommended to incorporate Priority Options 3 and 7 in MCD&R approach.

4.5 Long Term Approaches

The options proposed are:
Long term Alternative 1: Ground holding
Long term Alternative 2: Generalized traffic flow management
Long term Alternative 3: Mid-term conflict resolution with areas-to avoid as constraints
Long term Alternative 4: Flexible airspace cells with flow restrictions
Long term Alternative 5: Flexible schedules for flow restrictions
Long term Alternative 6: Geometric characterization of complexity
Long term Alternative 7: Lyaponuv exponents
Long term Alternative 8: Local trajectory flexibility
Long term Alternative 9: Conflict probability

Long Term alternatives 1-5 have not been studied within iFly. Long Term Alternatives 6-9 have been studied within WP3.

Alternative 1 is based on ground-holding for which there are sort of algorithms available.
Alternative 2 (generalized traffic flow management) is in need of algorithms that require less computational load.
For Alternatives 3-5 algorithms remain to be developed.

The complexity metrics proposed in Alternatives 6 to 9 are determined based on the aircraft predicted trajectories (positions and velocity). As a consequence, they all account for both density and traffic dynamics when assessing the traffic complexity. Only in Alternative 9, uncertainty in the future aircraft position is considered when evaluating complexity.
Among Alternatives 6 to 9, Alternative 7 appeared to be the most computationally demanding. Though some improvement was achieved within the iFly project, the approach remains critical for application to high density airspace. Also, in its current implementation timing information is neglected so that situations where two aircraft get close to the other rather than occupy close positions but in different time slots may be undistinguishable. The approach has been recently extended to solve this issue, but this extension appears even more computationally intensive.
The complexity metric proposed in Alternative 8 turned out to be highly sensitive to some design parameters when applied to 3D airspace and was not further studied nor tested.
Since the goal of the geometric approach to complexity in Alternative 6 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 operations and, more specifically, for the identification of those complex areas that the aircraft should better avoid in order to reduce the need for excessive tactical manoeuvring. These areas could be computed on the ground based on the aircraft RBTs and distributed onboard to support trajectory management operations.
Through a correlation analysis with collision risk, the probabilistic method in Alternative 9 was found to be better suited for supporting onboard mid term conflict detection and resolution operations by predicting those air traffic configurations that are difficult to control and may overload the ASAS conflict resolution module.
A possibility to explore is then to adopt a combined approach where both the approaches in Alternative 6 and 9 are used: one to support onboard trajectory management operations and the other one to support distributed conflict detection and resolution operations. Apart from the weaknesses related to the individual approaches, some further weaknesses could emerge from the co-existence of the two methods. The analysis of this issue deserves further investigation.

4.6 Cockpit/Airborne Architecture

The options proposed are:
Architecture Option 1 (follows A3 ConOps in D1.3)
Architecture Option 2 (proposed in WP5)
Architecture Option 3 (proposed in WP8 based on A3 ConOps in D1.3 evolution)

Option 1 and Option 2 have been used in the Monte Carlo simulations of WP7 and WP5 respectively. Within WP5, the pilot and the systems followed (exactly and without delay) the outcomes of the decision support system. Within WP7, the human performance model was more refined, i.e it included a simulation model of the cognitive performance of the pilots in using the outputs of the decision support system in support of their own decision-making. Both within WP5 and WP7 options 1 and 2 have shown to work well.

Development of new airborne applications typically requires several iterative steps to design cockpit/airborne system and the first approach may appear already within the development of a concept of operations. Although a limited amount of information is available at this stage, in most cases the overall role of the airborne system, its interaction with the human actors (flight crew) as well as main associated operational procedures are already known. This can be used for drafting a high level system architecture describing main functional elements associated with the different parts of the envisioned onboard processes (e.g., conflict detection, conflict resolution, etc.). Such initial design can be particularly useful in case of a subsequent distributed development of individual concept elements (e.g., of different types of algorithms) as it allows preliminary assessment of their applicability in the overall concept.

From the perspective of avionics development the next step is refinement of the initial definition of operations (concept of operations) into the Operational Services and Environment Description (OSED) and derivation of the resulting operational requirements. The latter are further complemented with the requirements generated within the operational performance and safety assessments of the concept. All these results are then used for definition of airborne functional requirements and the functional architecture results from mapping of the functional requirements on concrete airborne systems. It is at this stage when the limitations of the available algorithms and data shall be already taken into account and appropriate mitigation means will be designed when some of the applicable requirements cannot be satisfied directly.

The alternatives presented in this document are related to the initial (conceptual) approach to the airborne system design. The alternative 1 was proposed directly in the A3 Concept of Operation (D1.3), and therefore it implicitly fits in the proposed concept. Nevertheless, the limitations of potential algorithms, existing onboard systems, current communication technologies, etc., are not taken into account in this type of design.

As developed algorithms typically does not fit exactly to the conceptual design, their validation requires an alternative design which may slightly deviate from the original concept. This is the case of the alternative 2, developed for validation of conflict resolution algorithms (WP5), where the main discrepancy (with respect to the A3 ConOps) lies in the fact that the pilot is out of the loop for short-term conflict resolution in this architecture.

Finally, the alternative 3 was developed in frame of WP8 and it aims to combine the two previous alternatives into one design.

The parallel process leading to a more detailed functional architecture of airborne system was in the scope of iFly WP9, where the OSED (D9.1), preliminary operational safety assessment (D9.2) and operational performance assessment (D9.3) were performed and the results were incorporated into a high-level functional design (D9.4).

The future steps should be based on combining the detailed functional definition (WP9) with the results of algorithms validation (WP3, WP4, WP5) considered together with the architecture design used for their validation, as well as with quantitative performance and safety requirements resulting from the operational validation of the concept itself. The final goal of this future activity should be a refined functional architecture design of the onboard system for airborne self separation.

4.7 Multi Agent Situation Awareness

The alternatives proposed are:
MASA Option 1: Acting upon disconformance between flightpath and intent of other aircraft
MASA Option 2: Mitigating critical states related to the absence of transmission.
MASA Option 3: Mitigating critical states related to the failure of onboard (ASAS) equipment
MASA Option 4: Mitigating critical states related to the general failure of CD functions
MASA Option 5: Mitigating critical states that do not affect own onboard functions

In [iFly D7.4] MASA Option 1 only has been evaluated. The rare event MC simulation results obtained show that the way option 1 has been implemented is working well.

Because managing the consistency of shared SA is of crucial importance for the safety of A3 operations, it is recommended that for the other four MASA options the basic ideas proposed in [iFly D4.2] are further developed and tested.

5 Concluding remarks.

This report has studied the best directions for further refinement of the A^3 ConOps from [iFly D1.3]. The options still open within the A^3 ConOps are further analysed and consequently reduced by taking advantage of the outcomes of WP3 (Prediction of complex traffic conditions), WP4 (Multi-agent Situation Awareness consistency analysis), WP5 (Pushing the limits of conflict resolution algorithms), WP7 (Safety/capacity analysis of A^3 ConOps) and WP9 (Safety requirements analysis). Specific options have been identified and analysed in this report for the following six functionalities within the A^3 ConOps:

- Surveillance;
- Short Term Conflict Detection & Resolution;
- Medium Term Conflict Detection & Resolution;
- Long Term Approaches;
- Cockpit/airborne functional architecture;
- Mult Agent Situation Awareness.

Regarding Surveillance, four relevant surveillance options have been identified to be of high potential value in the further development of the A3 ConOps. These four are: Space-based ADS-B, Datalink for surveillance, Airborne Information Data-link Network, and Non-Cooperative Sensors.

Regarding SCD&R, the following approach has proven to fit well within the A3 ConOps design: Velocity Obstacles based conflict resolution and prevention, in combination with allowance of a temporarily undershooting of minimum separation minima in case there is no alternative. Rare event MC simulations have shown that in the latter case typically other neighboring aircraft help resolving the remaining conflicts within the applicable separation minima. Also simulations conducted with the NF based SDC&R approach has shown remarkably results. Nevertheless, there are several issues that remain to be addressed before an NF based SDC&R approach forms a valid alternative. The key remaining issues are:

- How to avoid unrealistically large accelerations in air speed?
- How to implement NF approach such that crew remains in the loop?
- Is NF able to handle failure situations in a resilient way?

An additional issue is that all simulations performed within iFly considered aircraft flying at the same flight level. Hence a remaining issue is to include height effects into the SCD&R algorithm and to evaluate the performance on safety, capacity and efficiency using large scale simulations which include the various aspects of the intended A3 ConOps.

Regarding MCD&R, two approaches have proven to be the most promising candidates for adequate refinement of the A3 ConOps design;

i) Decentralized MPC with a simplified aircraft model, and adhering to a pairwise priority scheme;
ii) Velocity Obstacles based conflict resolution in combination with the allowance to temporarily undershoot minimum separation minima if there is no alternative way out, and Dynamic prioritization with priority reversal if needed (using handicap broadcasting).

The latter approach has the advantage that their proper working has been shown under realistic conditions regarding pilots in the loop and potential failures. The former approach has the advantage that it aims to minimize the extra distance jointly flown in a combinatorial way. The open questions are;

- How approaches i) and ii) compare regarding the extra distance flown?
- Whether approach ii) can be made as resilient as approach i) has proven to be?

The former question remains to be investigated by running large scale traffic scenario for both options and to compare the extra distance and fuel results obtained. The latter question should address how to avoid the need to discard too complex cases (e.g. 20%) and how to deal with missing information. For example, to use approach ii) as a resilient back-up in the few cases that approach i) falls short?
Finally, for both approaches i) and ii) applies that they remain to be extended to include height. Subsequently additional MC simulations have to be performed in order to validate their proper working.

Regarding Long Term Approaches, several existing and novel approaches have been identified (nine in total). Based on the analysis performed and the simulations conducted, there is no objective argument to give priority to any of the nine proposed options. This remains for further evaluation in follow-up research. In doing so, it also seems to be of crucial importance to take into account which MCD&R methods eventually are being selected.

Regarding cockpit/airborne architecture, three approaches have been identified. One approach was fully in line with the architecture in the A3 ConOps. The other two had some novel aspects which in theory might have an advantage, whereas interfacing with the crew was not completely solved. The one in line with the A3 ConOps only has undergone large scale simulations, and the outcomes of these simulations are very positive. For this reason it is recommended to stick to the cockpit/airborne architecture of the original A3 ConOps [iFly D1.3].

Regarding managing consistency in Multi Agent Situation Awareness, five options have been identified. Only one of these five has been tested through large scale MC simulations, and the results obtained were positive. Because this area is so new and unexplored, we recommend that all five MASA approaches are further studied and evaluated in future follow-up research.

I A^3 operations

Under the A^3 ConOps, a typical airborne self separation flight may have the following progression. When an aircraft takes off from an airport it first climbs through a Terminal Manoeuvring Area (TMA), where the traffic flow is controlled by the Air Navigation Service Provider (ANSP) who is responsible for aircraft separation. Already at that moment in time for each flight there is an agreed and shared flight trajectory plan (so-called Reference Business Trajectory (RBT)) up to the destination allowing to balance the capacity/demand enroute and at the destination TMA and airport. For this purpose there is a flow constraint associated to the flight at the entering fix of the destination TMA in the form of a 3D point with a Constrained Time of Arrival (CTA) restriction.

From the moment that the aircraft leaves the TMA, it enters the en route Self Separation Airspace (SSA), and the responsibility for separation is shifted from the ANSP to the flight crew. Once being within SSA, the flight crew can modify the SSA-part of the RBT without negotiation with any ANSP, provided that defined Autonomous Flight Rules (AFR) are satisfied and that the CTA at the destination TMA will be achieved. In case there is a need to modify the current CTA constraint, then the change must be negotiated with the ANSP of the destination TMA. In SSA the aircraft need not follow any predefined airway structure. When the aircraft approaches the destination TMA, the responsibility for separation is shifted back from the flight crew to the ANSP and the self-separation part of the flight is terminated.

According to the A^3 ConOps, within SSA information exchange between aircraft is assured through **datalink**. Voice communication will be limited and mainly for use under emergency situations. When flying in SSA, each aircraft is obliged to broadcast information about its state and intent to the other aircraft. This allows each aircraft to predict the intended trajectories of all aircraft, and to act such that minimum separation criteria are not violated.

Coordination of actions by conflicting aircraft is done in line with the AFR, which are binding to all participants. The A^3 ConOps also foresees that aircraft that cannot be reached by broadcasting receive the missing information through a **System Wide Information Managemen**t (SWIM) network.

In order to ensure separation and onboard trajectory management tasks, the flight crew takes advantage of the onboard equipment, which is monitoring the surroundings and helps the flight crew to detect and resolve conflicts. The onboard equipment supports two lines of defence in the timely resolution of potential conflicts: **Medium Term Conflict Resolution** (MTCR) and **Short Term Conflict Resolution** (STCR).

The time horizon for **MTCR** starts out some 5 to 20 minutes prior to potential loss of separation (LoS) and the resolution is based on **priority rules** (see section xxx). When a Medium Term Conflict between two aircraft is detected, then the aircraft having lowest priority has to resolve the conflict. The aircraft with higher priority simply continues to fly its original trajectory. The priority of an aircraft evolves during the flight and is primary determined by the aircraft manoeuvrability, mission statement and the remaining time to CTA. The lower priority aircraft should adapt its RBT in order to solve the conflict as well as not creating a conflict with any of the other aircraft RBT's. Ideally, all conflicts should be solved through the Medium Term Conflict Resolution line of defence.

When the **MTCR** equipment proposes a change in the intent, it first has to be approved by the flight crew, then its own RBT is updated and then the aircraft broadcast their new intent to other aircraft.

When the **MTCR** line of defence is not able to solve the conflict then the next line of defence is Short Term Conflict Resolution (STCR). STCR starts some 5 minutes ahead of potential loss of minimum separation (LoS). When such an event is detected, then no priority exists and all aircraft involved have to manoeuvre The applied manoeuvres shall be coordinated through so-called implicit coordination. Implicit coordination means the use of compatible algorithms that generate complementary manoeuvres when used by involved conflicting aircraft. In case this second line of defence does not timely resolve all potential conflicts, then TCAS forms the third line of defence.

II Acronyms List

Acronym	Definition
A^3	Autonomous Aircraft Advanced
A^4	Autonomous Aircraft Advanced ATM-Supported
ACARS	Aircraft Communication Addressing and Reporting System
ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependant Surveillance - Broadcast
ADS-C	Automatic Dependant Surveillance - Contract
AFR	Autonomous Flight Rules
AIS	Aeronautical Information Service
AMAN	Arrival Manager
ANSP	Air Navigation Services Provider
AOM	Airspace Organisation & Management
ASAS	Airborne Separation Assurance and Conflict Avoidance System
ASAS	Airborne Separation Assistance System
ASEP	Airborne Separation
ASP	Aeronautical Surveillance Panel
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATN/CLNP	Air Traffic Network/Connectionless Network Protocol
ATS	Air Traffic Services
ATSEP	Air Traffic Safety Electronics Personnel
CD	Conflict Detection
CD&R	Conflict Detection and Resolution
CDM	Collaborative Decision Making
CDTI	Cockpit Display of Traffic Information
CNS	Communication, Navigation and Surveillance
ConOps	Concept of Operations
COTS	Commercial Off-The-Shelf
CP	Conflict Prevention
CR	Conflict Resolution
CSZ	Comfort Separation Zone
CTA	Controlled Time of Arrival
DCB	Demand and Capacity Balancing
DL	Data Link
DST	Decision Support Tools
ECC	Error Correction Codes
EGPWS	Enhanced Ground Proximity Warning System
FACES	Free flight Autonomous and Coordinated Embarked Solver
FFAS	Free Flight Airspace (outdated)
FMS	Flight Management System
FOC	Flight Operations Centre
GA	General Aviation
GNSS	Global Navigation Surveillance System

Acronym	Definition
HF	Human Factors
HMI	Human Machine Interface
HS	Head of State
IAS	Indicated Airspeed
ICAO	International Civil Aircraft Association
IFR	Instrumental Flight Rules
IOC	Initial Operational Capability
IP	Implementation Package
LoC	Lines of Change
LoS	Loss of Separation
LTACD	Long Term Area Conflict Detection
LTAZ	Long Term Awareness Zone
MA	Managed Airspace
MC	Monte Carlo
MET	Meteorological Service
MMPC	Multiplexed Model Predictive Control
MSZ	Minimum Separation Zone
MOC	Minimum Obstacle Clearance
MTAZ	Medium Term Awareness Zone
MPC	Model Predictive Control
MTCD&R	Medium Term CD&R
NFU	Non-FOC Airspace User
NVFR	Night Visual Flight Rules
OI	Operational Improvement
OPA	Operational Performance Assessment
OPSP	Operations Panel
OSA	Operational Safety Assessment
PANS	Procedures for Air Navigation Services
PAZ	Protected Airspace Zone
PBA	Performance Based Airspace
R/T	Radio Telecommunications
RAA	Restricted Airspace Area
RBT	Reference Business Trajectory
RNP	Required Navigation Performance
RNPC	RNP Capability
RSP	Required Surveillance Performance
RTA	Required Time of Arrival
RTD	Research, Technology and Development
RVSM	Reduced Vertical Separation Minima
S&M	Sequencing and Merging
SA	Situational Awareness
SARP	Standards and Recommended Practices
SASP	Separation and Airspace Safety Panel
SBT	Shared Business Trajectory
SES	Single European Sky
SESAR	SES Advanced Research

Acronym	Definition
SFM	Strategic Flow Management
SI	Spacing Interval
SL1	Service Level 1
SL2	Service Level 2
SL3	Service Level 3
SM	Separation Minima
SSEP	Airborne Self Separation
SSR	Secondary Surveillance Radar
STAZ	Short Term Awareness Zone
STCD&R	Short Term CD&R
SVFR	Special Visual Flight Rules
SWIM	System Wide Information Management System
TA	Traffic Alert
TBD	To Be Defined
TCAS	Tactical Collision Avoidance System
TCP	Trajectory Change Point
TIS-B	Traffic Information Service - Broadcast
TIS-C	TIS-Contract
TMA	Terminal Area
TS	Trajectory Synthesizer
TTF	Traffic To Follow
UA	Unmanaged Airspace
UAV	Unmanned Air Vehicle
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
WHA	Weather Hazard Areas
WP	Work Package

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