Network Management under uncertainty

The ONBOARD project: research objectives and current status

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***Foreword*— This paper describes a project that is part of SESAR Workpackage E, which is addressing long-term and innovative research. The project was started early 2011 so this description is limited to an outline of the project objectives augmented by some early findings.**

***Abstract*— The ONBOARD project aims at improving the performances of the ATM system (e.g. predictability) in the planning and execution phases by developing new models and algorithms to enable the Network Manager to better manage the two factors that account for two thirds of the ATFM delay in Europe (weather and knock-on effects), in particular by addressing the key sources of uncertainty (weather forecast, unscheduled demand, and the airspace users response to disruptions). This paper describes the specific research objectives, expected results and the current status of the project.**

Keywords—network management, airspace users planning, uncertainty management, disruption recovery

I. Introduction

One of the difficulties in improving the performances of the ATM system (e.g. delays) is that it presents many of the features associated with a Complex System, i.e. there are a lot of sources of uncertainty in the initial conditions (e.g. unscheduled demand) and the environment (e.g. weather), it involves many agents (e.g. airspace users) that adapt their behavior to the system state, and the dynamics of the constituents of the system (e.g. the aircrafts) are no linear and may present a chaotic behavior (e.g. due to the knock-on effect).

However, neither nowadays, nor in the SESAR concept of operations, are those complex features of the ATM system addressed in order to exploit to the limit the performances improvement that they could yield. For instance, the uncertainty in the ATM planning phase is usually managed by contingency planning (e.g. predefined recovery plans), robust planning (to make an operation plan resilient to small changes) and re-planning.

Hence, these methods pose a challenge for improvement because the information that could be available on the uncertainty associated with the system is not used, in particular airspace users may update dynamically their robust operational plan or even prepare dynamically alternative courses of action (recovery plans), and the network manager may dynamically prepare alternative capacity and traffic load scenarios that may actually happen taking into account not only the available uncertainty information (e.g. unscheduled demand and weather) but also the alternative courses of action that airspace users have planned.

Furthermore, it is envisioned that if the network manager received not only the alternative course of actions that the airspace users had planned to cope with adverse probable scenarios but also the relevant information on the operational links between their scheduled flights in the nominal plan (i.e. the connection between flights that may cause rotational delays) when deciding how to balance demand and capacity, the overall outcome would mitigate the knock-on effects and therefore improve the performances of the ATM system (e.g. predictability).

II. Project Objectives

The goal of the ONBOARD project is to research how to exploit the key features of the ATM system as a complex system (uncertainty, adaptive agents, and non-linearity) in the Network Management planning and execution phases to benefit the ATM performance.

Furthermore, this project will focus on the two factors that jointly account nowadays for two thirds of the total ATFM delay in Europe, i.e. weather and knock-on effects.

The attainment of this goal will be based mainly on the prototyping of a brand new decision making model (including its mathematical models and algorithms) for the Network Manager in the planning and execution phases that will take into account as distinctive features: a) the flights connections information provided by the airspace users for their nominal plan, b) the uncertainty information on the unscheduled demand and the probabilistic weather forecast and c) the alternative recovery plans that the airspace users would prepare to deal with the adverse scenarios.

To include all these features into a Network Manager algorithm for decision making that could be used operationally (i.e. able to solve a large dimension problem in a operationally reasonable runtime) is a very challenging task well beyond the state-of-the-art, especially if MILP techniques were used to solve the problem in the domain of individual trajectories, because the number of variables involved (and hence the computational time) grow rapidly when increasing the modeling resolution (e.g. time step) or the model size (e.g. number of flights).

On the contrary, when MPC techniques are used to solve aggregated models the model size does not depend on the number of flights, so finding near-optimal solutions may be achieved in a short computational time. However, robust MPC has not been applied to the ATM demand and capacity balance problem despite its very promising characteristics, which seem especially well-suited to address the research questions of this project.

Hence, robust MPC techniques will be used for the first time in the ATM domain to solve the demand and capacity problem under uncertainty in operationally representative (e.g. problem size, computation time) conditions.

To accomplish the overall goal just described we first aim at defining an operational concept and the expected operational improvements that we expect it would bring to the ATM system (in terms of KPIs), then we intend to build a prototype (Evaluation Platform) that will integrate the new algorithms (Network Management and Airspace Users Planning) necessary to assess, in a third step, and by running the proper set of Evaluation Exercises (designed to represent a real operational setting, in terms of scenario size, runtime performances, closed-loop dynamics of the ATM agents emulated, etc.) the ATM benefits that could be achieved with the operational concept and underlying technologies developed.

The Evaluation Platform will consist of two main components, the Network Manager (NM) and the Airspace Users Operations Centre (AOC) prototypes, being their main goal to integrate the new algorithms to be developed in the project, and to exchange data in closed loop in a way that resemble their expected operational dynamical behavior.

Fig. 1 below depicts the high level logical architecture envisioned for the ONBOARD Evaluation Platform.

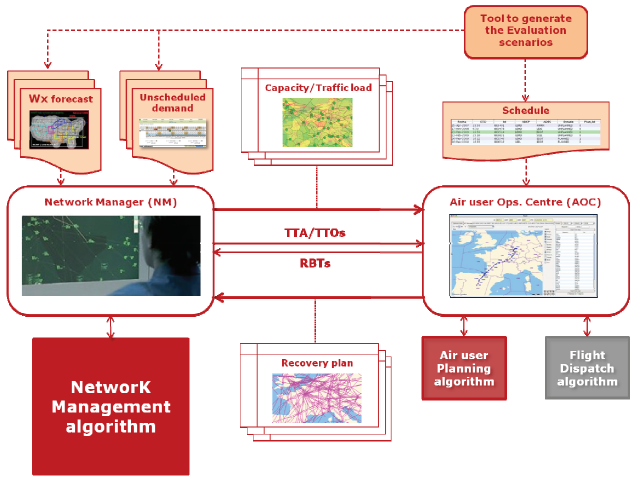

Figure 1. ONBOARD Evaluation Platform logical architecture

Two brand new algorithms will be developed, the Network Management algorithm, which is the core research goal of the project, and the Airspace User Planning algorithm, that not only pursuits its own research challenges but it is absolutely necessary in the project to interact with the Network Management algorithm.

The main role of the Airspace User Planning algorithm will be to calculate the necessary airspace user recovery plans to cope with adverse scenarios (e.g. significant traffic congestion at an airport or at an airspace volume), by updating the aircraft rotation plan (e.g. delaying, re-routing or cancelling flights; swapping slots) and retiming part of the flights schedule until the original flight schedule can be resumed

Two types of deliverables will be produced in the project, namely documents (being the main deliverables the Operational Concept, the Algorithmic Framework Definition, the Evaluation Platform User Manual, and the Evaluation Exercises Report) and Software prototypes (being the main deliverables the Network Management and the Airspace User Planning algorithms integrated into the NM and AOC components of the Evaluation Platform).

III. CONCEPT OF OPERATIONS

In the ONBOARD project we aim to contribute to the SESAR research main stream, and consequently we have taken the SESAR concept of operations as reference.

Moreover, it is worth noticing that if some of the research concepts we are proposing in ONBOARD were eventually implemented in SESAR they would require some changes to the SESAR concept of operations as it is understood today, but those changes must be seen as an evolution (e.g. requiring that some of the ATM actors received or exchanged additional data items, such as a probabilistic weather forecast or an enhanced 4D trajectory including information on flights connection) and not as an operational concept breakthrough.

Thus, one of the first steps of the ONBOARD project has consisted in reviewing the documentation available on the SESAR concept of operations (we have used [1] and [2] for that purpose) in order to, on the one hand, identify the operational phases, layers and principles that we want to address and, on the other, to point out to the data and control flows (and the processes concerned) that would be affected if the ONBOARD operational changes were implemented

However, the SESAR concept of operations only addresses partially how the airspace users are expected to plan their operations in the future: in fact, only the trajectory management process (due to its relationship with the network management process) is analyzed in detail, as Fig 2. (taken from [3]) illustrates.

Finally, one must notice that in ONBOARD we will not be able to model and implement all the detailed processes involved in the complete network management problem. On the contrary, we need to make some simplifications (described later in this paper) that will allow us to reach some tangible results out of the project while addressing the key research questions and keeping a realistic representation of the problem.

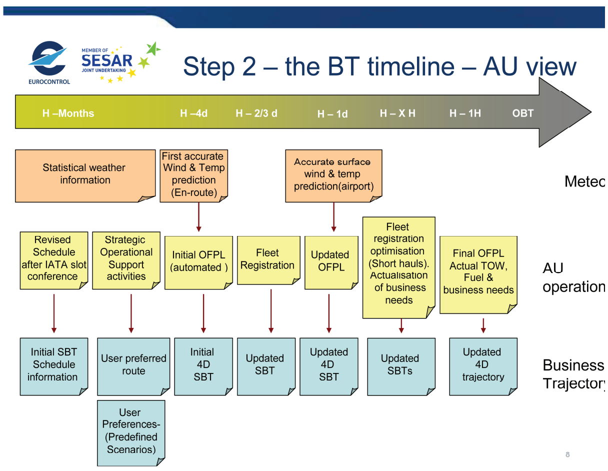

Figure 2. Air users trajectory management as seen by SESAR ([3])

A. *Network Management*

Using the terminology of [1] and [2] in the ONBOARD project we want to address the medium/short term planning and execution *operational phases*, the Network Management (local and sub-regional) and Airspace user operations (trajectory management) *operational layers*, and the Network Management and Air user operations (when interacting with the network management function) *operating principles*.

Therefore, we have reviewed the processes and sub-processes concerned, and we have identified those relevant for the ONBOARD project and how they may need to change, as the example depicted in Fig.3 outlines

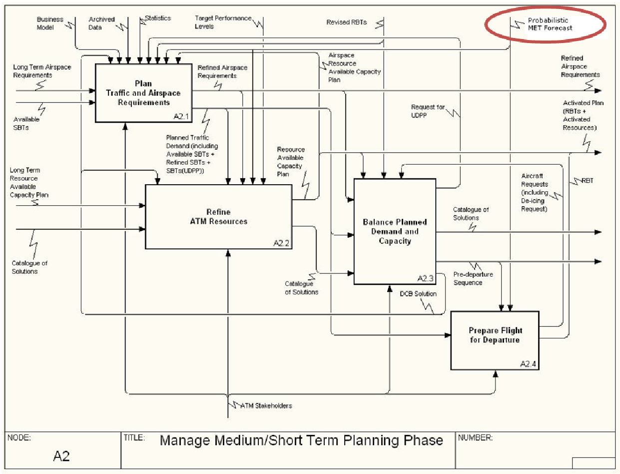

Figure 3. Manage Medium/Short Term Planning Phase in ONBOARD

B. *Airspace User Operations Planning*

Determining the operational plan of an airline is a very complex problem consisting in finding a flight schedule (i.e. a set of flight legs, each one defined by a departure and arrival airport, and a departure and arrival dates and times), an airline resources plan (aircrafts and crews, but also arrival and departure slots at the airports), and the flight plans for each individual flight leg that, all together, maximizes/minimizes an objective function (e.g. expressed in terms of revenue, direct operations cost, or other operational performances such as robustness, flexibility or recoverability) satisfying a large number of technical and operational constraints and airline policies (e.g. for buffer times, stand by resources).

Furthermore, once an operations plan for the next planning period is determined (e.g. for the next six months period in the case of scheduled airlines), it needs to be verified and updated (if necessary) in a rolling window fashion in order to cope with unforeseen changes that may disrupt (or, on the contrary, pose an opportunity for improvement) of the initial operations plan.

The problem of disruption recovery presents its own specific features, both in terms of operational decisions that can be taken (e.g. cancel flights, call in reserve crews, deny boarding to passengers) and in terms of additional cost factors (e.g. passenger compensation), operational performances (e.g. stability) and level of service parameters (e.g. number of disrupted passengers) to be considered.

The current approach to solve this complex problem has some distinctive characteristics:

- Operations planning (when the flight schedule is determined) is separated from operations control (when the flight plan of each flight is calculated): the link between the two planning steps is established through the calculation in the first step of the CI nominal value (and allowed CI range) which is then passed on, several days prior to the scheduled flight departure, to the second step where the optimum flight plan is calculated few hours prior to the actual departure.

- Operations planning are carried out in a staggered manner: for instance, once the flight schedule is defined, to calculate the aircrafts plan a fleet assignment and a maintenance routing problems are solved sequentially, and then refined/updated (e.g. tails may be assigned up to few hours prior to departure) as the plan gets closer to execution (and a similar staggered process is followed to define the crew plan)
- The operations disruption recovery is also carried out in a staggered manner: typically the first step consists in re-routing the aircrafts (delaying and cancelling flights if necessary), next crew is re-routed (and reserve crew called in), and finally passengers are re-accommodated.
- The operations planning and disruption recovery as well as operations control are calculated solving deterministic problems which, in some cases, incorporate some features that aims at taking into account the intrinsic uncertainty present in the problem (e.g. robustness indicators such as the length of the ground buffers, or flexibility indicators such as the number of aircrafts on ground or the potential aircraft and crew swaps, are considered in the objective function of the planning process that is optimized).

To overcome these limitations there are several research trends that aim at be part of the common air uses operational practice in the short to the midterm:

1) Integrated operations planning, solving simultaneously the optimal assignment of airspace user resources (aircraft, crew) to the flight schedule in order to satisfy the passengers itineraries; this line of research is the more prolific and present a lot of examples in the literature, solving partial integrated operations planning, e.g. fleet assignment and aircraft routing; fleet assignment and passengers demand (so called Itinerary Based Fleet Assignment); or flight re-timing, aircraft routing and passenger re-accommodation

2) Integration of operations planning and operations control for disruption recovery (see [4]), that proposes a new approach and optimization algorithms to calculate the optimum recovery plan (in terms of minimizing the direct operations cost associated with fuel consumption and passengers re-accommodation) combining flight schedule re-timing (and flight cancellations), aircrafts re-routing (keeping the maintenance plan unchanged and ensuring that the aircrafts rotation is preserved at the end of the recovery window), and passengers re-booking with modification of the flight plans (changing the CI of the flights up to half an hour prior to their departure).

3) Predictive optimization for robust operations planning (see [5]), that is a new approach that aims at minimizing the expected cost of delay propagation along the operational plan (through the aircrafts rotation knock-on effect) of a primary delay and block deviation statistical scenario that is generated on the basis of delay historical data collected for the network concerned. To calculate the optimum operational plan the proposed algorithms are able to simultaneously calculate the optimum flight times, aircraft rotations and crew pairing.

4) Multi-objective optimization addressing passenger centric operations, where a weighted combination of direct operational costs, operational performances (e.g. efficiency, robustness, flexibility, stability or predictability) and level of service (e.g. on the basis of delays, misconnections or cancellations suffered by the passengers) are proposed as the appropriate objective function to be considered when determining the optimum plan.

C. Project scope and simplifications

As it was mentioned before in this paper, in the ONBOARD project we are going to focus on those aspects of the network management process that we consider key for the purpose of our research and so, we need to make some assumptions and simplifications in the ATM actors, operating principles, and simulation scenarios (e.g. in terms of air traffic pattern and the airspace structure) we want to tackle:

1) ATM actors: in ONBOARD we are not going to model as independent entities (as far as the DCB processes are concerned) the regional, sub-regional and local (ACC, airports) DCB actors. Therefore, there are some research issues that we are not going to address in this project such as

- How to deal with different DCB actors with different planning cycles, different (and possibly overlapping) planning horizons, and different (and possibly contradictory) goals.
- How to deal with different DCB actors that make decisions on certain segments (e.g. departure, en-route phase within an ACC or a FAB, arrival) of a (possibly overlapping) subset of the flights that form the overall traffic (e.g. flights departing from an airport, flights going through a FAB).
- And hence, how to ensure that the ATM performances at network level are achieved in a collaborative distributed decisions making context (e.g. what type of DCB actors' coordination is needed and what type of role the regional network manager needs to play).

Nevertheless, the key goal of the ONBOARD project is to research how the performances of an ATM system formed by an actor that represents the airspace users demand and an actor that solves the mismatch between network capacity and demand by means of multi-scoped queue management are improved when uncertainty information on capacity and demand, on the one hand, and network-wide information, on the other, are collected, exchanged and used by those two actors.

Furthermore, as Fig. 4 illustrates below, we think that a single network management actor (representing either a local or a Sub-Regional Network Manager) very well represents within the ONBOARD context the complex interactions that may arise between all the DCB actors (airports, local, sub-regional and regional network managers) involved.

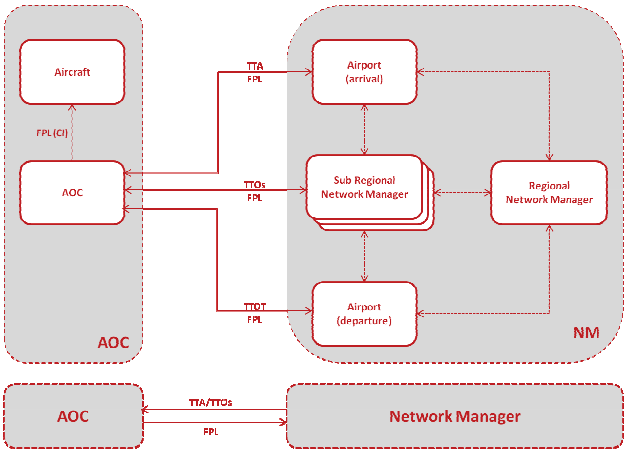

Figure 4. DCB actors in the Network Management planning phase

Hence, we envision that the conclusions that we will draw from the ONBOARD project will be to a large extent applicable to each of the DCB actors individually.

2) Operating principles, in ONBOARD we are going to model the queue management actions that the Network Manager could take to balance demand and capacity, but not the capacity management actions that it could had taken before. Anyhow, as far as the queue management process is concerned, we intend to model it as close as possible (except for the UDPP that will not be modeled) to the SESAR concept of operations (as in [1] and [2]). In particular, the following operating principles are worth mentioning:

- Short term planning and the execution phase are interlaced, and thus the NOP is a dynamic rolling plan for continuous operations rather than a series of discrete daily plans.
- The network includes both the airspace and the airports ("airport-in-the-network").
- The reference traffic demand will be based on intentions and predictions.
- DCB will not optimize just flows, regardless of the flights they consist of.
- The Network Manager will assess the network resource situation with regard to potential demand and will set a TTA/TTO on the congested point. The airspace user will decide on how to absorb the delay.
- The DCB solution will need to meet the SLAs on the day of operations.
- The NOP will provide visibility on the demand and capacity to the airspace users.
- Trajectories revisions are initiated by the airspace users or on any other ATM stakeholder request.

3) Traffic pattern and airspace structure, finally, there are other simplifications and assumptions that we are going to consider in ONBOARD and that are worth mentioning:

- Only IFR GAT traffic flying within the ECAC will be modeled. Thus, inbound and outbound IFR GAT traffic external to the ECAC, VFR flights, and OAT traffic are excluded. Besides, military airspace reservations are not considered either.
- Free route airspace and a constant airspace configuration will be assumed. Thus, no ATS routes or temporary route structures, FL usage constraints, etc. will be considered. Besides, dynamic airspace configuration will not be considered either.
- The 4D trajectory that any aircraft flies in the execution phase is assumed to coincide exactly with the predicted trajectory calculated in the planning phase (i.e. the effect of wind uncertainty or any other cause of deviation will not be considered either).

Note that the simplifications and assumptions presented in this section may change throughout the project to take account of stakeholder's feedback, SESAR program evolution, and intermediate research results of the project.

Besides, in the last phase of the project it is envisaged to review and assess the final set of simplifications and assumptions made in order to evaluate the validity of the research conclusions drawn from the project and, specially, to analyze their potential extrapolation to the SESAR context.

IV. Expected Benefits

The ONBOARD project shares the same objectives of SESAR, i.e. to carry out research activities to develop new technologies (that currently do not form part of the SESAR mainstream) in order to bring additional ATM performances improvement in the long term.

Hence, to assess the benefits brought by the concepts and algorithms proposed by ONBOARD in the simulation exercises we have planned in the project we will need to calculate the same KPIs that SESAR proposes (see [1]).

However, in ONBOARD we are not going to address the full list of those KPIs (e.g. environmental sustainability), but only the subset of KPIs that can be calculated (or the network manager decisions based upon) on the basis of the planned and realized time of departure, block time, and time of arrival of any individual flight; its fuel consumption, and on the basis of any modification (retiming or full update) and/or cancellation of any individual flight in the planning or execution phases.

These KPIs are: fuel efficiency (occurrence and severity), temporal efficiency (occurrence and severity), flexibility for retiming (demand flexibility, frequency, severity) and full business trajectory update (demand flexibility, frequency, severity), and predictability expressed in terms of knock-on effect (number of cancelled flights, reactionary delay), arrival punctuality (frequency, severity), block time variation, and service disruption (number of cancelled flights and total delay due to disruption per type of disruption)

V. State of the Art

The goal of the ONBOARD project is to improve ATM performance by explicitly incorporating information about uncertainty into the traffic flow management. This naturally brings together two technologies: robust Model Predictive Control (MPC), which addresses the incorporation of uncertainty models into online optimization; and optimization of air traffic flow.

MPC provides a rigorous and well-researched framework for on-line planning and re-planning, including analysis of stability and robustness. The key challenge of applying robust MPC is to find the right balance between (i) predicting a response to every eventuality, giving high performance at high computational expense, and (ii) trying to find one solution that fits all eventualities, giving conservative performance but a much simpler optimization to solve.

In terms of handling stochastic uncertainty, two families of work dominate, corresponding to different extremes in the trade above. Chance-constrained MPC is well developed, but primarily for a particular class of uncertainty, Gaussian parameter variation. These methods are unlikely to be applicable within ONBOARD, although the concept of a chance constraint may prove useful. Scenario-based MPC is more general but more complex.

ATM research provides a variety of models that can be optimized by MILP or LP methods, making them conceptually compatible with many of the MPC formulations surveyed. Again, a spectrum of approaches exists, offering progressively higher levels of detail at higher computational cost. Most work looks at static problems.

The works of Liu, Hansen and Mukherjee ([6]) and Chang ([7]) stand out as the most relevant here: although they have not explicitly stated the link, they apply scenario-based MPC to the air traffic flow problem. Liu et al show good results for an aggregated model of flow to a single airport, while Chang shows the potential to extend to a more detailed problem, albeit with simpler weather scenarios. There is clearly more left to be explored.

VI. Challenges and Opportunities

The state of the art indicates that the way forward for ONBOARD, as far as the Network Management algorithm is concerned, lies in the adoption of scenario-based MPC in some form. This section highlights the key questions to be tackled:

1) How do we manage the scenarios? The number of uncertainties can grow very quickly. Every time an uncertain element in the problem has a "decision" between two options – a weather system goes east or west; an unscheduled flight takes off or holds – the number of scenarios doubles. As Liu et al suggest ([6]) the key to success is to be smart in the generation of scenarios.

2) How do we plan responses to scenarios? The literature tells us that closed-loop prediction, permitting different responses to different as different scenarios unfold, is key to good performance. An open loop solution, corresponding to the "robust planning" concept, will be conservative. Its extremely unlikely that a single plan exists to suit all possible scenarios in our problem. However, it will be impractical to plan for a different response to all possible scenarios. Can we group them? An interesting idea would be to try and use feedback formulations in robust MPC, optimizing for a feedback law. For example, delay could be linearly scaled with capacity restrictions in some way. This approach seems more suited to aggregated models of flow, and would revisit some of the early works using simple linear feedback. Menon et al ([8]) were able to apply linear quadratic regulation, for example.

3) Where do we put the probabilities? The literature includes some work where probabilities are used to derive an expected cost. But then, what is the right cost? How should the probabilities be used to weight the outcomes? Similar questions arise with the constraints. Robust MPC typically tries to be clever with the cost but satisfy the constraints for all eventualities. Is this too conservative? Could chance constraints help here?

4) To re-route or not to re-route? On the scale of problem that we are studying, re-routing around weather systems looks a natural strategy. Is it worth the added complication? Or can a limited routing structure suffice?

5) How can we exploit dynamic decision making? We can get a great deal of robustness "for free" by simply re-planning when things change. How can we use this to simplify our problem? What are the right rolling windows and planning horizons to use? Since we're going to re-plan, do we need to plan the far future in the same detail as the near term? The possibility of a hybrid, multi-resolution scheme is enticing, with some many different models available. Could we re-route locally but plan only for timing in the far term? These "receding horizon" ideas have been shown greatly to help MPC in complex problems.

On the other side, in regard to the Airspace User Planning algorithm, two additional issues to be tackled arise:

6) How should we incorporate the research trends in the airspace users operations planning? the current lines of research that seems more promising in terms of operational benefits to the airspace users are the integration of operations planning and control for disruption recovery, and the concept of predictive optimization for uncertainty management but, how can we incorporate them into our research framework?

7) Which airspace users operational decisions should we model for disruption management? from the literature review one can conclude that the key planning problem from a cost, operational performances, and level of service perspective involves the calculation of the optimum aircraft rotation but, which specific operational decisions (e.g. delay flights, swap aircrafts, flight re-timings) should we model in our concept?

VII. Next Project Steps

This paper has presented the work carried out in the ONBOARD project in its first few months of life, period in which we have analyzed the operational concept we want to address in the project, and reviewed the state of the art in the models and algorithms applicable to the Network Management and Airspace Users Planning algorithms we are going to develop over the next 12 months, a challenging but still a long way to go.

VIII. Acronyms

This section enumerates the acronyms used in the paper

4D	4 Dimensions
ACC	Area Control Centre
AOC	Airspace user Operations Centre
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Traffic Services
CI	Cost Index
DCB	Demand and Capacity Balance
ECAC	European Civil Aviation Conference
FAB	Functional Airspace Block
FL	Flight Level
FPL	Filed Flight Plan
GAT	General Air Traffic
IFR	Instrument Flight Rules
KPI	Key Performance Indicator
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
NM	Network Manager
NOP	Network Operations Plan
OAT	Operational Air Traffic
SLA	Service Level Agreement
TTA	Target Time of Arrival
TTO	Target Time of Overfly
TTOT	Target Time of Take-off
UDPP	User Driven Priorisation Process
VFR	Visual Flight Rules

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