Final Project Results Report

Deliverable ID:	1.3
Dissemination Level:	PU
Project Acronym:	TBO-Met
Grant:	699294
Call:	H2020-SESAR-2015-1
Topic:	Sesar-04-2015 - Environment and Meteorology in ATM
Consortium Coordinator:	Universidad de Sevilla
Edition date:	06 Sep 2018
Edition:	00.01.02
Template Edition:	02.00.01

Authoring & Approval

Authors of the document

Name/Beneficiary	Position/Title	Date
Damian Rivas / USE	USE contribution leader	20/04/2018
Antonio Franco / USE	USE contributor	20/04/2018
Alfonso Valenzuela / USE	USE contributor	20/04/2018

Reviewers internal to the project

Name/Beneficiary	Position/Title	Date
Damian Rivas / USE	USE contribution leader	16/07/2018
Manuel Soler / UC3M	UC3M contribution leader	16/07/2018
Jürgen Lang / MetSol	MetSol contribution leader	16/07/2018
Carl-Herbert Rokitansky / PLUS	PLUS contribution leader	16/07/2018
Juan Simarro / AEMET	AEMET contribution leader	16/07/2018

Approved for submission to the SJU By - Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date
Damian Rivas / USE	Project Coordinator	06/09/2018
Antonio Franco / USE	USE contributor	06/09/2018
Alfonso Valenzuela / USE	USE contributor	06/09/2018
Manuel Soler / UC3M	UC3M contribution leader	06/09/2018
Jürgen Lang / MetSol	MetSol contribution leader	06/09/2018
Carl-Herbert Rokitansky / PLUS	PLUS contribution leader	06/09/2018
Juan Simarro / AEMET	AEMET contribution leader	06/09/2018

Rejected By - Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date

Document History

Edition	Date	Status	Author	Justification
00.00.00	01/04/2018	Initial Draft	Damian Rivas	New document
00.00.01	01/05/2018	Second Draft	Damian Rivas	Updated document
00.01.00	16/07/2018	First Issue	Damian Rivas	Updated document
00.01.01	02/08/2018	Revised Issue	Damian Rivas	Reviewed following SJU assessment report
00.01.02	06/09/2018	Revised Issue	Damian Rivas	Reviewed following SJU assessment report

Copyright Statement

TBO-Met

METEOROLOGICAL UNCERTAINTY MANAGEMENT FOR TRAJECTORY BASED OPERATIONS

This deliverable is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 699294 under European Union's Horizon 2020 research and innovation programme.

Abstract

This document presents all the research activities performed within the TBO-Met project. It is divided into three main sections. First, a project overview is presented, which includes a description of the problem addressed, the scope of the project, the methodologies developed, a summary of the key project results, and a brief description of the technical deliverables. Afterwards, the links between the TBO-Met project and the SESAR programme are identified, describing the contribution of the project to the ATM Master Plan, and providing an assessment of the Technology Readiness Level of the concepts developed in the project. Finally, the last section outlines the main conclusions drawn from the results, the key communication and dissemination activities, the technical lessons learned, the recommendations for future research activities, and a roadmap for next steps.

Table of Contents

List of Tables

List of Figures

1 Executive Summary

In this document the results of the TBO-Met project are presented. TBO-Met deals with the objectives of the SESAR 2020 Exploratory Research programme related to 1) the enhancement of meteorological capabilities and their integration into Air Traffic Management (ATM) planning processes for improving ATM efficiency and 2) to the development of 4D trajectories that are optimised to take account of all environmental considerations. The **overall objective** of TBO-Met is threefold:

1) To advance in the understanding of the effects of meteorological uncertainty in Trajectory Based Operations (TBO).

2) To develop methodologies to analyse, quantify and manage the effects of meteorological uncertainty in TBO.

3) To pave the road for a future integration of the management of meteorological uncertainty into the air traffic management system.

In TBO-Met three **research topics** have been addressed: 1) trajectory planning at pre-tactical level (mid-term planning) under meteorological uncertainties, 2) storm avoidance at tactical level (short-term planning and execution), and 3) sector demand analysis under meteorological uncertainties, both at pre-tactical and tactical levels. The weather information is obtained from Ensemble Prediction Systems (EPS) and Nowcasts, which provide two types of **meteorological uncertainties**: wind uncertainty and convective zones (including individual storm cells).

For the trajectory planning problem at pre-tactical level (up to three hours before departure), a methodology has been developed to plan efficient trajectories with low levels of uncertainty. In particular, two problems have been analysed: On one hand, the trade-off between predictability (measured by the flight-time dispersion) and cost-efficiency (flight time or fuel consumption) considering only uncertain winds, and, on the other, the trade-off between exposure to convective risk and cost-efficiency considering now uncertain winds and convection risk. As part of this work, a tool has been developed that provides the probability of convection from the information contained in the EPS. Two simulation scenarios have been designed to validate the methodologies developed.

At tactical level (during the flight), a probabilistic trajectory predictor under thunderstorm activity has been developed, taking into account the uncertainty in the location of the convective cells (modelled as stochastic no-fly zones). The output is an ensemble of deviation trajectories that avoid the possible storm realisations and reattach to the optimal reference route (computed at the pre-tactical phase). An already existing deterministic tool for generating the deviation trajectories (DIVMET) has been adapted to account for the uncertainty in the cell evolution. As part of this work, a tool has been developed that models synthetically the uncertainty in the location of the cells (because the Nowcasts considered are deterministic). One simulation scenario has been designed to validate the methodologies developed.

For the sector demand problem, the objective has been to quantify the impact of trajectory planning under weather uncertainty (as performed at the trajectory scale) on sector demand. A methodology has been developed to analyse the uncertainty of sector demand (probabilistic sector loading) in terms of the uncertainty of the individual trajectories. The approach is based on the statistical characterization of the entry and occupancy counts, and is quite general, not depending on the specific tools developed in the project. At pre-tactical level, the methodology is able to quantify the reduction of the dispersions of the entry and occupancy counts when the dispersion of the individual trajectories subject to wind uncertainty is reduced. On the other hand, the methodology is able to quantify the reduction of the dispersions of the two counts at tactical level, taking into account the uncertain evolution of the convective cells, when the convection risk of the individual trajectories is reduced in the mid-term planning phase. This analysis has provided an understanding of how weather uncertainty is propagated from the trajectory scale to the sector scale. Two simulation scenarios have been designed to validate the methodologies developed.

In this document, the links between the TBO-Met project and the SESAR programme are also identified. The project has proposed three new Operational Improvement (OI) Steps for their inclusion in the future release of the ATM Master Plan dataset, and has contributed to start maturing them. To evidence the project contribution, an assessment of the Technology Readiness Level (TRL) of the concepts developed in the project have been performed. The assessment is divided into three parts that correspond to the three research topics addressed in the project. The three individual assessments are developed following the criteria identified in the Maturity Assessment Tool (MAT). All the questions posed have been answered and the level of satisfaction of the criteria has been evaluated, leading to a positive assessment. From the TBO-Met perspective, the conclusion is that the three research topics show maturity to go from TRL 0 to TRL 1.

The **overall conclusion** of TBO-Met is that the ATM efficiency can be enhanced by integrating into the ATM planning process the available information about the uncertainty of weather forecasts. In particular, the results have shown that the predictability of aircraft trajectories can be increased, the storm avoidance strategy can be better anticipated, and the accuracy of sector demand forecast can be improved. As **potential benefits**, the following has been identified: reduction of the buffer times used by airlines, better-informed decision making, increase of declared sector capacities, and better identification of demand-capacity balancing measures.

Three **technical lessons** have been learned in this project: 1) the need for an enhanced module for meteorological data processing (including calibration of EPS) and improved probabilistic Nowcasts, 2) the need for an improved robust trajectory planner (with hypotheses relaxation) both at mid-term and short-term levels, and 3) the need for an extended methodology for sector demand analysis at network scale. Consequently, for each one of the research topics **further research** is possible:

- For the trajectory planning problem: inclusion of other sources of uncertainty different from the meteorological one, use of calibrated EPS obtained through statistical post-processing techniques, enrichment of aircraft performance modelling, consideration of structured airspaces, consideration of three-dimensional flights, and consideration of meteorological forecasts that evolve over time.
- For the storm avoidance problem: inclusion of other sources of uncertainty different from the location of the convective cells, improvement of thunderstorm uncertainty modelling, consideration of vertical avoidance manoeuvres, and consideration of operational environment constraints.
- For the sector demand problem: extension to the Terminal Manoeuvring Area (TMA) environment, multi-sector analysis, and variable sector configuration.

Finally, three possible **technical solutions** have been identified:

- Enhanced flight-planning predictability
- Probabilistic storm avoidance human decision support tool
- Probabilistic sector demand considering meteorological uncertainty

These solutions are described and a roadmap for their future exploitation steps is presented.

2 Project Overview

The TBO-Met project corresponds to the research topic “Environment & Meteorology for ATM”, which is part of the research area “ATM Excellent Science & Outreach” of the SESAR 2020 Exploratory Research programme (call H2020-SESAR-2015-1 [32]). TBO-Met is coordinated by the University of Seville (Spain) and the rest of the consortium is formed by the following members: University Carlos III of Madrid (Spain), University of Salzburg (Austria), MeteoSolutions GmbH (Darmstadt, Germany) and the Spanish meteorological agency AEMET (Agencia Estatal de Meteorología).

In this chapter a technical overview of TBO-Met is presented, which includes the description of the problem addressed by the project, the operational/technical context in which the proposed solution fits, the scope and objectives, and a summary of the work performed (methods, tools, main results, validation exercises) with reference to the project deliverables.

2.1 Operational/Technical Context

The **context** of the TBO-Met project can be described as follows. **Uncertainty** is a key factor that affects the achievement of the high-level goal set for the Single European Sky of increasing the capacity of the ATM system while maintaining high safety standards and improving the overall performance, and in particular the **weather uncertainty**, which is one of the main sources of uncertainty that affect ATM. Therefore, to achieve that goal, the uncertainty levels in ATM have to be reduced and new strategies to deal with the remaining uncertainty must be found.

As indicated in the Grant Agreement [33], the problem addressed in TBO-Met is the **management of meteorological uncertainties in Trajectory Based Operations**, focussing on two particular problems:

1. trajectory planning under meteorological uncertainties,
2. sector demand forecast under meteorological uncertainties,

both at mid-term and short-term levels. These two problems correspond to two different scales of the system: trajectory (micro) scale and sector (meso) scale. In each problem two types of meteorological uncertainties are considered: wind uncertainty and convective zones (including individual storm cells).

The weather uncertainty information is modelled using a **probabilistic approach**. The uncertainty of the wind field and of the convective region is derived from Ensemble Prediction Systems, and the uncertainty of the individual cells within the convective region is derived from Nowcasts. Therefore, the trajectory planning and sector demand analyses are made using **probabilistic approaches** as well.

An interesting feature of this project is that it is highly multidisciplinary, involving several branches of knowledge: meteorology, aeronautics (ATM), and mathematics (optimisation and statistics).

TBO-Met is fully aligned with the objectives of the SESAR 2020 Exploratory Research programme, in particular the following ones related to the “Meteorology” topic: “to enhance meteorological capabilities and their integration into ATM planning processes for improving ATM efficiency” and “to develop 4D trajectories that are optimised to take account of all environmental considerations”, and where the following impact is expected: "to enhance ATM efficiency by integrating meteorological information".

2.2 Project Scope and Objectives

2.2.1 Objectives

In the context described in the previous section, the **overall objective** of the project is threefold (as indicated in the Grant Agreement [33]):

4) To advance in the understanding of the effects of meteorological uncertainty in TBO.

5) To develop methodologies to analyse, quantify and manage the effects of meteorological uncertainty in TBO.

6) To pave the road for a future integration of the management of meteorological uncertainty into the air traffic management system.

And for the two particular problems addressed in TBO-Met, the two **specific objectives** are (as indicated in the Project Management Plan [1]):

1) At the trajectory scale, to assess and **improve the predictability** of aircraft trajectories when subject to weather uncertainty, keeping acceptable levels of efficiency, both at the mid-term level (up to three hours before departure) and at short-term level (during the flight).

2) At the sector scale, to analyse the **impact on sector demand** of such improved trajectory planning under weather uncertainty (with enhanced predictability), including an understanding of how weather uncertainty is propagated from the trajectory scale to the sector scale.

As indicated in the Grant Agreement [33], the **expected impacts** of TBO-Met are as follows:

From the point of view of the integration of meteorological information into the ATM planning, the expected impact is twofold: a) assessment of how **existing** meteorological products can be used to enhance predictability of 4D business trajectories within TBO; b) assessment of how **improvements** of the existing meteorological products could enhance predictability of 4D business trajectories within TBO.

And from the point of view of the overall efficiency of the ATM system, the expected impact is threefold: a) from the airlines perspective, the **reduction of costs and risks**; from the side of the Air Navigation Service Providers (ANSP), the **better allocation of resources** and **reduced Air Traffic Control (ATC) workload**; from the Network Manager, the **better identification the Air Traffic Flow and Capacity Management (ATFCM) measures** to be applied in the pre-tactical and tactical flow management phases (for example, rerouting, advancing traffic, or slot allocation).

2.2.2 Scope

To achieve those objectives, TBO-Met has addressed three specific problems, which define the scope of the project:

1. Trajectory planning at mid-term level considering weather forecast uncertainties.
2. Short-term trajectory prediction under thunderstorm activity (storm avoidance problem).
3. Sector demand analysis considering weather forecast uncertainties.

Complementary to these problems, three additional tasks have been carried out:

- Conduction of a survey among stakeholders.
- Provision and processing of the meteorological input data.
- Validation via simulation of the methodologies developed in the project.

The description of the work performed (section 2.3) and of the key project results (section 2.4) is done with reference to these problems and complementary tasks.

The block diagram describing the project scope (as included in the Grant Agreement [33]) is shown in Figure 1, including the work packages (WP) in which the project has been divided.

In this project two external tools have been used:

- DIVMET, a storm avoidance tool (see Section 2.3.4), and
- NAVSIM, an advanced air traffic simulation infrastructure used for the validation tasks (see Section 2.3.6).

Furthermore, the following input data have been considered:

- two EPS: ECMWF-EPS (European Centre for Medium-Range Weather Forecasts-EPS) and GLAMEPS (Grand Limited Area Model-EPS);
- Nowcast data provided by AEMET;
- aircraft models provided by Eurocontrol's Base of Aircraft Data (BADA); and
- air traffic data provided by Eurocontrol's Network Strategic Tool (NEST).

Figure 2 sketches the input data flow and interconections among the main tasks of the project, and lays out the external tools used.

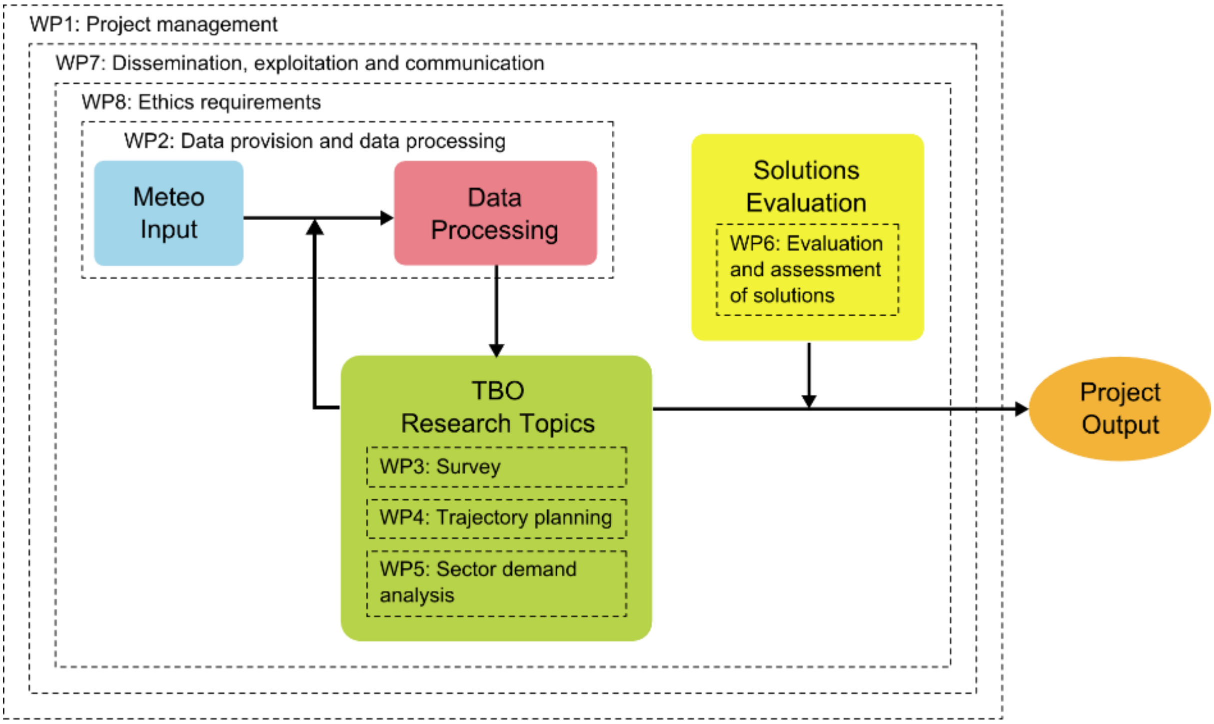

Figure 1. Work plan breakdown

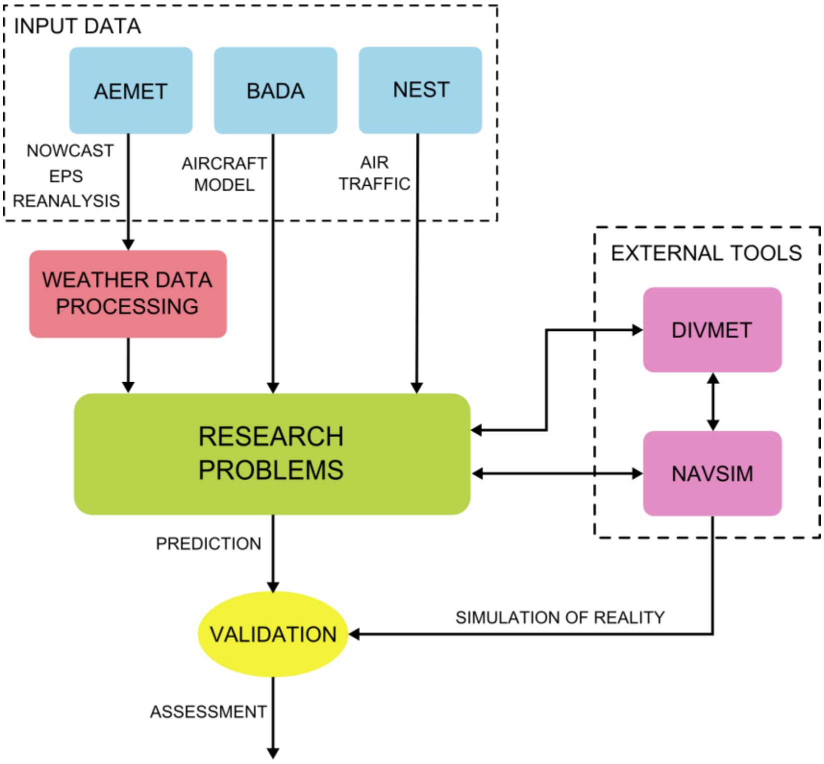

Figure 2. Input data and external tools

2.2.3 Concept

The overall concept of the project is the **development of methodologies** to analyse, quantify and manage the effects of weather uncertainty in TBO. For the previous three problems, the particular concepts are as follows:

1) for the mid-term trajectory planning problem, the concept developed in TBO-Met is a **stochastic optimisation methodology** capable of trading-off cost-efficiency and predictability and/or exposure to convective risk;
2) for the storm avoidance problem, the concept developed is a **probabilistic trajectory predictor** with storm avoidance, taking into account the uncertainty in the location of the convective cells (modelled as stochastic no-fly zones); and
3) for the sector demand problem, the concept developed is an **ensemble-based stochastic methodology** to predict the sector demand based on the uncertainty of the individual trajectories.

A sketch of the different methodologies developed and of the existing relationships among them is shown in Figure 3.

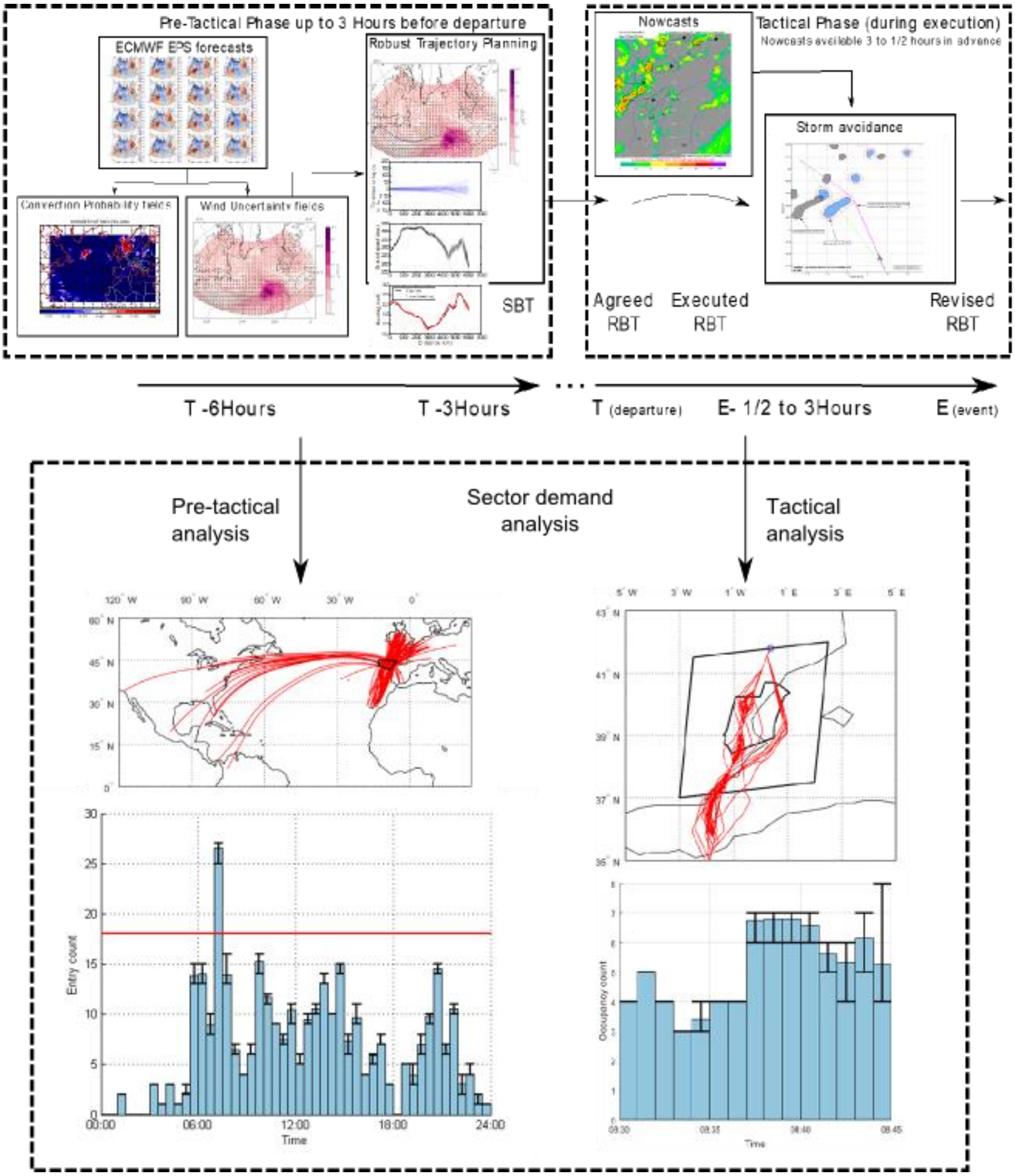

Figure 3. Methodologies developed in TBO-Met: mid-term trajectory planning (top left), short-term storm avoidance (top right), and ensemble-based sector demand (bottom left and right).

2.3 Work Performed

The project has been executed following the requirements stated in the Project Execution Guidelines [35]. In this section, the work performed in the problems and complementary tasks is described.

2.3.1 Stakeholders Survey

A survey among relevant stakeholders was conducted at the beginning of the project. The goals were: to ensure that TBO-Met was aligned with current meteorological practices in aviation (particularly any issue regarding meteorological uncertainty); and to understand future expectations regarding meteorological uncertainty management.

The work performed can be divided into three main tasks:

- The production of the TBO-Met Survey Questionnaire, including its scope, potential participants, ethical issues to be considered, the questions to be posed and the instructions to be followed by participants. This is included in Deliverable 3.1 [7].
- The conductions of the interviews themselves.
- The analysis of the answers to the TBO-Met Survey Questionnaire. These are included in Deliverable 3.2 [8], which contains information on the interviews that were conducted and the analysis of the collected answers.

2.3.2 Data provision and data processing

2.3.2.1 Provision of input meteorological data

The Spanish Met Office (AEMET) has provided the meteorological data for the project. The data was uploaded to an AEMET ftp server, so all the partners could download the data. Two types of weather prediction information have been used: numerical forecasts given by EPS and Nowcasts.

The numerical weather prediction outputs were obtained from the ECMWF and the GLAMEPS ensemble forecasting systems. Those systems provide several different deterministic forecasts, with slightly different initial conditions and model configurations, and it is the most popular method to provide probabilistic weather forecasts, and thus, to estimate the uncertainty in the weather conditions.

The meteorological fields selected can be grouped in two sets. The first set is formed by the wind and temperature at different isobaric or flight levels; they were used for finding optimal trajectories at the pre-tactical level. The second set consists in meteorological fields related to the formation of convection, as convection is one of the most usual causes of flights re-routing and delays.

In the tactical level analysis it was necessary to provide products related to the nowcasting of convection. That is, very short range forecasts about the presence or absence of convective precipitation. Convective precipitation is produced in dense, towering vertical clouds. The cloud base is usually near the top of the planetary boundary layer, and the top of the cloud near the tropopause in most of the cases.

The problem of forecasting convection in the very short range (in the next few hours) is a field of intense activity in the National Meteorological Services over Europe. And it is an open problem, in the sense that there is not still a satisfactory well developed tool for facing this problem. In the operational forecast offices, there are a myriad of different nowcasting tools. Those tools are fed by observations. The most usual observations are obtained from weather radars, meteorological satellites, and lightning detection networks (in this order), mixed with products derived from numerical meteorological models (in Rapid Update Cycle mode). Usually these tools analyse the latest observations and try to provide a forecast for the next hours, which is, most of the times, deterministic.

The AEMET has developed one of such nowcasting tools, based on the analysis of radar images. There are two versions, one based on bidimensional radar images, and another that uses the full three dimensional radar observations. The AEMET tool is based on convective cell objects. The nowcasting consists in providing an estimation of the situation and size of each convective cell, as well as the direction and speed of the movement. The tool has limitations, for instance, it does not provide an estimation of the evolution of the size and shape of each cells. Moreover, the tool provides a deterministic forecast.

As one of the main interest of the TBO-Met project is the study of the effects of uncertainty, it was necessary to estimate the uncertainty of the products provided by the AEMET nowcasting tool. To this end, a verification exercise was performed, and the result of the verification was used to determine the uncertainty of the nowcasting.

2.3.2.2 Processing of input meteorological data

The objective of this task was to generate suitable meteorological data for the research problems addressed in the project, both for mid-term and short-term analyses. In order to achieve this, requirements on the meteorological data were collected together with the project partners and analysed with respect to the available meteorological data. This relates to the selection of data, their spatial and temporal resolution and the data format. The provided data was checked against the defined requirements and the necessary data processing methods were identified. Subsequently a concept was worked out to transform the provided data into the needed form. For the pre-tactical level this is described in Deliverable 2.1 [3], for the tactical level in Deliverable 2.3 [5].

At **pre-tactical level**, with respect to the spatial-temporal grid of the EPS model output, the processing covers coordinate transformation from hybrid model levels to pressure levels, vertical interpolation, temporal downscaling and interpolation, spatial bilinear interpolation and the extraction of polygons which delimit areas of deep convection. Further data processing is defined in order to calculate the ensemble mean and spread of wind components and temperature which is used to quantify the forecast uncertainty of these meteorological parameters. Where wind and temperature data is readily available as model output, information about convection had to be derived from numerous parameters; detailed information on the definition of suitable indicators to describe convection is provided in Deliverable 2.1 [3].

The software to process EPS data was developed in Python programming language so that it was straightforward to integrate it into the scientific environment which is used in trajectory planning.

Contrary to the ensemble forecasts, which directly give a measure of uncertainty, a specific approach had to be followed at **tactical level**, where Nowcasts are used, to determine the uncertainty of convective cells. The uncertainty of individual cells is determined as the spread between the nowcast of a cell and the observation of the same cell at the same time in terms of position, spatial extent and strength. Appropriate measures of uncertainty based on Nowcast data were defined. One specific topic here is the definition of an uncertainty margin for the nowcasted convective cells. This was done by statistical analysis of Nowcast data by AEMET (Deliverable 4.2 [10]).

Unfortunately, available Nowcast data did not provide outlines of convective cells in the form of polygons, but centroid and box shaped limits. Thus the outline of a convective cell was adapted by the approximation of an ellipse. This ellipse was constructed on the basis of the given limits in which the real convective cell is assumed to be located, and was then extended by the uncertainty margin according to the given lead time of the convective cell. Additionally, a safety margin is added to the extended ellipse. Thus the processing uses methods of vector algebra to construct, extend and translate ellipses.

The software to process data of Nowcast systems was written in Java so that, again, it was easily added to the scientific environment used in storm avoidance.

2.3.3 Trajectory planning

Robust trajectory planning at pre-tactical level (mid-term planning; in this context, three hours before departure; left-hand side of Figure 3) is presented in Deliverable 4.1 [9]. The methodology for robust route optimization makes use of EPS and optimal control techniques. Both wind and convection are considered as the sources of uncertainty.

In this method, the objective is to minimise the following cost function

$$J = \frac{1}{N}\sum_{i=1}^{N} t_i(r_f) + dp\left(t_{f,max} - t_{f,min}\right) + cp\int_o^{r_f} p_c(\lambda, \phi)dr$$

where the first term is the expected flight time (average among all the members of the EPS), the second one is the dispersion of the flight time, and the third one is the convection risk, which is measured as the integral along the route of the probability of convection p_c, which is one of the parameters provided by the software developed in Deliverable 2.2 [4].

The parameters dp and cp are the dispersion penalty and the convection penalty, respectively. Large values of dp lead to routes with low dispersion and therefore with high predictability, and large values of cp lead to routes with low exposure to convection risk.

The method also requires the post-processing of the wind data into differentiable functions that can be included in the optimal control formulation.

The optimization problem is solved with direct methods, discretizing the trajectory with a trapezoidal scheme and then solving the resulting nonlinear optimization problem with Non-Linear Programming techniques.

The scenarios and indicators defined to validate the methodology are presented in Deliverable 4.3 [11].

2.3.4 Storm avoidance

Short-term trajectory prediction in the presence of thunderstorms is presented in Deliverable 4.2 [10]. This work is a first step towards the understanding of the inherent uncertainty of convective cells, and its consideration for the re-routing of aircraft at the tactical level. The uncertain evolution of convective cells is considered to be the only source of uncertainty.

The methodology developed carries out multiple short-term trajectory predictions (using DIVMET algorithm [34]) of the same initially planned route under randomly variable cell locations, which is the way of taking uncertainties of convective cells into account. The results of the simulations were analysed to investigate the predictability and efficiency of the predicted trajectories.

Trajectories calculated by using the algorithms presented in Deliverable 4.1 [9] were used as input to the simulations. These trajectories acted as Business Development Trajectories (BDT). The simulations were carried out by applying DIVMET algorithm to calculate an updated trajectory capable of avoiding convective cells i.e. thunderstorms. The resulting trajectory becomes the revised Reference Business Trajectory (RBT). In order to investigate the effects of uncertainty on the RBT one simulation consisted of multiple runs of DIVMET on the same BDT while varying the location of the convective cells stochastically. It was also of concern to see the effect of different uncertainty models on the efficiency and predictability of the trajectories. So the lead-time dependent uncertainty function, which is the basis of the uncertainty model, was varied. Thus simulations were repeated for uncertainty models with five different uncertainty functions. A set of simulations was conducted and results were analysed and compared.

For the analysis of the predicted trajectories, the focus was on the efficiency and predictability of the trajectories. For each RBT the length and related arrival time were determined. The arrival time distribution was calculated. If the arrival times are close to each other, that is if the dispersion of arrival time distribution is low, the enforced route deviations are of little impact and predictability of arrival times is high. Vice versa, if arrival times are highly scattered, the enforced route deviations have a strong impact. The arrival time distribution may thus serve as a measure of route predictability. Mean delay is an inverse measure of efficiency (as wind is not considered in this task). Dispersion of the distributions is an inverse measure of predictability of trajectories. This means that a low dispersion among predicted trajectories can be viewed as high predictability. The dispersion is expected to increase with growing uncertainty.

The scenarios and indicators defined to validate the methodology are presented in Deliverable 4.3 [11].

2.3.5 Sector demand

The methodology to compute probabilistic sector demand forecasts, from a set of individual trajectories that take into account meteorological uncertainty was presented in Deliverable 5.1 [12], and its adaptation to handle the tactical problem in Deliverable 5.2 [13]. The general scheme of the methodology is shown in Figure 4.

Initially, a scenario is defined in terms of:

1) ATC sector (e.g., geometry and capacity),
2) flights that cross the sector (e.g., origin and destination, departure times, flight levels, and cruise speeds), and
3) weather forecasts (e.g., forecast to be considered, release time, and forecast times).

The meteorological data provided by EPS and Nowcasts need to be processed for its use by the trajectory predictor. For example, the necessary values of wind and air temperature are extracted, and information about convection need to be derived from different parameters.

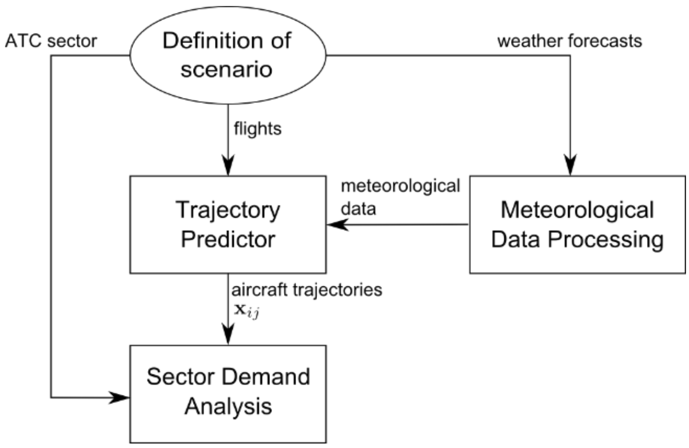

Figure 4. General scheme for the analysis of sector demand

The trajectory predictor computes, for each flight and for each weather prediction, a different aircraft trajectory. Any trajectory predictor can be considered, the one developed in TBO-Met or any other currently existing predictor. The only requirement is that it has to provide an ensemble of trajectories for each flight, since it is the base for the statistical analysis.

The computed trajectories, along with the information of the ATC sector, are then used to perform the analysis of the sector demand. The different trajectories lead to different predicted entry and exit times and, therefore, to different entry and occupancy counts (number of flights entering or inside the sector during a selected time period, respectively). The analysis is based on the statistical characterization of the times and of the counts. Mean, maximum, and minimum values, and the spread of the times and of the counts, measured as the difference between the maximum and minimum values, are examined. The probability of the counts exceeding given thresholds can be also obtained.

This methodology is general in the sense that it is applicable regardless the forecast horizon. It can be applied at mid-term, forecasting the sector demand several days before the operation, or at short-term, just some minutes before operation. In the latter case, it is of special interest to update the sector demand according to the regular release of new Nowcasts and the actual movement of the aircraft.

The scenarios and indicators defined to validate the methodology are presented in Deliverable 5.3 [14].

2.3.6 Validation

The results of the validation of the concepts proposed in TBO-Met have been presented and analysed in Deliverable 6.1 [15]. To validate the methodologies developed in WP 4 and WP 5, five different scenarios have been defined (see Deliverables 4.3 [11] and 5.3 [14]), namely,

- **VS1**: to validate the robust flight-planning concept considering only wind uncertainties
- **VS2:** to validate the robust flight-planning concept considering both wind uncertainties and convective risk
- **VS3:** to validate the short-term trajectory prediction concept considering the uncertain evolution of storms
- **VS4:** to validate the sector-demand prediction at pre-tactical level considering only wind uncertainties
- **VS5:** to validate the sector-demand prediction at tactical level considering both convective risk and the uncertain evolution of storms

Each scenario is analysed, on the one hand, using the algorithms developed in TBO-Met (leading to the **prediction results**) and, on the other hand, using the NAVSIM/USBGSim advanced air traffic simulation infrastructure of University of Salzburg (leading to the **simulation results**). Then, several key validation indicators are computed (different from each validation scenario, defined in [11] and [14]), which compare both set of results and express, in a quantitative way, the success of the validation scenario considered. Note that to perform the storm avoidance tasks, NAVSIM is linked to DIVMET (a storm avoidance tool owned by MeteoSolutions GmbH).

The sets of flights considered in the different scenarios are retrieved from Eurocontrol's Demand Data Repository (using NEST software). The meteorological data retrieved consists of the following: the weather forecast ensemble ECMWF-EPS, composed of 50 perturbed members and 1 control member; the ensemble GLAMEPS, composed of 48 perturbed members and 4 control members; and AEMET Nowcasts.

The "real" meteorology used by NAVSIM is, on one hand, the Reanalysis generated by ECMWF, which provides a numerical description of the recent atmospheric state by combining models with observations, and, on the other hand, the Nowcasts provided by AEMET.

2.4 Key Project Results

In the following sections the key results of the project are described.

2.4.1 Stakeholders Survey

In principle, the number of answers to the questionnaire was rather small and statistics, therefore, were poor for a proper differentiating analysis, but still high enough to draw some general conclusions, as follows:

- Because the stakeholders interviewed form a heterogeneous group, in general the answers differed, essentially depending on the stakeholder's role and their different interests.
- In general, there exists confidence on weather forecasts, although the confidence level was different for different Met products.
- There exists a dialogue between ATM and Met Provision, although it must be improved. In particular, there exists a gap between met provision capabilities (including EPS and Nowcasts) and Met products usage in ATM, and thus room for research and development. Moreover, harmonization of knowledge and tools, not only between ATM and Met but in general among all stakeholders, is required.
- In general, it can be said that the meteorological uncertainty is not so-well understood, and handled rather subjectively. Most of the answers agreed that meteorological uncertainty has a rather high impact, however it seems it lacks quantification.
- The importance of uncertainty depends strongly on the time scale of the task and objective. All answers agreed that an increase in predictability would improve operations, specifically, in terms of efficiency and capacity of the system.
- According to the participants' opinions, it should be interesting to include weather uncertainty in decision support tools. However, they argued that it does not seem to be easy, nor straightforward; hence, posing a challenge for future research.

Finally, it can be said that the objectives of the survey were met, both, with respect to the project alignment and about getting input for future research, as follows:

Project alignment The importance of Met uncertainty in air traffic operations, and more especially its quantification, and the importance of integrating Met uncertainty information into the ATM planning process, aiming at improving predictability as a Key Performance Area, have been stressed by the stakeholders, in coincidence with the TBO-Met goals. In general, nothing told us that the TBO-Met project has not aligned with the stakeholders' interests.

The following topics for **future research** were identified by the stakeholders:

- to bridge the gap between Met products and their utilisation by users, which will require harmonization of knowledge among all stakeholders,
- to develop methodologies to quantify the impact of Met uncertainty, and
- to integrate Met uncertainty into decision support tools.

2.4.2 Data provision and data processing

The aim of this task was to devise methods to generate suitable data of meteorological parameters which were needed to do research in the mid-term and short-term problems addressed in the project. Thus major results were two software implementations (in Python and Java) to process the data and generate the desired output.

Intermediate results comprise the documentation of requirements, definition of meteorological data sources which meet these requirements and the concepts for data processing of the various meteorological parameters. This is described in detail in Deliverable 2.1 [3]. Besides outputting the meteorological parameters themselves, the determination of the ensemble mean and spread is also described in detail. This description represents the basic concept for the implementation of the software which was used to process the data and generate the suitable output. Deliverable 2.1 [3] also gives an overview of the characteristics of available Ensemble Prediction Systems ECMWF-EPS and GLAMEPS.

For short-term tactical analyses, Nowcast data derived from radar reflectivity observation were identified to be suitable, i.e. outlines of convective cells which delimit areas of high reflectivity (>37dBZ). In this project, AEMET is providing the Nowcast data which is based on radar reflectivity observations (from the AEMET radar network) and lightning data. AEMET developed a function to model uncertainty margins by statistical analysis of the absolute deviation of forecasted and observed convective cells (see Deliverable 4.2 [10]).

Data Processing Software for the pre-tactical problem: The software developed considers three use cases: first, a grid-based data processing for wind and temperature; second, a trajectory-based data processing for wind components and temperature; and third, data processing for convection indicators. The software is capable of processing data of ECMWF-EPS or GLAMEPS according to the use case. ECMWF-EPS data is used to provide wind and temperature, and GLAMEPS data is used to provide convection indicators (see Figure 5 and Figure 6). The software is documented in Deliverable 2.2 [4] which is confidential.

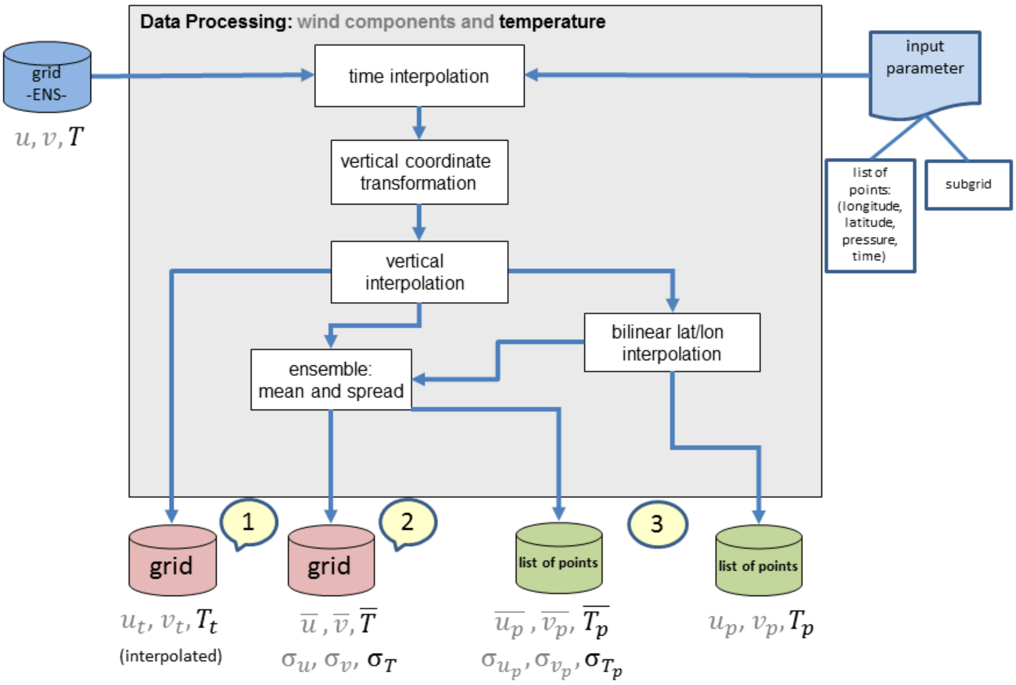

Figure 5: Flowchart of data processing for wind (grey) and temperature (black) at pre-tactical level. Available outputs: 1) grids for each ensemble member, 2) grids of average and spread values, and 3) values at specified points.

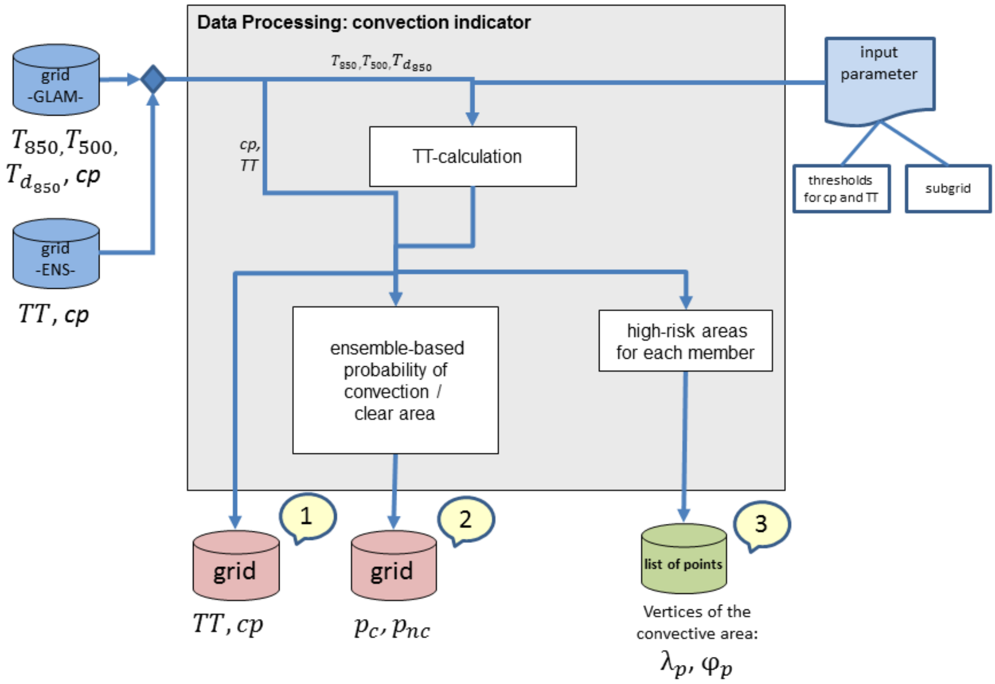

Figure 6. Flowchart of data processing for convection at pre-tactical level. Available outputs: 1) grids of convection indicators, 2) grid of probability of convection, and 3) areas of convection risk.

Examples are given in Figure 7 and Figure 8. In Figure 7 the dispersion of the meridional wind is presented, which is measured as the difference between the maximum and the minimum values provided by the ensemble members, and in Figure 8 the probability of convection is displayed.

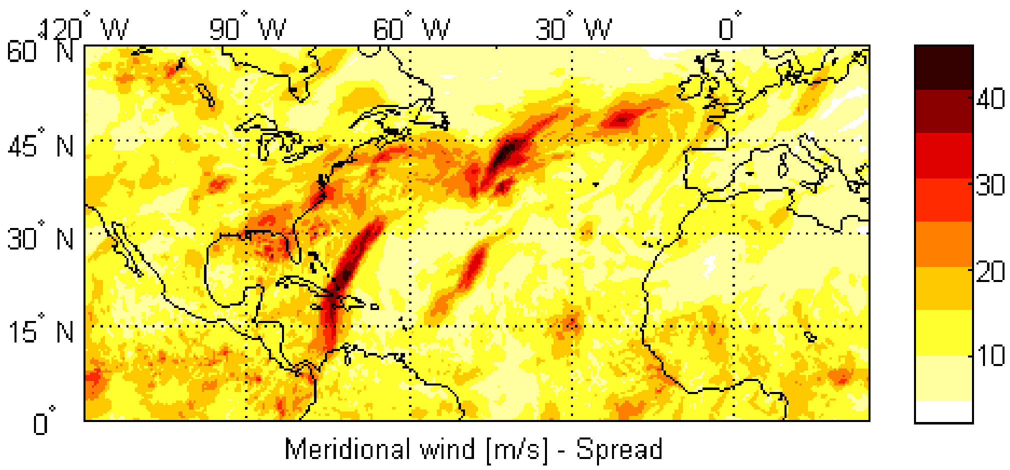

Figure 7. Dispersion of the meridional wind (in meters per second), ECMWF-EPS released at 00:00, 31/08/16, step 36 hours.

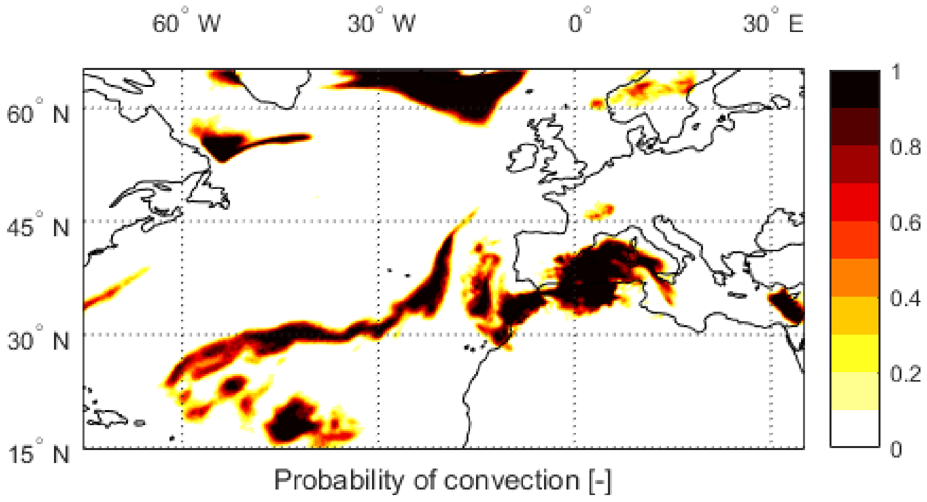

Figure 8. Probability of convection (between 0 and 1), GLAMEPS released at 00:00, 19/12/16, step 6 hours.

As the TBO-Met partners integrated the provided software into their already running systems, the software was implemented in Python 2.7 on UNIX platform. So, for each use case the software offers one Python script for execution.

Data Processing Software for the tactical problem: The software developed considers two use cases: first, for the given vector data of convective cells, extract the needed parameters of all Nowcasts and construct the ellipses for each cell, and put these out as polygons in one data file for each lead time; and second, for the given vector data which are polygons of convective cells from use case one, determine the uncertainty margins, vary the location of the original polygons randomly within the limits of the uncertainty margin, and put these out as polygons in one data file for each lead time. The software is documented in Deliverable 2.4 [6] which is confidential.

The data processing comprises the following steps: the geographical parameters of each cell (centroid, limits) are cartographically projected in order to construct the ellipse and to add the uncertainty and safety margins (which are given in nautical miles); for the output, the polygons are projected inversely in geographical coordinates and written to a file (the output data is formatted as GeoJSON files); for the storm-avoidance problem, the ellipses are randomly varied in location within the uncertainty margin to model the uncertain behaviour of convective cells (see Figure 9), using a Gaussian distribution for the stochastic location variation.

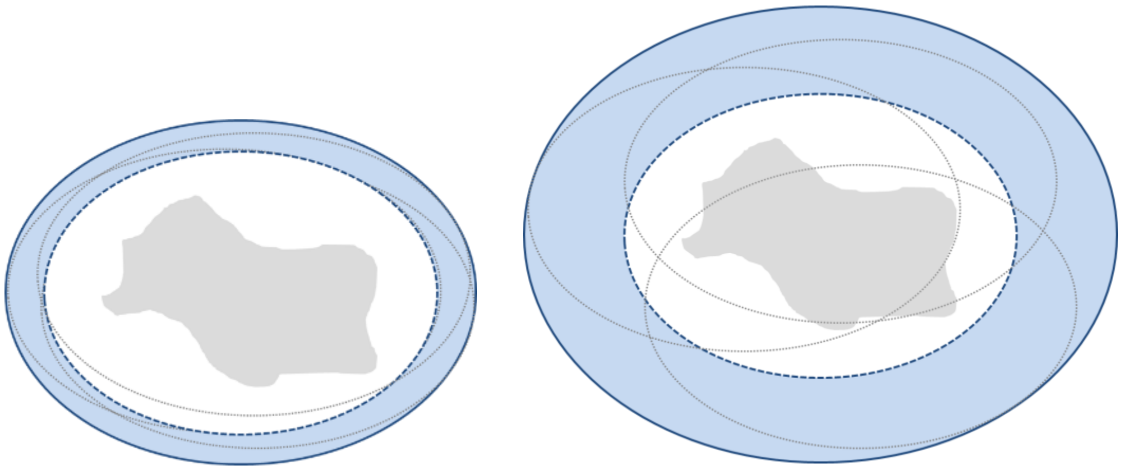

Figure 9. Schematic illustration of the stochastic location variation of the elliptically shaped convective cell within the uncertainty margin, for two different lead times

2.4.3 Trajectory planning

The results obtained for the trajectory planning problem are described in detail in Deliverable 4.1 [9]. They are summarized in the following.

A novel robust optimal control methodology for computing robust optimal routes based on EPS has been developed (as described in Section 2.3.3), which has demonstrated its utility in studying trade-offs between efficient and predictable routes. It can be concluded that by using this method, uncertainty (in this case due to wind and/or exposure to convective risk) can be not only quantified, but also reduced by proposing alternative trajectories.

As part of the optimal control approach, a novel methodology to model wind data has been also developed, in such a way that can be introduced in optimal control formulations (in which twice differentiable functions are needed to guarantee local optimality). This methodology has demonstrated to substantially reduce wind-modelling errors when compared to canonical approaches, e.g., global regression analysis. According to the case study presented in Deliverable 4.1 [9], the methodology reaches a standard deviation error below 2 m/s (in wind speed values) when comparing wind data (as they come in the EPS forecast) and our fitting function. Existing approaches, e.g., global regression analysis, might double this error (however, a systematic analysis, on different days and meteorological circumstances, and its impact on calculated trajectories should be done to quantitatively assess the improvements obtained based on an example).

Two applications of the above mentioned methodology have been made. First, an application to a case study in which wind is considered the only source of uncertainty. The ensemble forecast ECMWF-EPS, released at 00:00 on 20th of January 2016, for a pressure of 200 hPa, and with a forecasting horizon of 6 hours is used in this application. Figure 10 shows optimal trajectories from New York to Lisbon, for values of dp from 0 to 50. Higher brightness in the trajectory colour indicates higher values of dp. In this figure, wind uncertainty is represented as $\sqrt{\sigma_u^2 + \sigma_v^2}$, with σ_u being the standard deviation of the u component of wind across different members and σ_v analogous for the v-component. Figure 11 shows the trade-off frontier of the problem, obtained by solving problems with different penalties dp

(from $dp = 0$ to $dp = 50$). For the case of minimum expected flight time ($dp = 0$), the time dispersion at the final fix is above 4.5 minutes, whereas for the maximum predictability case ($dp = 50$), the time dispersion at the final fix is slightly above 1.5 minutes. In other words, around 3 minutes reduction in time uncertainty could be achieved by flying the most predictable trajectory ($dp = 50$). This would be at roughly 2500 kg of extra fuel burnt. Something more realistic would be the increase in predictability of about 1.25 minutes with 500 kg of extra fuel consumption. In any case, the trade-off frontier (Figure 11) shows different trade-off solutions.

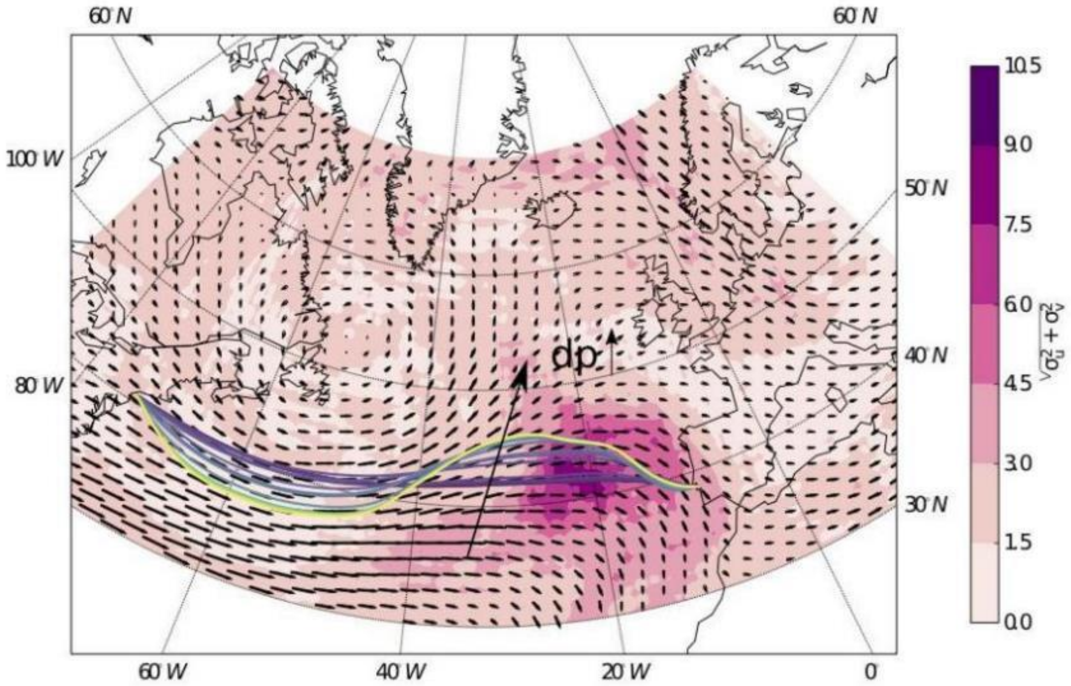

Figure 10. Optimal trajectories from New York to Lisbon, for values of dp from 0 to 50.

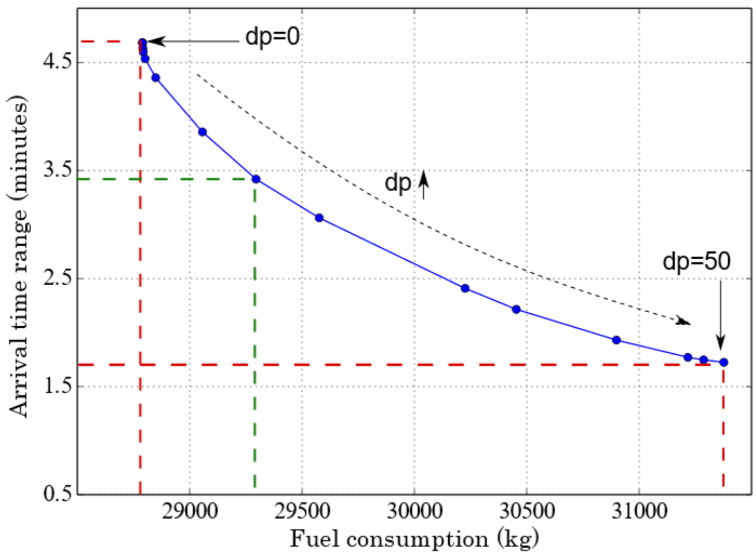

Figure 11. Trade-off between fuel consumption and flight time dispersion

Second, an application to a case study in which both wind and convective phenomena are considered to be the only sources of uncertainty. The ensemble forecasts ECMWF-EPS and GLAMEPS, released at 00:00 on 19th of December 2016, for a pressure of 200 hPa, and with a forecasting horizon of 9 hours is used in this application. With this case study, it has been shown that the algorithm is able to take into consideration convection risk: Figure 12 displays the geographical routes, from New York to Alger, for different values of the convective penalty cp (setting $dp = 0$). It can be seen that routes computed with higher cp tend to reduce the exposure to high convection risk zones, but at the cost of taking a more indirect route.

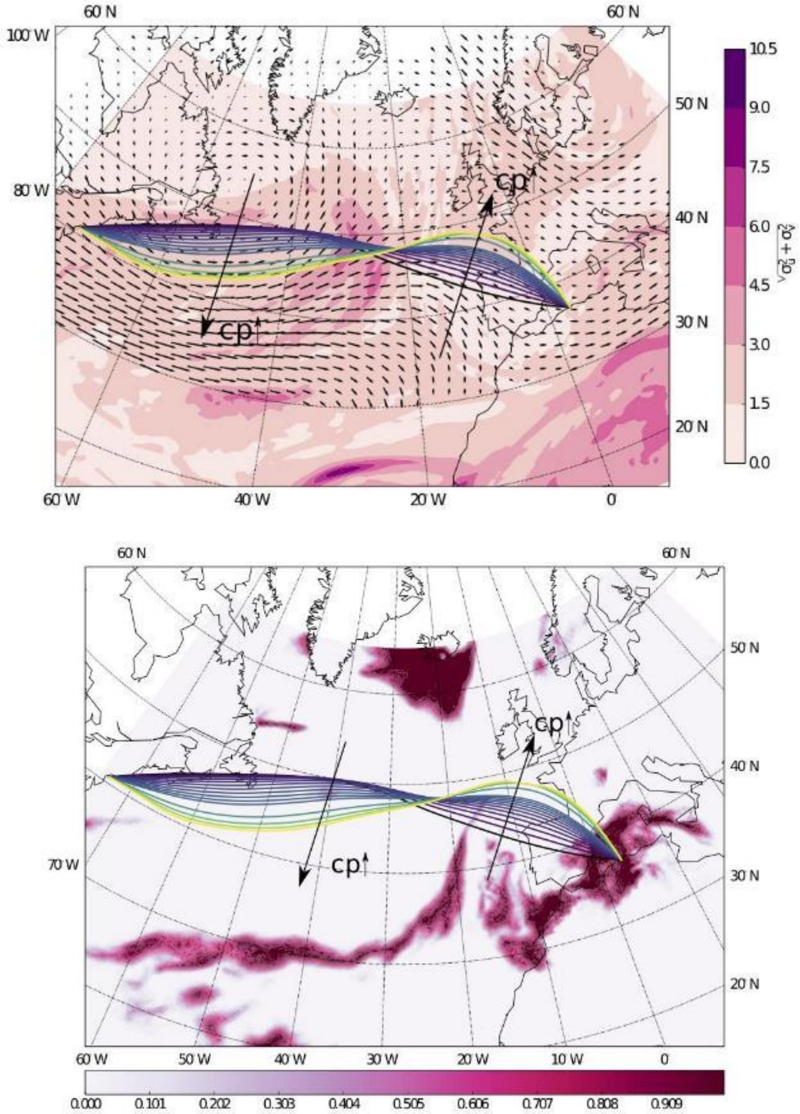

Figure 12. Optimal trajectories for different values of cp (from 0 to 0.03 s/m) and $dp = 0$. Top: trajectories over a map with colour regions of wind uncertainty. Bottom: trajectories over a map of convection risk

2.4.4 Storm avoidance

In the storm-avoidance problem research on trajectory prediction at the tactical level (short-term and execution) considering uncertainty in the evolution of convective cells has been done. The main goal was to observe the characteristics of the resulting deviation trajectories with respect to predictability and efficiency under different uncertainty conditions. The results are described in detail in Deliverable 4.2 [10].

A methodology for short-term trajectory prediction which is capable of taking uncertainties of convective cells was introduced. The methodology was applied to a number of BDT which were provided by the mid-term trajectory planning algorithm (as described in Section 2.3.3). For each BDT an ensemble of deviation trajectories is generated. Figure 13 shows the different deviation solutions generated by DIVMET when facing stochastically-varied convective cells locations, and Figure 14 depicts in more detail one of such deviation trajectories.

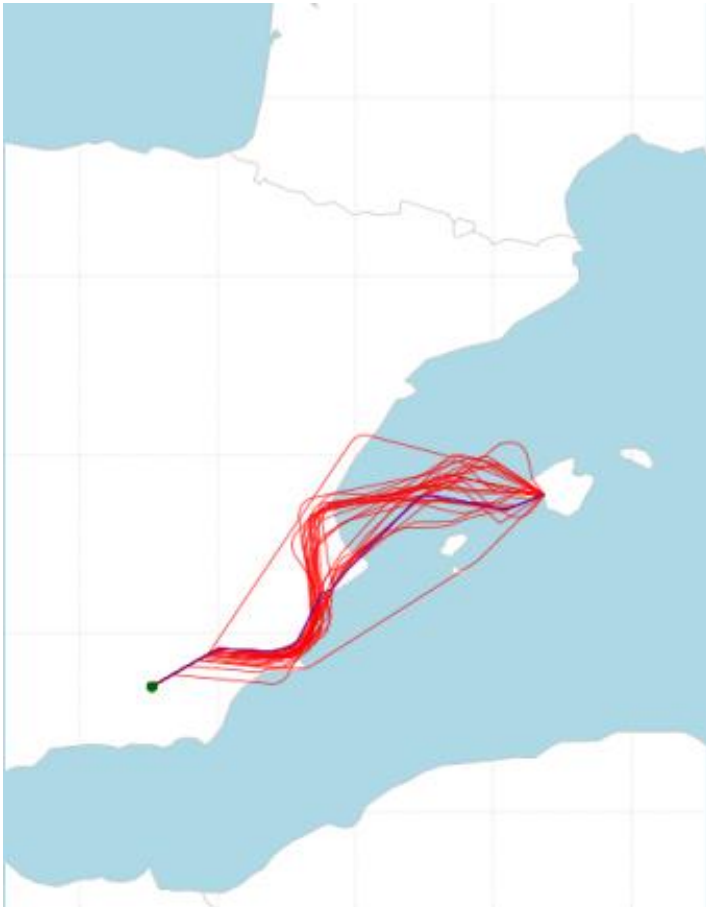

Figure 13. Example of multiple trajectory predictions as calculated by DIVMET according to the stochastically varied convective cells. Initial BDT is in dark blue

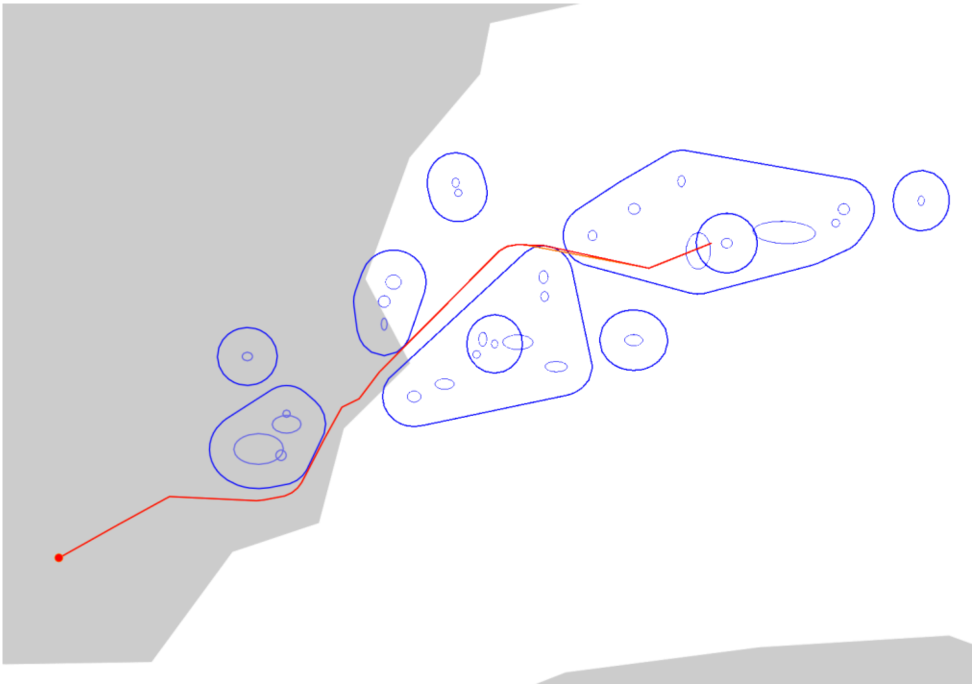

Figure 14. Example of one trajectory prediction as calculated by DIVMET facing one realisation of convective cells. The aircraft is located at the red dot on the left end of the trajectory. Notice that the destination is located inside a cell

Appropriate measures to quantify predictability and efficiency of trajectory predictions have been defined. Dispersion of arrival times was identified to be an inverse measure of predictability, and mean delay was identified to be a measure of efficiency.

Statistical parameters (dispersion of arrival times and mean of delays) were derived from the multiple trajectory predictions in order to estimate the effect of uncertainty on predictability and efficiency of the predicted trajectories. The case studies confirmed the working hypothesis that with growing uncertainty, predictability and efficiency of the predicted trajectories decreases.

The case studies contained also the comparison of results obtained with different uncertainty functions. A clear dependency of predictability and efficiency on the different uncertainty conditions was found.

By detailed analyses of intermediate results of single trajectory predictions, it was shown that predictability and efficiency are affected strongly by the course of the BDT in relation to the convective cells. Additionally, it was found that the safety margin plays a major role as well.

In Figure 15 the mean delay as a function of lead time is presented for different functions giving the uncertainty margin as a function of lead time (see Deliverable 4.2 [10] for more details). By comparing these curves it can be seen that any uncertainty, which is put into the trajectory prediction algorithm, results in an increase of the mean delay. The curve from the simulations without uncertainty is steadily lower than those considering uncertainty. So it can be concluded that efficiency is always worse when considering uncertainty. Note that the constant level from 40 to 60 minutes is due to the fact that the aircraft has virtually passed the area of convective activity and has no further cells ahead, so that the predicted trajectory does not change anymore.

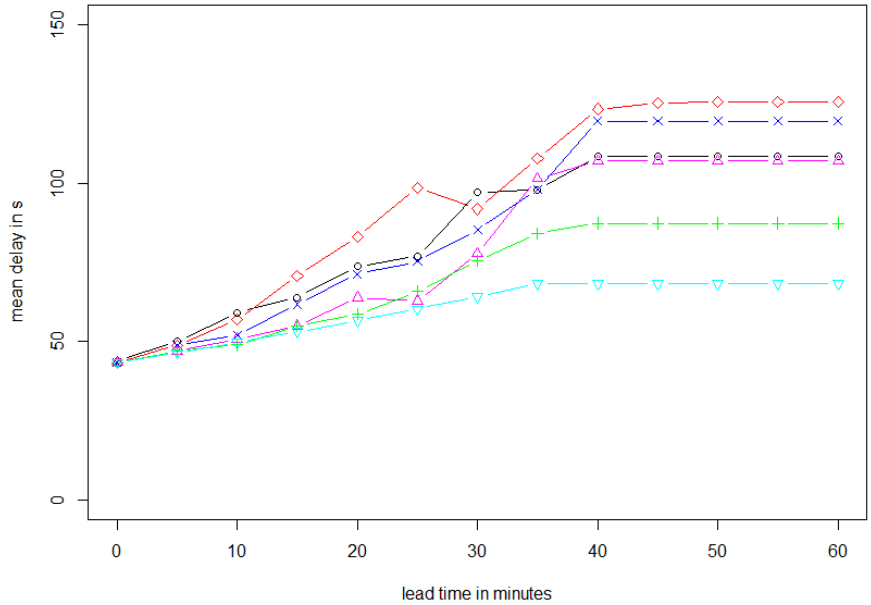

Figure 15. Mean delay as a function of lead time for one BDT with different uncertainty margins as functions of lead time. The light blue curve shows the delay without uncertainty

The dispersion of arrival times can be shown to increase with growing uncertainty as well. Since the dispersion of arrival times is an inverse measure of predictability it can be concluded that predictability is also worse when considering uncertainty.

2.4.5 Sector demand

The methodology to compute probabilistic sector-demand forecasts presented in Section 2.3.5 has been applied at pre-tactical level (medium-term, one day in advance) and tactical level (short-term and execution, some minutes before operation). The sector demand has been analysed at pre-tactical level when subject to wind uncertainty, and at tactical level when subject to storm uncertainty. In each case, two different scenarios are considered: trajectories planned with and without improved predictability, using the algorithms developed in Section 2.3.3. In this way, the benefits of improving the predictability of individual trajectories on the traffic scale is assessed. Next, a summary of both applications is presented, a complete description can be found in Deliverable 5.2 [13].

2.4.5.1 Sector demand analysis at pre-tactical level

The demand of the ATC sector LECMSAU is analysed for a whole day, 01 September 2016 (from 00:00 to 24:00), when predicted the day before, 31 August at 00:00. The sector LECMSAU is an en-route sector located in the Northwest of Spain, see Figure 16. In this application, 328 flights are considered.

This traffic is composed of short flights (departing from Portugal, Spain, and France), medium flights (from the Canary Islands, the British Isles, the Scandinavian Peninsula, and Eastern Europe), and long flights (from South, Central, and North America). The ECMWF-EPS weather forecast, composed of 50 perturbed members, is used. In particular, the forecasts released at 00:00 on 31 August 2016, for a 200 hPa pressure level, with forecasting horizons of 12, 18, 24, 30, 36, 42, 48, 54, and 60 hours are considered. In this application the convection penalty is $cp = 0$.

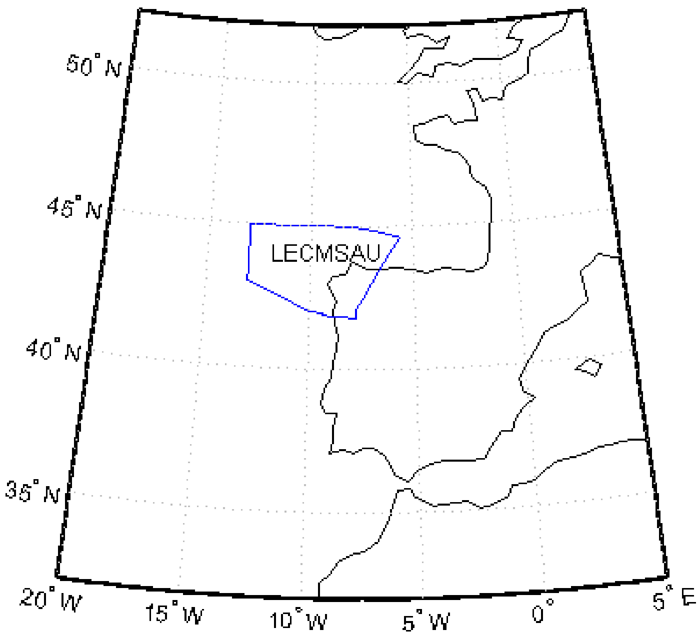

Figure 16. Geographical location of ATC sector LECMSAU

First, the scenario in which the trajectories are planned for minimum flight time (without dispersion penalty, $dp = 0$), is analysed. The entry count, with a time-period duration of $\delta t = 30$ minutes, is presented in Figure 17. In this figure, the average entry count is shown as vertical bars, and the minimum and maximum entry count as whiskers. The capacity of the sector is depicted as a red horizontal line, which is assumed to be 18 flights/30 minutes. The traffic peak is forecasted for the period 07:00-07:30; it is between 25 and 27 flights, with an average value of 26.6 flights.

The uncertainty on the entry count is on the spread of the number of flights, that is, the height of the whiskers in Figure 17; it is also represented in the left side of Figure 18 for convenience. In this application, the difference between the maximum and the minimum values of the entry count is as large as 3 flights for a total of 0.5 hours, 2 flights for 5.5 hours (in disjoint periods), 1 flight for 9 hours, and 0 flights for the remaining 9 hours; on average, 0.89 flights. Notice that larger values of uncertainty may be expected in scenarios with larger levels of traffic, forecasted more time in advance, or with more uncertainty sources as, for example, air temperature.

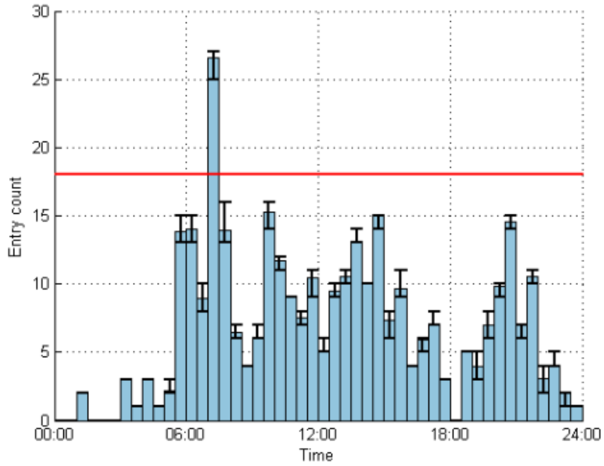

Figure 17. Entry count for $\delta t = 30$ min and $dp = 0$

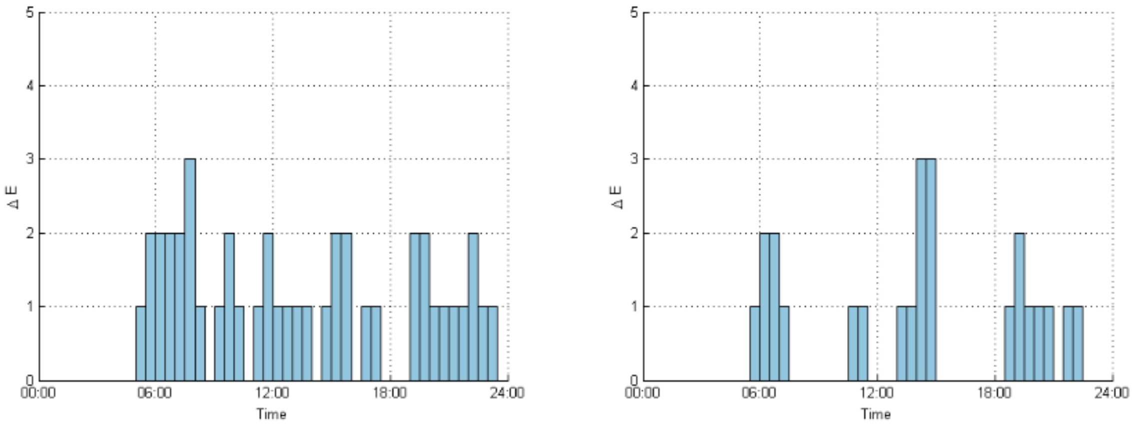

Figure 18. Dispersion of the entry count, ΔE, for $\delta t = 30$ min. Left: $dp = 0$. Right: $dp = 20$

For shorter durations of the time periods (e.g., $\delta t = 10$ minutes), it has been observed that the uncertainty becomes more important: the average entry counts are proportionally reduced whereas the largest dispersion values increase. For example, for 30-minute duration, the largest dispersion on the entry count is 3 flights and the average entry count is 6.83 flights/period, 44 % in relative terms; whereas for 10-minute duration the largest dispersion on the entry count is 4 flights and the average entry count is 2.28 flights/period, 175 %.

For the second scenario, trajectories planned with improved predictability, $dp = 20$, the average entry count is slightly different to the one found for $dp = 0$ because of differences in the average entry times; it is not shown for brevity. The main difference between the two scenarios is found in the dispersion of the entry count, as can be seen in Figure 18 left compared to Figure 18 right. The dispersion can be occasionally larger for some periods (for example, for 14:00-14:30 the dispersion is 2 flights for $dp = 0$ and 3 flights for $dp = 20$) but, on average, the dispersion has been, as intended, significantly reduced: from 0.89 to 0.69 flights.

2.4.5.2 Sector demand analysis at tactical level

In this second application, the demand of the ATC sector LECBLVU is analysed for seven hours, from 6:00 to 13:00 on 19 December 2016. The sector LECBLVU is an en-route sector located in the East coast of Spain, see Figure 19. A total number of 257 flights is considered in this application. Every 10 minutes, according to the release of new Nowcasts, new possible deviation trajectories are generated and the predicted demand is updated. For each flight, the deviation trajectories are generated once the aircraft enters an extended area around the sector. In this application the dispersion penalty is $dp = 0$.

As an example, in Figure 20 it is shown the deterministic Nowcast provided by AEMET and released at 08:10, which identifies 55 different storm cells. In this figure, the rectangle that encloses each cell is presented in blue, and the estimation of its future positions in red. It can be seen that the sector is greatly affected by these storms. In general, the cells travel Eastwards at different speeds.

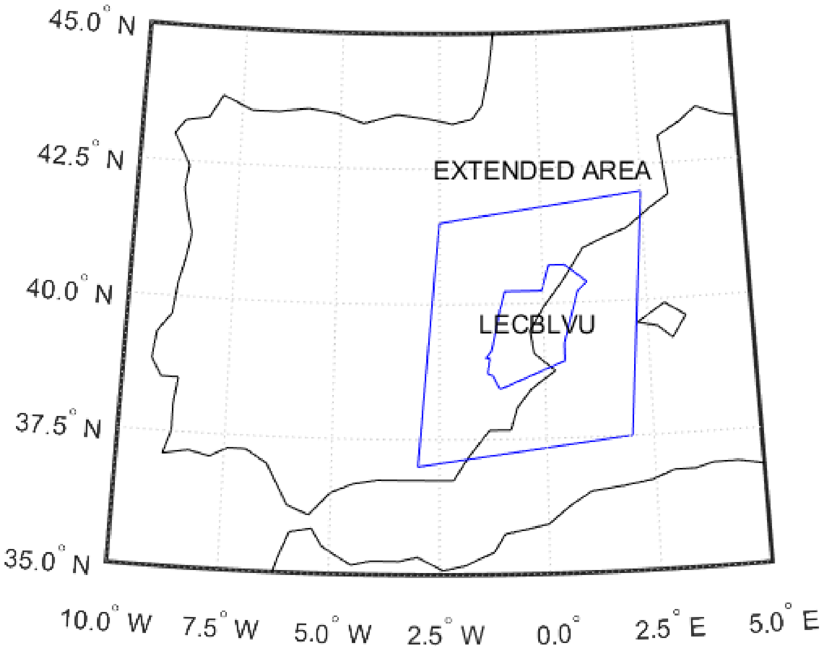

Figure 19. Geographical location of ATC sector LECBLVU

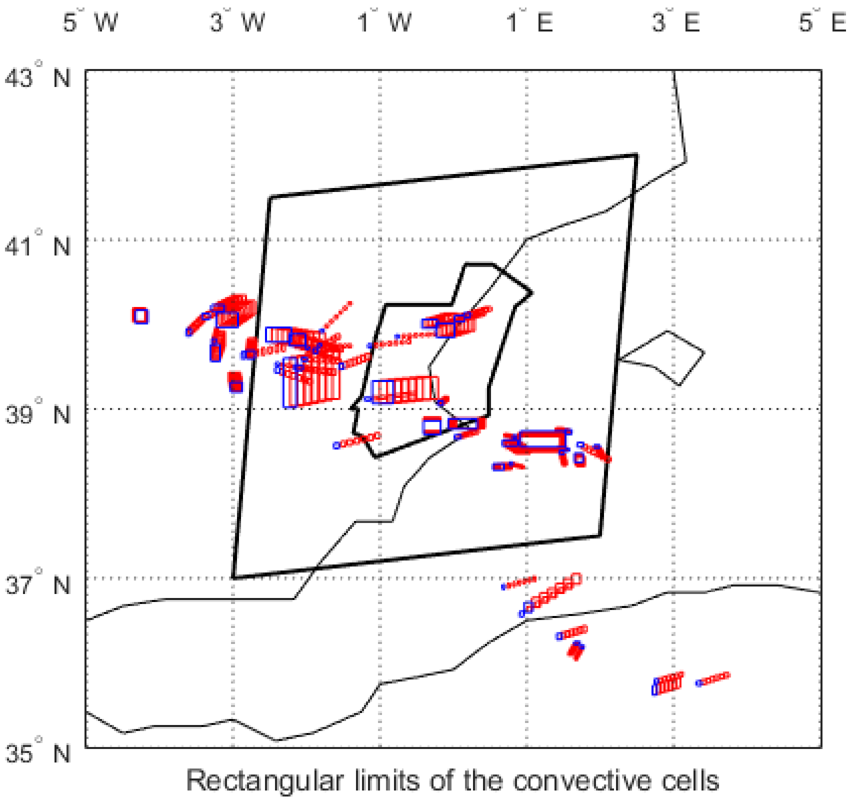

Figure 20. AEMET Nowcast released at 08:10; detected storm cells (blue), and estimation for 10, 20, 30, 40, 50, and 60 minutes (red)

The possible deviation trajectories computed at different time instants for one particular flight (flight number 203221283) are shown in Figure 21. At the first prediction time, 09:28, when the aircraft enters the extended area, the possible deviation trajectories are very disparate among them. This dispersion comes from the uncertain location of the storm cells, which increases as the lead time increases. As the flight progresses, the aircraft comes closer to the storm cells, thus the dispersion is reduced and the deviation trajectories are more similar among them.

The dispersion of the possible deviation trajectories leads to dispersions on the entry and the exit times to/from the sector. As a reference, for the same previous flight, at the first prediction time (09:28), the dispersion of the entry time, measured as the difference between the maximum and the minimum value, is rather large (294.9 seconds), because the entry point can be located at the Northeast or at the Northwest of the sector, see Figure 21. The dispersion of the exit time is even larger (766.3 seconds), because the aircraft can exit the sector by the Northeast or by the South. These dispersions are reduced as the aircraft approaches the entry and the exit points, respectively. The dispersion of the entry (exit) time is zero once the aircraft enters (exits) the sector. This behaviour can be extended, in general, to all the flights.

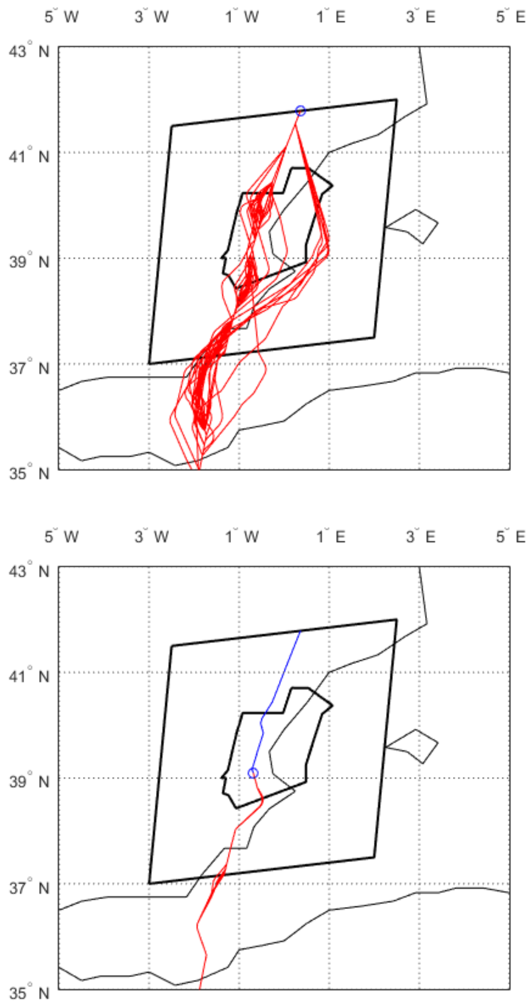

Figure 21. Flight 203221283 and reference route obtained for $cp = 0.005$ s/m: possible deviation routes (red) and executed trajectory (blue). Time instants 09:28 (top left), 09:38 (top right), 09:48 (bottom left), and 09:58 (bottom right)

Next, the occupancy count is analysed for the scenario in which the trajectories are planned for minimum flight time (without convection penalty, $cp = 0$). In Figure 22, the occupancy count is depicted when predicted at two consecutive time instants, 08:30 and 08:40; it is shown for time periods of 1-minute duration and a maximum forecasting horizon of 15 minutes. Although the maximum forecasting horizon is short, the presence of the uncertain convective cells leads to a dispersion of up to 4 flights. This is a large dispersion, taking into account that the maximum average occupancy is just 7 flights. In this figure, one can see how the expected occupancy count evolves as the predictions are updated. As an example, the occupancy of the time period 08:44-08:45 is between 4 and 8 flights when predicted at 08:30, and it is narrowed to be between 5 and 6 flights when predicted at 08:40.

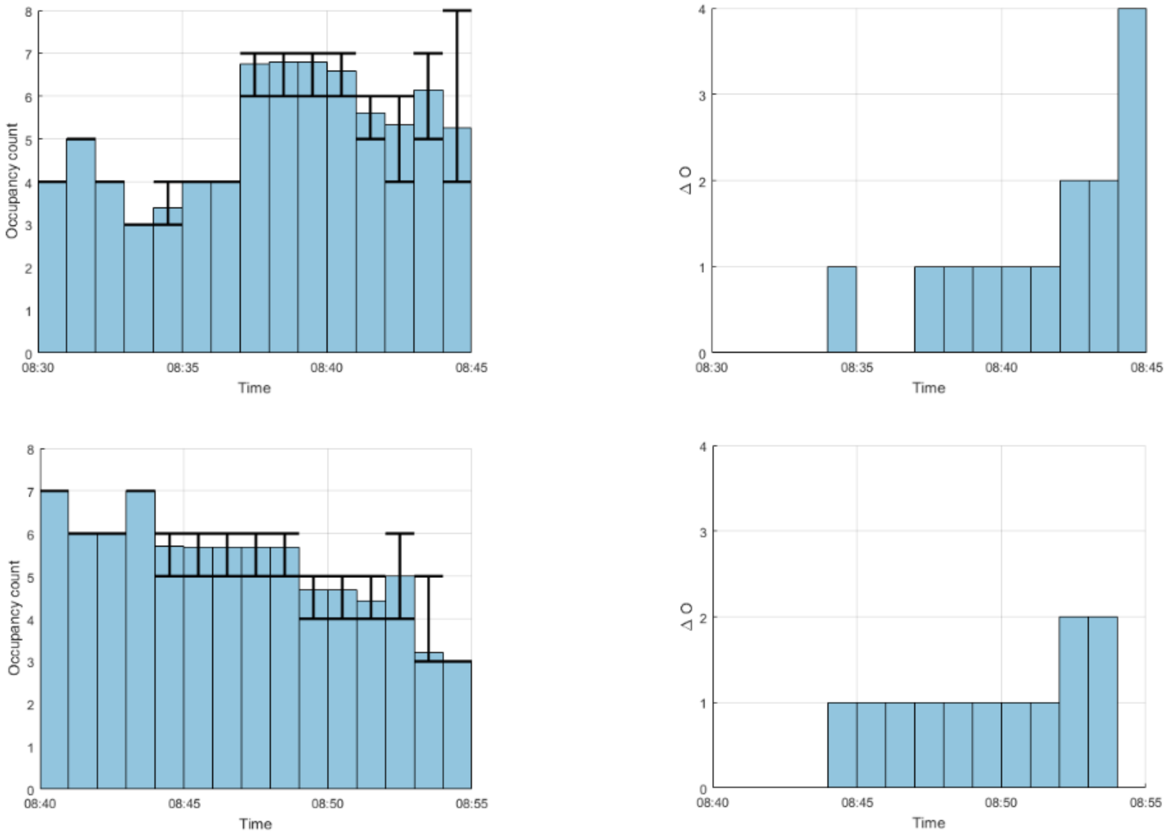

Figure 22. Occupancy count (left) and its dispersion (right) for $cp = 0$, predicted at two time instants: 08:30 (top) and 08:40 (bottom)

The previous example is a clear illustration of how the dispersion is reduced when the period to be forecasted is closer to the time instant at which the prediction is generated. This relationship between the dispersion and the forecasting horizon is shown in Figure 23 for the two scenarios considered in this application, $cp = 0$ (minimum flight time) and $cp = 0.005$ s/m (reduced convection risk). In this figure it is represented the average of the dispersion for all the predictions generated every 10 minutes between 07:30 and 11:00, the period most affected by the storm activity. This average can be interpreted as the average of the dispersions shown on the right side of Figure 22, but for all the predictions made between 07:30 and 11:00. In Figure 23, T_P generically represents the time instant at which each prediction is made.

One can see that, as expected, the average dispersion is almost nil for time periods very close to T_P, and that it increases, almost linearly, as the forecasting horizon increases. Notice that this average dispersion takes into account periods with different traffic density and storm intensity; therefore, although the maximum average value is about 0.8 flights, the maximum dispersion at a specific prediction time can be as large as 4 flights, as it was observed in Figure 22.

Finally, in Figure 23, it can be seen that, as intended, the average dispersion is reduced when the convection penalty cp of the individual flights is increased, although locally, for particular forecasting horizons it may increase. The average dispersion for all the forecasting horizons is reduced from 0.52 flights for $cp = 0$ to 0.37 flights for $cp = 0.005$ s/m.

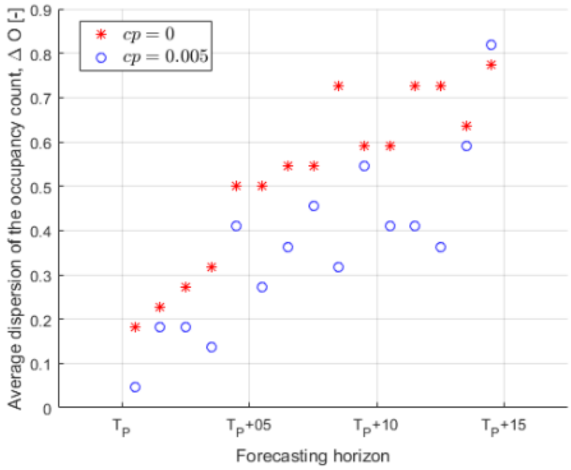

Figure 23. Average dispersion of the occupancy count for different forecasting times

2.4.6 Validation

In this section, the main results obtained in the validation tasks are described in terms of the key validation indicators defined for the different scenarios. Note that the third validation scenario (VS3) is described in the last place.

Validation scenario VS1

The aim of VS1 is to validate the concept of robust trajectory planning at pre-tactical level considering only wind uncertainties. One of the key ideas in TBO-Met project is that, at the mid-term planning level, a robust trajectory planning algorithm can be developed that takes into consideration the exposure to uncertain winds and improves predictability by penalizing the flight time dispersion. Hence, the concept to be validated in VS1 is that penalizing flight time dispersion leads to more predictable trajectories, although at the cost of additional flight time and fuel consumption, in average.

The validation is made in terms of two global variables: Flight Time (FT) and Fuel Consumption (FC), and the penalization of the flight time dispersion is made using the dispersion penalty parameter dp (see section 2.3.3).

First, to assess the predictability of the trajectories, the difference between the simulated and the average predicted values of FT and FC (say, ΔFT and ΔFC) are computed for all flights considered in VS1 (the average in each case is performed over all the members of the EPS), and then the averages of these difference values for all the flights are computed (say, ΔFT^{Avg} and ΔFC^{Avg}). This process is done for two values of the dispersion penalty: $dp = 0, 20$. And, second, to assess the increase in cost caused by the increased predictability, the averages of the simulated values of FT and FC for all the flights are computed (say, FT^{Avg} and FC^{Avg}), which is again done for the two values of dp.

To perform the simulations, NAVSIM is provided with the planned routes to be followed (different for each flight and each value of dp) and computes the flight time and the fuel consumption subject to the "real" meteorological conditions described in section 2.3.6 (namely, the Reanalysis provided by ECMWF).

The validation consists in showing that when dp increases, the average difference values ΔFT^{Avg} and ΔFC^{Avg} decrease, that is, when the flight time dispersion is more penalized, the trajectories become more predictable (because the difference between simulation and prediction decreases). But this improvement in predictability has an extra cost, which is validated by showing that when dp increases, the average values FT^{Avg} and FC^{Avg} increase, that is, in average the flight time and the fuel consumption are larger.

For convenience, the definitions of the four key validation indicators previously considered are listed in Table 1. And the quantitative values obtained in the validation are collected in Table 2, where one can see that all the indicators follow the appropriate trends when dp increases. Therefore, the concept for robust trajectory planning in the presence of wind uncertainties developed in TBO-Met is validated.

Table 1. VS1: Key Validation Indicators

KVI	Description
ΔFT^{Avg}	Average over all flights in VS1 of the differences between the simulated Flight Time and the average predicted (at mid-term) Flight Time, for each value of dp.
ΔFC^{Avg}	Average over all flights in VS1 of the differences between the simulated Fuel Consumption and the average predicted (at mid-term) Fuel Consumption, for each value of dp.
FT^{Avg}	Average over all flights in VS1 of the simulated Flight Time, for each value of dp.
FC^{Avg}	Average over all flights in VS1 of the simulated Fuel Consumption, for each value of dp.

Table 2. VS1: Aggregated Key Validation Indicators

dp	ΔFT^{Avg} (s)	ΔFC^{Avg} (kg)	FT^{Avg} (s)	FC^{Avg} (kg)
0	88	74	11744	11345
20	81	66	12321	11820

Validation scenario VS2

VS2 is devoted to validate the concept of robust trajectory planning at pre-tactical level considering not only wind uncertainties, but also convective risk. Another key idea in TBO-Met is that, at the mid-term planning level, a robust trajectory planning algorithm can be developed that takes into consideration the exposure to convection risk and improves predictability by penalizing a quantitative measure of such exposure. Hence, the concept to be validated in VS2 is that penalizing the exposure to convection risk leads to more predictable trajectories because, at the execution phase, these routes imply less storm avoidance manoeuvres; again, enhanced predictability comes, nevertheless, at the cost of additional flight time and fuel consumption, in average.

The validation is made again in terms of the two variables Flight Time and Fuel Consumption, and the penalization of the exposure to convection risk is made using the convection penalty parameter cp (see section 2.3.3). The validation procedure is similar to the one described above for VS1, but now the flights considered are different, and the process is done for two values of cp (note that in VS2, dp =0). For clarity this procedure is repeated next.

First, to assess the predictability of the trajectories, the difference between the simulated and the average predicted values of *FT* and *FC* (say, ΔFT and ΔFC) are computed for all flights considered in VS2 (the average in each case is performed over all the members of the EPS), and then the averages of these difference values for all the flights are computed (say, ΔFT^{Avg} and ΔFC^{Avg}). This process is done for two values of the convection penalty: $cp = 0, 0.02$ s/m. And, second, to assess the increase in cost caused by the increased predictability, the averages of the simulated values of *FT* and *FC* for all the flights are computed (say, FT^{Avg} and FC^{Avg}), which is again done for the two values of cp.

Again, to perform the simulations, NAVSIM is provided with the planned routes to be followed (different for each flight and each value of cp) and computes the flight times and the fuel consumptions when the flights are subject to the "real" meteorological conditions described in section 2.3.6 (namely, the Reanalysis provided by ECMWF and the Nowcasts provided by AEMET). The functionality to avoid storms is provided by DIVMET.

The validation consists in showing that when cp increases, the average difference values ΔFT^{Avg} and ΔFC^{Avg} decrease, that is, when the convection risk measure is more penalized, the trajectories become more predictable (because the difference between simulation and prediction decreases). But this improvement in predictability has an extra cost, which is validated by showing that when cp increases, the average values FT^{Avg} and FC^{Avg} increase, that is, in average the flight time and the fuel consumption are larger.

For convenience, the definitions of the four key validation indicators previously considered are listed in Table 3. And the quantitative values obtained in the validation are collected in Table 4, where one can see that all the indicators follow the appropriate trends when cp increases. Therefore, the concept for robust trajectory planning considering the exposure to convection risk developed in TBO-Met is validated.

Table 3. VS2: Key Validation Indicators

KVI	Description
ΔFT^{Avg}	Average over all flights in VS2 of the differences between the simulated Flight Time and the average predicted (at mid-term) Flight Time, for each value of cp.
ΔFC^{Avg}	Average over all flights in VS2 of the differences between the simulated Fuel Consumption and the average predicted (at mid-term) Fuel Consumption, for each value of cp.
FT^{Avg}	Average over all flights in VS2 of the simulated Flight Time, for each value of cp.
FC^{Avg}	Average over all flights in VS2 of the simulated Fuel Consumption, for each value of cp.

Table 4. VS2: Aggregated Key Validation Indicators

cp (s/m)	ΔFT^{Avg} (s)	ΔFC^{Avg} (kg)	FT^{Avg} (s)	FC^{Avg} (kg)
0	93.7	102.1	8185	6181
0.02	74.1	96.2	8816	6639

Validation scenario VS4

VS4 is intended to validate the sector-demand prediction at pre-tactical level considering only wind uncertainties. Now two TBO-Met concepts are to be validated in VS4: The first concept is that the sector demand can be accurately predicted at pre-tactical level (one day before operation) when wind uncertainties are considered; the second concept is that the uncertainty of the pre-tactical prediction of the sector demand decreases as the predictability of the planned aircraft trajectories increases.

The validation is made in terms of two variables: the entry count (E) and the occupancy count (O). To perform the counts several time periods, of duration δt, and several values of the dispersion penalty parameter dp are considered. The sector demand is computed for a whole day.

First, to assess that the methodology developed in TBO-Met to predict the sector demand at pre-tactical level considering wind uncertainties is accurate, the percentages of predictions (for the time periods considered in VS4) that bracket the simulated demand are computed, both for the entry count ($\%E$) and for the occupancy count ($\%O$). And, second, to assess the decrease in the uncertainty of the sector demand prediction caused by the increase in the predictability of the planned trajectories, the average differences (over all time periods considered in VS4) between the average predicted and the simulated entry and occupancy counts (δE and δO, respectively) are computed. Note that the more predictable trajectories are those planned for large values of dp (as in VS1). This process is done for three values of the time period duration (δt=10, 30, 60 minutes) and for two values of the dispersion penalty (dp=0, 20). Since the sector demand is computed for 24 hours, the different time period durations lead to different numbers of time periods: 24 time periods for δt =60 minutes, 48 for 30 minutes, and 144 for 10 minutes.

The predictions of the counts are made considering the trajectories planned at pre-tactical level (as described in sections 2.3.3 and 2.4.3). For each time period, a prediction of a count consists of a set of values of the count, each one corresponding to a different members of the EPS; it is characterized by the maximum, the minimum, and the average over all values. To perform the simulations, NAVSIM is provided with the planned routes to be followed (different for each flight and each value of dp) and computes the entry and exit times to the sector subject to the Reanalysis provided by ECMWF (the "real" meteorological conditions considered in TBO-Met). The simulated counts are obtained from these times.

The validation of the first concept consists in showing that the percentages of predictions that bracket the simulations (that is, the percentage of predictions whose maximum and minimum values encompass the simulated value) are above the thresholds defined in the validation criteria (see Deliverable 5.3 [14]), that is, that $\%E$ and $\%O$, for the different values of δt and dp, are all above 70%. And to validate the second concept, one must show that when dp increases, the average differences δE and δO decrease, that is, when the flight time dispersion is more penalized, the sector demand is less uncertain (because the difference between simulation and prediction decreases).

For convenience, the definitions of the four key validation indicators previously considered are listed in Table 5. The quantitative values obtained in the validation are collected in Table 6 for the entry count and in Table 7 for the occupancy count. First, one can see that all the percentages are above 70% (in fact, they are above 90%), which implies a very good agreement between the predicted results and the simulation results, therefore the first concept is validated. Notice that this is one of the main contributions of TBO-Met project, i.e., that the ensemble-based stochastic methodology is able to successfully predict sector demand based on the uncertainty of the individual trajectories (see the third Operational Improvement Step proposed in Section 3). Now, for the second concept the results show that only in four out of six cases the average differences decrease as dp increases, that is, there is not full validation. In fact, it is shown that penalizing the flight time dispersion of the individual trajectories does not seem to have a clear impact on the dispersion of the entry count; this result has identified a lesson learned (see section 4.3).

Table 5. VS4: Key Validation Indicators

KVI	Description
$\%E_{i,j}$	Percentage of predictions over all time periods that bracket the simulated entry count, for each value of the dispersion penalty dp (index i), and each value of the duration of the time period δt (index j).
$\%O_{i,j}$	Percentage of predictions over all time periods that bracket the simulated occupancy count, for each value of the dispersion penalty dp (index i), and each value of the duration of the time period δt (index j).
$\delta E_{i,j}$	Average over all time periods of the differences between the average predicted and the simulated entry count, for each value of the dispersion penalty dp (index i), and each value of the duration of the time period δt (index j).
$\delta O_{i,j}$	Average over all time periods of the differences between the average predicted and the simulated occupancy count, for each value of the dispersion penalty dp (index i), and each value of the duration of the time period δt (index j).

Table 6. VS4: Entry count Key Validation Indicators

	$\delta t = 60$ minutes	$\delta t = 30$ minutes	$\delta t = 10$ minutes
$dp = 0$	$\%E_{0,60} = 100.0$ $\delta E_{0,60} = 0.28$	$\%E_{0,30} = 100.0$ $\delta E_{0,30} = 0.27$	$\%E_{0,10} = 99.3$ $\delta E_{0,10} = 0.30$
$dp = 20$	$\%E_{20,60} = 91.7$ $\delta E_{20,60} = 0.26$	$\%E_{20,30} = 95.8$ $\delta E_{20,30} = 0.32$	$\%E_{20,10} = 97.9$ $\delta E_{20,10} = 0.33$

Table 7. VS4: Occupancy count Key Validation Indicators

	$\delta t = 60$ minutes	$\delta t = 30$ minutes	$\delta t = 10$ minutes
$dp = 0$	$\%O_{0,60} = 91.7$ $\delta O_{0,60} = 0.46$	$\%O_{0,30} = 97.9$ $\delta O_{0,30} = 0.47$	$\%O_{0,10} = 97.9$ $\delta O_{0,10} = 0.39$
$dp = 20$	$\%O_{20,60} = 91.7$ $\delta O_{20,60} = 0.40$	$\%O_{20,30} = 95.8$ $\delta O_{20,30} = 0.38$	$\%O_{20,10} = 97.2$ $\delta O_{20,10} = 0.35$

Validation scenario VS5

The aim of VS5 is to validate the sector-demand prediction at tactical level considering both convection risk and the uncertain evolution of storms. Now, again, two TBO-Met concepts are subject to validation: the first concept is that the sector demand can be accurately predicted at tactical level (some minutes before operation) when thunderstorm uncertainties are considered; the second concept is that the uncertainty of the tactical prediction of the sector demand decreases as the predictability of the planned aircraft trajectories increases.

Recall that (as described in section 2.4.5.2), according to the release of new Nowcasts, every 10 minutes new possible deviation trajectories (up to 31 per flight) are generated to avoid the convective cells and the predicted demand is updated; this predicted demand is in fact a set of predictions given for time periods of 1-minute duration and a maximum forecasting horizon of 15 minutes, labeled T_p + 1,..., T_p + 15 (where T_p is the time instant at which the prediction is made, which changes every 10 minutes). The validation is made now in terms of one variable: the occupancy count (O), considering several values of the prediction time T_p and several values of the convection risk penalty cp (in VS5, dp =0). Note that, for each value of T_p, 15 predictions of the occupancy count are made (O_k). In this validation scenario, only uncertainty in the location of the centroids of the individual storm cells is considered.

First, to assess that the methodology developed in TBO-Met to predict the sector demand at tactical level, considering both convection risk and the uncertain evolution of storms, is accurate, the percentages of predictions (for all the different predictions made for the time periods considered in VS5) that bracket the simulated occupancy count are computed, both aggregated for each value of T_p ($\%O$) and disaggregated for each 1-minute time period T_p + k ($\%O_k$). And, second, to assess the decrease in the uncertainty of the sector demand prediction caused by the increase in the predictability of the planned trajectories, the average (over all the different predictions made for the time periods considered in VS5) of the differences between the predicted and the simulated occupancy counts (δO) are computed. Note that now the more predictable trajectories are those planned for large values of cp (as in VS2). This process is done for several values of T_p (every 10 minutes after reaching the extended area around the sector described in section 2.4.5.2) and two values of the convection risk penalty (cp=0, 0.005 s/m).

The predictions of the occupancy count are made considering the deviation trajectories provided by DIVMET, obtained for each flight following the procedure described in sections 2.3.4 and 2.4.4, which starts with a reference (BDT) trajectory planned at pre-tactical level (as described in sections 2.3.3 and 2.4.3) for the given value of cp. Each prediction of the count consists of the maximum, minimum, and average values of the count.

To perform the simulations, NAVSIM is provided with the reference routes to be followed (different for each flight and each value of cp) and computes the entry and exit times to/from the sector subject to the Reanalysis provided by ECMWF and the Nowcasts provided by AEMET (the "real" meteorological conditions considered in TBO-Met). The simulated occupancy count is obtained from these times. The functionality to avoid storms is provided by DIVMET.

The validation of the first concept consists in showing that the percentages of predictions that bracket the simulated occupancy count are above the threshold defined in the validation criteria (see Deliverable 5.3 [14]), that is, that $\%O$ and $\%O_k$, for the different values of T_p and cp, are all above 70%. And to validate the second concept, one must show that when cp increases, the average difference δO decreases, that is, when the exposure to convection risk is more penalized, the sector demand is less uncertain (because the differences between simulation and prediction decreases).

For convenience, the definitions of the three key validation indicators previously considered are listed in Table 8. The quantitative values obtained in the validation are collected in Table 9 for $\%O$ and δO, and in Figure 24 for $\%O_k$. First, one can see that all the percentages are above 70% (in fact, they are above 85%), which implies a very good agreement between the predicted results and the simulation results, therefore the first concept is validated. Notice again that this is one of the main contributions of TBO-Met project, i.e., that the ensemble-based stochastic methodology is able to successfully predict sector demand based on the uncertainty of the individual trajectories (see the third Operational Improvement Step proposed in Section 3). Now, for the second concept the results show that the average difference δO follows the appropriate trend, decreasing when cp increases, therefore the second concept is validated as well.

Table 8. VS5: Key Validation Indicators

KVI	Description
$\%O$	Percentage of predictions over all predictions made that bracket the simulated occupancy count, for each value of the convection penalty cp.
$\%O_k$	Percentage of predictions over all predictions made that bracket the simulated occupancy count for each prediction time period (index k), for each value of the convection penalty cp.
δO	Average over all predictions made of the differences between the average predicted and the simulated occupancy count, for each value of the convection penalty cp.

Table 9. VS5: Key Validation Indicators $\%O$ and δO

cp (s/m)	$\%O$	δO
0	96.4	0.12
0.005	96.7	0.08

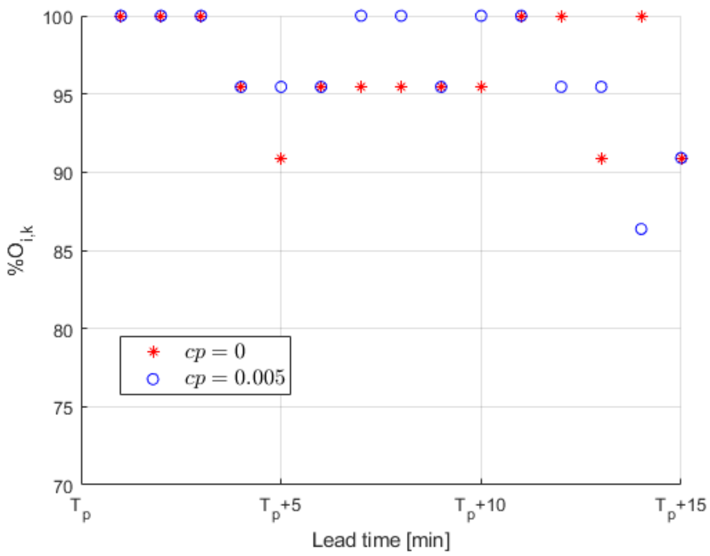

Figure 24. VS5: Key Validation Indicator $\%O_k$

Validation scenario VS3

The aim of VS3 is to validate the short-term trajectory prediction considering the uncertain evolution of storms. Now, two TBO-Met concepts are to be validated. The first concept is that, in the presence of thunderstorm uncertainties, the trajectory can be accurately predicted at tactical level (with some minutes in advance) by the algorithm developed in TBO-Met; in this algorithm a set of possible storm cell fields is synthetically generated and, then, a set of possible deviation trajectories (one per storm cell field) is obtained, which constitutes the short-term trajectory prediction (as described in sections 2.3.4 and 2.4.4). The second concept is that the uncertainty of the tactical prediction of the trajectory decreases as the predictability of the planned (at pre-tactical level) aircraft trajectories increases; now the more predictable trajectories are those planned for large values of cp (as in VS2 and VS5).

The validation is made in terms of two variables: the entry time (t_E) and the exit time (t_X) to/from the sector considered in VS5 and described in section 2.4.5.2. The validation is based on the comparison between the multiple possible deviation trajectories provided by the trajectory predictor and the real trajectory followed by the aircraft (the one that would happen in the real world). In particular, the validation is based on the comparison between the predicted entry and exit times and the true times obtained by NAVSIM.

Recall that, as in VS5, new possible deviation trajectories (up to 31 per flight) are generated every 10 minutes, according to the release of new Nowcasts. Also, only uncertainty in the location of the centroids of the individual convective cells is considered.

In this scenario four parameters are computed: δt_E and δt_X, which are the differences between the simulated and the average predicted entry and exit times, respectively, and Δt_E and Δt_X, which are the dispersions of the predicted entry and exit times, respectively. The averages in each case are performed over the 31 members of the set of deviation trajectories generated, and the dispersions are defined by the maximum and minimum values of the set.

From these parameters, two key validation indicators are computed: δt_E^{Avg} and δt_X^{Avg}, which are the average values of the differences for all the flights considered in VS3 and for all the predictions made; and two auxiliary variables are computed as well: Δt_E^{Avg} and Δt_X^{Avg}, which are the average values of the predicted dispersions again for all the flights considered in VS3 and for all the predictions made. All these computations are made for two values of the convection risk penalty (cp=0, 0.005 s/m).

As in VS5, the predictions of the entry and exit times are made considering the deviation trajectories provided by DIVMET, and to perform the simulations, NAVSIM is provided with the reference routes to be followed (different for each flight and each value of cp) and computes the entry and exit times to/from the sector subject to the “real” meteorological conditions considered in TBO-Met (Reanalysis and Nowcasts). Again, the functionality to avoid storms is provided by DIVMET.

To validate, first, that the methodology developed in TBO-Met is able to predict accurately the trajectory at tactical level in the presence of thunderstorm uncertainties, one must show that the average differences δt_E^{Avg} and δt_X^{Avg} are smaller than the average predicted dispersions Δt_E^{Avg} and Δt_X^{Avg}, that is, that the errors in the predictions are encompassed by the dispersions, which is an indication of good agreement between the predictions and the reality. And, second, to validate the decrease in the uncertainty of the tactical prediction caused by the increase in the predictability of the planned trajectories, one must show that when cp increases, the average differences δt_E^{Avg} and δt_X^{Avg} decrease; that is, when the exposure to convection risk is more penalized, the entry and exit times are less uncertain (because the differences between the simulated and predicted times are smaller).

For convenience, the definitions of the two key validation indicators previously considered are listed in Table 10. The quantitative values obtained in the validation are collected in Table 11 and Table 12. First, one can see that the average differences (about 20-40 seconds) are smaller than the average predicted dispersions (about 100-200 seconds), hence validating the first concept. And, second, the results show that the average differences (Table 11) decrease as cp increases, therefore the second concept is validated as well.

Table 10. VS3: Key Validation Indicators

KVI	Description
δt_E^{Avg}	Average over all flights and all predictions of the differences between the simulated entry time and the average predicted entry time, for each value of the convection penalty cp.
δt_X^{Avg}	Average over all flights and all predictions of the differences between the simulated exit time and the average predicted exit time, for each value of the convection penalty cp.

Table 11. VS3: Key Validation Indicators

cp (s/m)	δt_E^{Avg} (s)	δt_X^{Avg} (s)
0	31.3	39.5
0.005	23.2	30.8

Table 12. VS3: Average value of the predicted dispersions

cp (s/m)	Δt_E^{Avg} (s)	Δt_X^{Avg} (s)
0	206.5	109.7
0.005	143.6	108.1

2.5 Technical Deliverables

In the following table all the technical deliverables produced in the project are briefly described (see the Grant Agreement [31]); for more details see references [3-15]. For the management work (non-technical deliverables) see references [1,2,16-24].

Reference	Title	Delivery Date[1]	Dissemination Level[2]
	Description		
D2.1	Requirements and concept for EPS processing	30/09/2016	Public
This document identifies the meteorological data input needed for the pre-tactical and tactical analyses, presents the requirements on the data of EPS, and defines necessary methods for data processing. The processing tasks cover coordinate transformation, spatiotemporal interpolation and the extraction of polygons. Further data processing is defined to calculate the ensemble mean and the spread of wind components and temperature; the spread is used to quantify the forecast uncertainty. While wind and temperature data is readily available as model output, information about convection must be derived from numerous parameters. Detailed information is provided on the definition of suitable indicators to describe convection.			
D2.2	Software documentation for EPS processing	30/11/2016	Confidential
This deliverable is intended to provide all information for using the software developed to conduct the research activities at pre-tactical and tactical levels, which is implemented in Python 2.7 on a UNIX platform. Based on the meteorological data needed and the processing methods identified in Deliverable 2.1 [3], three use cases have been identified: a grid-based data processing for wind components and temperature, a trajectory-based data processing for wind components and temperature, and a data processing for convection indicators. This document describes the process of installation and the usage of the Python scripts referring to the use cases; especially, information about the data format (input and output) is given.			
D2.3	Requirements and concept for Nowcast processing	03/04/2017	Public
This deliverable describes the requirements and concept for the processing and provision of Nowcast data and the associated uncertainty, which will be input for the pre-tactical and tactical analyses. In particular, the requirements on the meteorological data include the criteria for the selection of data, their spatial and temporal resolution, and the data format. Appropriate measures of uncertainty based on Nowcast data are defined. The provided data is checked against the defined requirements in order to identify the necessary data processing methods. A specific topic addressed is the definition of an uncertainty margin for the nowcasted convective cells. Some improvements on Nowcast data provision for future research are identified.			
D2.4	Software documentation for Nowcast data	31/05/2017	Confidential
This document describes the implementation of the software for the processing and provision of Nowcast data and the associated uncertainty which will be input for the pre-tactical and tactical analyses. As the software provides weather forecasts we called it WxService. The pre-tactical and tactical analyses will use the data output of WxService with the aim to improve predictability in trajectory planning and to quantify the effects of weather uncertainty on			

[1] Delivery data of latest edition
[2] Public or Confidential

the sector demand at tactical level (short term planning and execution during flight). This deliverable serves also as a user guide for applying the software, which is written in JAVA.			
D3.1	Survey questionnaire	04/10/2016	Public
This deliverable addresses the scope, potential participants, ethical issues to be considered, the questions to be posed and the instructions to be followed by participants of the TBO-Met Survey Questionnaire. The objectives of the survey are to ensure that TBO-Met project is aligned with current meteorological practices in aviation; and to understand future expectations and needs regarding meteorological uncertainty management. The survey provides information on the type of meteorological services/products being used; the common understanding of meteorological uncertainty; how the different actors provide robustness to the systems; the desired values of predictability; and the efficiency cost they are willing to pay.			
D3.2	Stakeholders' survey report	03/02/2017	Public
This document presents and analyses the answers to the TBO-Met's Survey Questionnaire, including also the stakeholders to which the survey has been addressed, the ethical issues that were considered, and the processes followed to conduct the interviews. The answers to the ten questions of the Questionnaire given by all the participants are included, and each question is commented individually. Some conclusions are drawn; in particular, the objectives of the survey have been met: on one hand, from the answers received, it cannot be said that the TBO-Met project is not aligned with the stakeholders' interests, and, on the other hand, some ideas for future research have been provided by the participants.			
D4.1	Efficiency/predictability trade-off of 4D trajectories at pre-tactical level	28/02/2017	Public
In the present deliverable, results on robust trajectory planning at the pre-tactical level (mid-term planning) are presented. The main goal is to plan trajectories that are efficient, yet predictable. State-of-the-art forecasts from Ensemble Prediction Systems are used as input data for the wind field and convective risk. An ad-hoc optimal control methodology to solve trajectory-planning problems considering meteorological uncertainty is developed. A set of trade-off optimal trajectories is obtained for different preferences between predictability, convective risk, and average efficiency; in particular, results are presented for the minimum expected flight time and the most predictable trajectory, including the trade-off between fuel consumption, time dispersion, and exposure to convection risk. It is shown how uncertainty can be quantified and reduced by proposing alternative trajectories.			
D4.2	Efficiency/predictability trade-off of 4D trajectories at tactical level	31/08/2017	Public
In this deliverable, results on trajectory prediction under thunderstorm activity are presented. Uncertainty associated to the evolution of thunderstorms is assumed to be the unique source of uncertainty. State-of-the-art short-term forecasts (Nowcasts) are used as input data for the uncertain evolution of thunderstorms. The main goal is to re-plan trajectories that are efficient, yet safe in avoiding the uncertainly evolving thunderstorms. Robust trajectories (computed at the pre-tactical phase) are used as reference trajectories. When any trajectory overflies a volume of airspace with storm activity, a set of possible deviation trajectories is computed that avoid the individual storms (modelled as stochastic no-fly zones) and reattach to the original reference route.			
D4.3	Catalogue of case studies for robust trajectory planning	13/12/2017	Public
This document includes the definition of the scenarios to further validate the algorithms developed at pre-tactical level. Three scenarios are defined: VS1, VS2, and VS3. The former is intended for the validation of the robust mid-term trajectory optimiser, only considering uncertainties due to wind; in the second, the aim is at the validation of the same trajectory optimiser, but now convective risk is also considered; the latter is aimed at validating the robust			

short-term trajectory predictor developed to consider the uncertain evolution of storms. Different validation indicators are defined for the scenarios.

D5.1	Methodology to assess the uncertainty of sector demand	23/03/2017	Public

In this deliverable, the methodology to assess the uncertainty of sector demand is presented. The methodology requires the definition of a scenario (in terms of Air Traffic Control sector, flights, and weather forecasts to be considered), the processing of meteorological data (provided by EPS and Nowcasts, which are composed of different possible atmosphere realizations), and a trajectory predictor (which, for each flight and for each atmosphere realization, computes a different aircraft trajectory). The computed trajectories, along with the information of the sector, are then used to analyse the sector demand, which is described in terms of entry count (number of flights entering the sector during a selected time period) and of occupancy count (number of flights inside the sector during a selected time period). The analysis is based on the statistical characterization of the entry and exit times of the flights to/from the sector, and of the entry and occupancy counts. The probability of the counts exceeding the declared capacity of the sector is obtained. A realistic application example is included in this deliverable, which clearly shows the suitability of the methodology for the purpose of TBO-Met.

D5.2	Effects of weather uncertainty on sector demand	20/12/2017	Public

In this deliverable, sector demand analyses are performed at pre-tactical level (mid-term planning) and tactical level (short-term planning and execution) with the objective of quantifying the effects of weather uncertainty. The analyses are based on the methodology developed in Deliverable 5.1 [12] for mid-term planning analysis, which is also suitable for the short-term and execution analysis after slight adaptations addressed in this deliverable. The sector demand analysis consists in the statistical characterization of the entry and exit times of the flights to/from the sector, and of the entry and occupancy counts. Results are presented for realistic applications. On one hand, the sector demand is analysed at pre-tactical level when subject to wind uncertainty. It is shown that, when the dispersion of the individual trajectories is reduced, the dispersions of the entry and occupancy counts are also reduced. On the other hand, the effects of storm uncertainty on sector demand are quantified by the sector demand analysis at tactical level. Furthermore, it is shown that, when the convection risk of the individual trajectories is reduced in the mid-term planning phase, the dispersions of the entry and exit times and of the occupancy counts are also reduced at the short-term planning and execution phase.

D5.3	Catalogue of case studies for sector demand analysis	20/03/2018	Public

In the present deliverable, the scenarios to validate the methodology and the analyses developed to study sector demand are presented. Two scenarios are defined: VS4 and VS5. VS4 is intended to validate the prediction of the sector demand at pre-tactical level and the benefits of increasing the predictability of the individual trajectories when only wind uncertainties are considered. VS5 is intended to validate the prediction of sector demand at tactical level and the benefits of reducing the convection risk of the individual trajectories when thunderstorm uncertainties are considered. In both scenarios, VS4 and VS5, the validation is based on the comparison between the predicted sector demand and the simulated sector demand under realised weather. The two scenarios are described including traffic information, meteorological products, trajectory predictors, and the simulation infrastructure. The validation criteria are also given, which are based on the computation of different Key Validation Indicators.

D6.1	Report on evaluation and assessment of proposed solutions	13/07/2018	Public

This deliverable presents the results of the simulations carried out to evaluate and assess the benefits of the concepts and solutions proposed in the TBO-Met project. The simulation activities are divided into five validation scenarios: VS1, VS2, VS3, VS4, and VS5. The first two, defined in Deliverable 4.3 [11], are devoted to validate the algorithms developed for trajectory planning at pre-tactical level (mid-term planning); the simulation results show that the values of the key validation indicators follow the appropriate trends. VS3, also defined in Deliverable 4.3 [11], aims

at validating the short-term trajectory prediction under the presence of uncertain convective cells. The simulation results show a good agreement between the predictions and the reality. Finally, VS4 and VS5, defined in Deliverable 5.3 [14], are intended to validate the methodology developed to study sector demand; the simulation results show that, in general, the key validation indicators are above the thresholds defined and follow the appropriate trends.

Table 13: Project Deliverables

3 Links to SESAR Programme

3.1 Contribution to the ATM Master Plan

Project contributions to the achievement of the SESAR programme.

Regarding the three problems addressed in TBO-Met, no Operational Improvement (OI) Steps have been identified. For this reason, in this project it is proposed the definition of three new OI Steps, as follows:

For the problem of trajectory planning: **Use of probabilistic forecasts to generate more predictable trajectories at mid-term planning level (AUO-XX01)**. The aim of this OI is to benefit from the existence of probabilistic forecasts in the mid-term planning horizon. These forecasts may refer to departure time and weather forecasts, among others.

For the problem of storm avoidance: **Use of probabilistic weather information to enhance trajectory prediction under thunderstorm activity (AUO-XX02)**. The aim of this OI is to benefit from the use of probabilistic weather information to compute a better short-term forecast for the trajectories when crossing an area with thunderstorm activity. That is, the aim is to enhance the decision making process of the ATM actors by enriching the information available in advance.

Finally, for the sector demand problem: **Use of probabilistic weather forecasts to enhance sector demand prediction (DCB-XX01)**. The aim of this OI is to benefit from the existence of probabilistic weather forecasts in order to provide enhanced sector demand predictions, ranging from the mid-term planning to the execution phases. The enhanced sector demand prediction shall include a quantitative measure of its uncertainty.

An overall view of the project maturity is given in Table 2. In this table, from the TBO-Met perspective, the stated maturity at project end is TRL 1.

Code (OI/EN code)	Name	Project contribution Summarize in one paragraph (~100 words)	Maturity at project start V-level / TRL	Maturity at project end V-level / TRL
AUO-XX01	Use of probabilistic forecasts to generate more predictable trajectories at mid-term planning level	The development of a stochastic optimisation methodology for trajectory planning which makes use of probabilistic weather forecasts. In particular, two problems have been analysed: On one hand, the trade-off between predictability (measured by the flight-time dispersion) and cost-efficiency (flight time or fuel consumption) considering only uncertain winds, and, on the other, the trade-off between	TRL 0	TRL 1

		exposure to convection risk and cost-efficiency considering now uncertain winds and convection risk. Specific tools for the provision and processing of probabilistic meteorological data have been also developed, such as a tool that provides the probability of convection from the information contained in the EPS.		
AUO-XX02	Use of probabilistic weather information to enhance trajectory prediction under thunderstorm activity	The development of a probabilistic trajectory predictor with storm avoidance, taking into account the uncertainty in the location of the convective cells, which are obtained from Nowcasts and modelled as stochastic no-fly zones. The output is an ensemble of deviation trajectories that avoid the possible storm realisations and reattach to the optimal reference route. An already existing deterministic tool for generating the deviation trajectories (DIVMET) has been adapted to account for the uncertainty in the cell evolution. With respect to the input, a tool has been developed that models synthetically the uncertainty in the location of the cells (because the Nowcasts considered are deterministic).	TRL 0	TRL 1
DCB-XX01	Use of probabilistic weather forecasts to enhance sector demand prediction	This methodology analyses the uncertainty of sector demand in terms of the uncertainty of the individual flights, and requires the previous computation of different possible trajectories for each flight. Each possible trajectory corresponds to a possible weather realization provided by the probabilistic weather forecasts. The methodology is able to rely on already existing deterministic trajectory predictors and is suitable to be applied to all ATM phases, from long term planning to execution	TRL 0	TRL 1

		phases. The output is an ensemble of possible sector loadings, which are statistically characterised. The analysis performed quantifies the impact of enhanced trajectory planning under weather uncertainty on sector demand.		

Table 14: Project Maturity

Project impact on the ATM Master Plan

The project will contribute to SESAR's ambitions in the following aspects:

- Improvement of the overall ATM system efficiency, coming 1) from the increased trajectory predictability, which might reduce the buffer times the airlines factor into schedules in order to increase their robustness to tactical time variations (which unavoidably lead to strategic delay costs), and 2) from the better identification of the ATFCM measures to be implemented, which might improve the traffic throughput.
- Improvement in the areas of safety and operational-efficiency, because the involved stakeholders (airspace users and ANSPs) would be better informed and, therefore, better prepared, some minutes in advance, to face the effects of an evolving thunderstorm field.
- Increase in capacity, because if sector demand probabilistic predictions are available, ANSPs can reduce the capacity buffers they factor in order to protect themselves from over-deliveries (when the actual number of aircraft that enter a regulated sector during a particular period exceeds the declared capacity), and, therefore, declared sector capacities can be increased.

3.2 Maturity Assessment

In the TRL-Assessment Report (Deliverable 1.2 [2]) an assessment of the TRL of TBO-Met is presented, which is divided into three parts that correspond to the three research topics addressed in the project:

1. Trajectory planning considering meteorological uncertainties.
2. Storm avoidance considering meteorological uncertainties.
3. Sector demand analysis considering meteorological uncertainties.

The three individual assessments are developed following the criteria identified in the Maturity Assessment Tool [37], which are the following:

TRL-1.1: Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? Where does the problem lie?

TRL-1.2: Has the ATM problem/challenge/need(s) been quantified?

TRL-1.3: Are potential weaknesses and constraints identified related to the exploratory topic/solution under research? The problem/challenge/need under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others.

TRL-1.4: Has the concept/technology under research defined, described, analysed and reported?

TRL-1.5: Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM Master Plan Level?

TRL-1.6: Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities? What are these new capabilities? Can they be technically implemented?

TRL-1.7: Are physical laws and assumptions used in the innovative concept/technology defined?

TRL-1.8: Have the potential strengths and benefits identified? Have the potential limitations and disbenefits identified? Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be that quantitative information already exists, in which case it should be used if possible.

TRL-1.9: Have Initial scientific observations been reported in technical reports (or journals/conference papers)?

TRL-1.10: Have the research hypothesis been formulated and documented?

TRL-1.11: Is there further scientific research possible and necessary in the future?

TRL-1.12: Are stakeholder's interested about the technology (customer, funding source, etc.)?

All the questions posed have been answered and the level of satisfaction of the criteria has been evaluated. The three individual assessments are included in Appendix B (Table 18, Table 19, and Table 20); a summary is presented in the following table. From the TBO-Met perspective, it can be concluded that the three individual assessments are positive and, therefore, that the three research topics show maturity to go from TRL 0 to TRL 1.

TRL-criteria ID	Trajectory planning	Storm avoidance	Sector demand
1	Achieved	Achieved	Achieved
2	Achieved	Partial – Non blocking	Partial – Non blocking
3	Achieved	Achieved	Achieved
4	Achieved	Achieved	Achieved
5	Achieved	Partial – Non blocking	Achieved
6	Achieved	Achieved	Achieved
7	Achieved	Achieved	Achieved
8	Partial – Non blocking	Partial – Non blocking	Partial – Non blocking
9	Achieved	Partial – Non blocking	Achieved
10	Partial – Non blocking	Partial – Non blocking	Partial – Non blocking
11	Achieved	Achieved	Achieved
12	Achieved	Achieved	Achieved

Table 15: Summary of the Maturity Assessments

4 Conclusions, Lessons Learned and Next Steps

4.1 Conclusions

When weather forecast uncertainty is taken into account, the results have shown that

- the predictability of aircraft trajectories can be increased
- the storm avoidance strategy can be better anticipated
- the accuracy of sector demand forecast can be improved

hence, based on these results, the **overall conclusion** is that **the ATM efficiency can be enhanced** by integrating into the ATM planning process the available information about the uncertainty of weather forecasts.

In relation to the three topics addressed in TBO-Met, the specific **achievements** of the project can be summarised as follows:

1) for the mid-term trajectory planning problem, the achievement is the **capability of generating more predictable trajectories** considering the uncertainty of weather predictions; the output is a set of alternative routes, according to the different trade-offs;
2) for the storm avoidance problem, the achievement is the **capability of being better informed about the evolution of the hazardous convective weather regions**; the output now is an ensemble of possible deviation trajectories that avoid the potential storm realisations, leading to a more proactive way of facing thunderstorms.
3) finally, for the sector demand problem, the achievement is the **capability of improving the accuracy of the sector demand forecast**; the output is a quantitative measure of the uncertainty of sector demand, which can be updated according to the release of new forecasts and the movement of the aircraft.

And the **potential benefits** are the following:

- Reduction of the buffer times used by airlines
- Better-informed decision making
- Increase of declared sector capacities
- Better identification of demand-capacity balancing measures

Finally, the overall **outcome** has been the development of methodologies to quantify and better understand the impact of wind uncertainty and convective weather in trajectory planning and sector demand, both at mid-term and short-term levels. To validate these methodologies five simulation scenarios have been analysed; for each scenario, several key validation indicators have been computed, which compare the predicted and simulated results. The following concepts have been validated:

- penalizing flight time dispersion leads to more predictable trajectories (although at the cost of extra flight time and fuel consumption),
- penalizing the exposure to convective risk leads to more predictable trajectories (again, at the cost of extra flight time and fuel consumption),
- in the presence of uncertain convective cells, the avoidance trajectory can be accurately predicted at tactical level,
- the uncertainty of the avoidance trajectory decreases as the predictability of the planned trajectories increases,
- the sector demand can be accurately predicted at pre-tactical level when wind uncertainties are considered,
- the sector demand can be accurately predicted at tactical level when thunderstorm uncertainties are considered,
- the uncertainty of the tactical prediction of the sector demand decreases as the predictability of the planned trajectories increases.

In contrast, the following concept has not been fully validated:

- the uncertainty of the pre-tactical prediction of the sector demand decreases as the predictability of the planned trajectories increases.

In fact, the validation results have shown that penalizing the flight time dispersion of the individual trajectories (dispersion of the final arrival time) may not imply a reduction of the dispersion of the entry count (at intermediate crossing times). This suggests that, from a sector demand point of view, the dispersion of the individual trajectories may not be properly characterized just by the flight time dispersion, and that different ways of that characterization should be explored.

4.2 Key Communication and Dissemination Activities

All the achievements described in the previous section have been communicated and disseminated through a number of channels (as indicated in the Project Management Plan [1]). The key activities are summarised next.

Poster and Presentation at SESAR Innovation Days conference '16	8-10 Nov 2016, Delft
Poster and Presentation at SESAR Innovation Days conference '17	28-30 Nov 2017, Belgrade
Journal Paper in JGCD, Vol. 41, No. 3	March 2018
Presentation at Eurocontrol ART Workshop	25 Apr 2017, London
Presentations at Met&ATM Workshop	24-25 May 2017, Seville
Presentation at ATIO'17	5-9 June 2017, Denver
Presentation at EUCASS'17	3-6 July 2017, Milan

Presentations at Unc&ATM Workshop	25-26 Oct 2017, Madrid
Presentation at WMO Conference	6-10 Nov 2017, Toulouse
Presentation at ENRI Workshop	14-16 Nov 2017, Tokyo
Presentation at PNOWWA Workshop	27-28 Feb 2018, Vienna
Presentations at TBO-Met Workshop	3-4 May 2018, Salzburg
TBO-Met Workshop	3-4 May 2018, Salzburg
TBO-Met press release	SESAR e-news - May issue
TBO-Met website https://tbomet-h2020.com/	Beginning of the project
PLUS stand at World ATM Congress	7-9 Mar 2017, Madrid 6-8 Mar 2018, Madrid
Social media activities (TBO-Met website, ResearchGate and Twitter)	Along the project
Communication of 1st and 2nd workshops on Met & ATM	Along the project
Description of the project at undergraduate and graduate courses	Along the project
Participation in the science week in Madrid in November 2017	6-19 Nov 2017, Madrid

Among all these activities, the TBO-Met Workshop stands alone https://www.university-salzburg.workshop.atmwx.com/.

It was framed as the 2nd International Workshop on Meteorology and Air Traffic Management and took place in Salzburg, Austria, May 3rd - 4th, 2018. It was hosted by the Aerospace Research Group of the Department of Computer Sciences, University of Salzburg, Austria.

The aim of the workshop was to bring together engineers, academicians, scientists, professionals, and students, to discuss and share ideas about the recent results in the field of Air Traffic Management under uncertain meteorological conditions, and especially about the management of the uncertainty present in weather predictions.

More than 40 participants, from 20 European institutions, attended this Workshop, coming from seven different countries (Austria, Croatia, Finland, France, Germany, Spain, and Sweden).

The workshop programme was composed of 12 presentations (with 16 speakers), divided into three sessions:

- Session 1: Improving safety and efficiency of Air Traffic Management under meteorological uncertainties.
- Session 2: Overview and main outcomes of the SESAR 2020 TBO-Met project.

- Session 3: Projects and Alliances on Meteorology and Air Traffic Management at European level.

In addition, a panel discussion with its focus on "How to apply probabilistic approaches to a deterministic world" and a concluding session on "Planning for the future" presented an opportunity to review and summarize the Workshop ideas and discuss future steps.

4.3 Lessons Learned

In this project there have been three technical lessons learned:

1) Ensuring high **quality of the meteorological data** is important to maximize the benefits of the concepts proposed in TBO-Met. Therefore, on one hand, the meteorological data processing tools developed should be enhanced by including calibration of the EPS, which reduces the ensemble forecast bias and underdispersion, therefore making it more accurate. On the other hand, an improved probabilistic Nowcast should be considered, instead of a synthetic uncertainty model added to a deterministic Nowcast, to increase the accuracy of the probabilistic trajectory predictor with storm avoidance.

2) One of the goals of TBO-Met is to show that one can decrease the uncertainty of the pre-tactical prediction of the sector demand by increasing the predictability of the planned aircraft trajectories. To analyze this uncertainty propagation, given the duration of the project, only one metric has been considered to characterize the dispersion of the planned trajectories, namely the dispersion of the arrival time to destination. Because the choice of this metric strongly affects this analysis, exploring **different metrics** is advised.

3) In the TBO-Met project, the sector demand analysis is restricted to one sector. This consideration has greatly simplified the problem and has reasonably adjusted the project scope to the project duration. However, it has also required introducing artificial assumptions such as the extended area around the sector, because when the aircraft modify their routes adjacent sectors may be also affected. Therefore, in order to remove these assumptions, an extended methodology for **multi-sector analysis** is required.

From the management point of view there has been an important lesson learned as well:

4) At the end of the project, the last technical deliverable (D6.1 – Report on evaluation and assessment of proposed solutions) has had a very large delay. Two main reasons have contributed to this delay: the large number of validation tasks defined and some technical difficulties encountered in the utilization of the external tools used for the validation (NAVSIM and DIVMET). Unfortunately, these validation tasks (WP 6 of the project) had only one deliverable, fact that has made impossible to perform a continuous assessment of the progress of the validation work. Hence, the lesson learned is that an important task, and specially a whole work package, must have several deliverables so that its progress can be properly monitored and assessed.

4.4 Recommendations for future R&D activities

To bring current research to higher technological levels, the following research is considered to be needed in the future:

For the **trajectory planning** problem:

- The inclusion of **other sources of uncertainty** different from the meteorological one, e.g., on aircraft dynamics.
- The **use of calibrated EPS** obtained through statistical post-processing techniques, for instance Ensemble Model Output Statistics.
- The enrichment of aircraft performance modelling, e.g., considering **BADA 4**, which accounts for compressibility effects.
- The consideration of **structured airspaces**.
- The consideration of **three-dimensional flights**, including thus variable barometric altitude. This would allow the computation of complete flights.
- The consideration of **meteorological forecasts that evolve over time**, e.g., to consider a series of snapshots of the forecasted status of the atmosphere for the whole duration of the flight.

For the **storm avoidance** problem:

- The inclusion of **other sources of uncertainty** different from the location of the convective cells.
- The improvement of thunderstorm uncertainty modelling, e.g., extracting probabilistic fields by using **probabilistic Nowcasts**.
- In case of the availability of Nowcasts providing 3D storm cells, the consideration of **vertical avoidance manoeuvres**.
- The consideration of **operational environment constraints**, such as preventing the deviation trajectories from entering into restricted or reserved airspaces or the fulfilment of time constraints at specific fixes.

For the **sector demand** problem:

- **Extension to the TMA,** considering climbing/descending trajectories which may enter/exit the sector not only by the lateral boundaries but also by the upper and lower limits.
- **Multi-sector analysis,** that is, the extension of the methodology developed in TBO-Met considering several sectors at once.
- **Variable sector configuration,** to take into account that the ATC sectors can be opened and/or merged.

4.5 Roadmap for Next Steps

Three possible technical solutions have been identified. They are described next.

4.5.1 Solution #1

Solution name

Enhanced Flight-Planning Predictability

Target users

Airlines/Flight dispatchers

Rationale

A major challenge for Trajectory-Based Operations is the existence of significant uncertainties in the models and systems required for trajectory prediction. Thus, the lack of predictability in Business Development Trajectories is claimed as rationale behind this solution. This is in turn depredating several Key Performance Indicators in key performance areas such as safety, capacity, efficiency, and cost effectiveness. There is a need to plan trajectories that are efficient, yet predictable at mid-term planning level.

The ambition is to develop a concept capable of working together with existing/future flight dispatching tools, enhancing its capabilities in terms of predictability. It should be incorporated into airlines' daily business activities and produce trajectories compatible with existing/future flight management systems.

Expected benefits / added value

Direct added value includes:

- Reduction of the expected flight time uncertainty.
- Reduction of the expected fuel burnt uncertainty.
- Reduction of fuel reserves.
- Reduction of airline's buffer times allocated to increase its robustness.

Indirect added value includes:

- Increase of capacity
- Reduction of holdings/ATC advisories
- Reductions of ATFCM tactical regulations
- Reduction of traffic complexity

Future exploitation steps

After the completion of TBO-Met project, the concept is in TRL-1. To reach further maturity, the following steps are proposed:

Step	Activities
Step 1 (2 years)	Oriented to enhance algorithmic capabilities and to reach V1 phase (TRL-2): - Inclusion of other sources of uncertainty, both meteorological (e.g., clean air turbulence; icing, windshear) and others different from the meteorological one (e.g., aircraft dynamics). - Enrichment of aircraft performance modelling. - Extension to complete flights, from take-off to landing - Involvement of target users (airlines) to better identify the required capabilities, potential contexts of use, and the related operational concepts and their possible implications.
Step 2 (4 years)	Oriented to reach V2 phase (TRL-4): - To build a pre-industrial prototype to perform realistic simulations. - To analyse operational feasibility, human factors, and safety.
Step 3 (2 years)	Oriented to reach V3 phase (TRL-6): - To integrate the pre-industrial prototype into airline systems to perform shadow mode or live trials.

4.5.2 Solution #2

Solution Name

Probabilistic Storm Avoidance Human Decision Support Tool

Target users

Airlines/Pilots and ANSPs/ATCOs

Rationale

A challenging aspect of aircraft trajectory planning at short-term level is the avoidance of hazardous convective weather regions, more commonly referred to as storms or thunderstorms. Existing systems today are typically limited to on-board weather radar. Moreover, existing meteorological products (that include storm information) are essentially deterministic. There is overall lack of integration of information in both airborne and ground systems (and in the case there is information, this is deterministic, thus it does not capture reality).

The ambition is to develop a concept capable of working together with existing/future airborne/ground systems for the anticipated detection of storms, probabilistic prediction of storms' evolution, on-board/ground display presentation, and the suggestions of alternative trajectories to the user (pilot/controller). Thus, it should be incorporated into airlines' daily business activities and produce trajectories compatible with existing/future flight management systems and pilots/ATCOs duties.

Expected benefits / added value

Direct added value includes:

- Increase of safety due to reduction of meteorological hazard's encounter.
- Increase of situational awareness for both pilots and ATCOs.
- Better-informed decision-making.
- Anticipated decision-making
- Reduction of traffic complexity.

Future exploitation steps

After the completion of TBO-Met project, the concept is in TRL-1. To reach further maturity, the following steps are proposed:

Step	Activities
Step 1 (3 years)	Oriented to enhance algorithmic capabilities and to reach V1 phase (TRL-2): - Enhanced probabilistic storm modelling. - Use of probabilistic Nowcasts. - Extension to 3D storm cells. - Inclusion of ATM related constraints. - Involvement of target users (airlines and ANSPs) to better identify the required capabilities, potential contexts of use, and the related operational concepts and their possible implications.
Step 2 (4 years)	Oriented to reach V2 phase (TRL-4): - To build a pre-industrial prototype to perform realistic simulations. - To analyse operational feasibility, human factors, and safety.
Step 3 (2 years)	Oriented to reach V3 phase (TRL-6): - To integrate the pre-industrial prototype into airborne/ground systems to perform shadow mode or live trials.

4.5.3 Solution #3

Solution name

Probabilistic Sector Demand considering Meteorological Uncertainty

Target user

Network Manager and Air Navigation Services Providers

Rationale

Since the atmosphere is intrinsically non-deterministic, it is inherently impossible to perfectly know its present or future state. Forefront meteorological forecasting products, formed by an ensemble of forecasts, allow us to estimate the uncertainty in weather forecasts. Each member of the ensemble represents a different possible weather realization; the uncertainty information is on the spread of the members in the ensemble. Examples of these products are EPS, which provide ensemble forecasts for weather variables such as wind and air temperature with time horizons from several hours to several days, and probabilistic Nowcasts, which extrapolate the movement and the temporal development of the cells, described by the position, size and number of storm cells, for the next hour.

From each ensemble member a different arrival time to an airspace can be predicted for a single flight, thus leading to an ensemble of possible arrival times. The arrival times obtained for all the flights arriving to an ATC sector lead to an ensemble of entry or occupancy counts.

The proposed solution provides a probabilistic prediction of the sector demand due to uncertainty on the meteorological prediction, from several days to minutes before operation.

Expected benefits / added value

The direct benefit of this solution is the improvement of the accuracy and credibility of the diagnosis and awareness of hotspots, serving as a support for better-informed decision making. It may happen that a deterministic prediction of the sector demand claims that the capacity of a sector is not exceeded, but with a probabilistic approach it is exceeded for some ensemble members. Large dispersions in the sector demand prediction may constitute a signal of high-impact weather phenomena. Therefore, with this solution, the risk of exceeding the capacity of a sector can be better assessed.

Indirect benefits of this solution are 1) a better identification of Demand-Capacity Balancing (DCB) measures, 2) an increased situational awareness of Air Traffic Controllers (ATCOs), and 3) a reduction of capacity buffers. Regarding the first, different DCB measures can be adopted depending on the probabilistic capacity shortfall provided by the prediction. In some cases, a least regret decision may be preferable. Regarding the second, ATCOs may become aware of the future evolution of the storms and its impact on its sector. Finally, if the confidence in the sector demand predictions is increased, the safety buffers allocated by the ANSPs may be reduced thus increasing the declared capacity of the ATC sectors.

Future exploitation steps

After the completion of TBO-Met project, the concept is in TRL-1. To reach further maturity, the following steps are proposed:

Step	Activities
Step 1 (3 years)	Oriented to enhance algorithmic capabilities and to reach V1 phase (TRL-2): • Extension to the TMA, considering climbing/descending trajectories which may enter/exit the sector not only by the lateral boundaries but also by the upper and lower limits. • To perform big-scale analyses to better quantify the potential benefits: at network level (several sectors) and for multiple weather scenarios (several days). • To consider a variable sector configuration, to take into account that the ATC sectors can be opened and/or merged. • To involve relevant stakeholders, e.g. the Network Manager and the ANSPs, to better identify the required capabilities, potential contexts of use, and the related operational concepts and their possible implications. • Other possible expansions of the work in this step: 1) to measure the exposure of the ATC sector to en-route weather hazards, such as convective weather, turbulence, or icing; 2) the inclusion of other uncertainty sources.
Step 2 (3 years)	Oriented to reach V2 phase (TRL-4): - To involve other relevant stakeholders, such as ECMWF (who produces EMCWF-EPS), National Meteorological Agencies (who produce Nowcasts), and systems developers. - To build a pre-industrial prototype integrating the Network Manager trajectory predictor (or other predictors, such as DIVMET) and weather forecasts from ECMWF and National Meteorological Agencies to perform real-time simulations. - To analyse operational feasibility, human factors, and safety. For example, to analyse how the information is presented to ATCOs so they make the best use of the information. The possibility of establishing alarm thresholds should be analysed.
Step 3 (2 years)	Oriented to reach V3 phase (TRL-6): - To integrate the pre-industrial prototype into the Network Manager's systems, area control centre systems, or in an approach control unit systems to perform shadow mode or live trials.

5 References

5.1 Project Deliverables

[1] "TBO-Met Deliverable 1.1, Project Management Plan," Edition 00.01.02, November 2016. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d1-1.pdf

[2] "TBO-Met Deliverable 1.2, TRL-Assessment Report," Edition 00.01.00, April 2018. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d1-2.pdf

[3] "TBO-Met Deliverable 2.1, Requirements and concept for EPS processing," Edition 00.01.01, September 2016. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d2-1.pdf

[4] "TBO-Met Deliverable 2.2, Software documentation for EPS processing," Edition 00.01.00, November 2016. Confidential.

[5] "TBO-Met Deliverable 2.3, Requirements and concept for Nowcast processing," Edition 00.01.00, April 2017. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d2-3.pdf

[6] "TBO-Met Deliverable 2.4, Software documentation for Nowcast processing," Edition 00.01.00, May 2017. Confidential.

[7] "TBO-Met Deliverable 3.1, Survey questionnaire," Edition 00.01.01, October 2016. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d3-1.pdf

[8] "TBO-Met Deliverable 3.2, Stakeholders' survey report," Edition 00.01.02, February 2017. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d3-2.pdf

[9] "TBO-Met Deliverable 4.1, Efficiency/predictability trade-off of 4D trajectories at pretactical level," Edition 00.01.00, February 2017. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d4-1.pdf

[10] "TBO-Met Deliverable 4.2, Efficiency/predictability trade-off of 4D trajectories at tactical level," Edition 00.01.00, August 2017. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d4-2.pdf

[11] "TBO-Met Deliverable 4.3, Catalogue of case studies for robust trajectory planning," Edition 00.01.00, Deceber 2017. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d4-3.pdf

[12] "TBO-Met Deliverable 5.1, Methodology to assess the uncertainty of sector demand," Edition 00.01.01, March 2017. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d5-1.pdf

[13] "TBO-Met Deliverable 5.2, Effects of weather uncertainty on sector demand," Edition 00.01.00, December 2017. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d5-2.pdf

[14]"TBO-Met Deliverable 5.3, Catalogue of case studies for sector demand analysis," Edition 00.01.00, March 2018. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d5-3.pdf

[15]"TBO-Met Deliverable 6.1, Report on evaluation and assessment of proposed solutions," Edition 00.01.00, July 2018. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d6-1.pdf

[16]"TBO-Met Deliverable 7.1, Dissemination plan," Edition 00.01.00, November 2016. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d7-1.pdf

[17]"TBO-Met Deliverable 7.2, Exploitation plan," Edition 00.01.00, November 2016. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d7-2.pdf

[18]"TBO-Met Deliverable 7.3, Communication plan," included in Deliverable 1.1.

[19]"TBO-Met Deliverable 7.4, Data management plan," Edition 00.02.00, March 2018. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d7-4.pdf

[20]"TBO-Met Deliverable 7.5, Proceedings of TBO-Met workshop," Edition 00.01.01, May 2018. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d7-5.pdf

[21]"TBO-Met Deliverable 7.6, TBO-Met press release," Edition 00.01.01, May 2018. Available at https://tbometsesar2020.files.wordpress.com/2018/08/tbo-met_d7-6.pdf

[22]"TBO-Met Deliverable 8.1, H - Requirement No. 3," Edition 00.02.00, September 2016. Confidential.

[23]"TBO-Met Deliverable 8.2, POPD - Requirement No. 2," Edition 00.02.00, September 2016. Confidential.

[24]"TBO-Met Deliverable 8.3, POPD - Requirement No. 1," Edition 00.02.00, September 2016. Confidential.

5.2 Project Publications

[25]D. González-Arribas, M. Soler and M. Sanjurjo, "Wind-Based Robust Aircraft Route Optimization using Meteorological Ensemble Prediction Systems," *6th SESAR Innovation Days*, Delft, The Netherlands, 2016. Available at https://www.sesarju.eu/sites/default/files/documents/sid/2016/SIDs_2016_paper_58.pdf

[26]D. González-Arribas, M. Soler, M. Sanjurjo-Rivo, J. García-Heras, D. Sacher, U. Gelhardt, J. Lang, T. Hauf and J. Simarro, "Robust Optimal Trajectory Planning under Uncertain Winds and Convective Risk," *ENRI Int. Workshop on ATM/CNS*, Tokyo, Japan, 2017. Available at https://e-archivo.uc3m.es/handle/10016/26962

[27]D. González-Arribas, M. Soler, and M. Sanjurjo, "Robust Aircraft Trajectory Planning under Wind Uncertainty using Optimal Control," *Journal of Guidance, Control, and Dynamics*, Vol. 41, No. 3, pp. 673-688, 2018. Available at http://hdl.handle.net/10016/26873

[28]A. Valenzuela, A. Franco, D. Rivas, "Sector Demand Analysis under Meteorological Uncertainty," *7th European Conference for Aeronautics and Space Sciences*, Milan, Italy, 2017. Available at https://www.eucass.eu/doi/EUCASS2017-263.pdf

[29]A. Valenzuela, A. Franco, D. Rivas, J. García Heras, M. Soler, "Effects of Reducing Wind-Induced Trajectory Uncertainty on Sector Demand," *7th SESAR Innovation Days*, Belgrade, Serbia, 2017. Available at https://www.sesarju.eu/sites/default/files/documents/sid/2017/SIDs_2017_paper_22.pdf

[30]A. Valenzuela, A. Franco, D. Rivas, D. Sacher, J. García Heras, M. Soler, "Effects of Weather Uncertainty in Sector Demand at Tactical Level," *International Symposium on Sustainable Aviation 2018,* Rome, Italy, 2018.

[31]TBO-Met website: *https://tbomet-h2020.com*.

5.3 Other

[32]«SESAR 2020 Exploratory Research: First Call for Research Projects. V 1.2» June 2015.

[33]Grant Agreement number: 699294 — TBO-MET — H2020-SESAR-2015-1.

[34]T. Hauf, L. Sakiew, M. Sauer, 2013 "Adverse weather diversion model DIVMET," *Journal of Aerospace Operations,* Vol. 2, No. 3-4, pp. 115-133, 2013.

[35]Project Execution Guidelines for SESAR 2020 Exploratory Research, Edition 01.00.00, 08/02/2016

[36]European ATM Portal. ATM Master Plan dataset 16. ESSIP Edition: MP L3 Plan 2016.

[37]Maturity Assessment Tool. SESAR 2020. V0.2.4.

[38]D. Rivas and R. Vazquez, "Uncertainty," in Complexity Science in Air Traffic Management, Ashgate Publishing Limited, 2016.

[39]J. Cheung, J.-L. Brenguier, J. Heijstek, A. Marsman and H. Wells, "Sensitivity of Flight Durations to Uncertainties in Numerical Weather Prediction," *4th SESAR Innovation Days*, Madrid, Spain, 2014.

[40]"The roadmap for delivering high performing aviation for Europe. European ATM Master Plan," European Union and Eurocontrol, 2015.

[41]S. Baran and S. Lerch, "Log-normal distribution based Ensemble Model Output Statistics models for probabilistic wind-speed forecasting," *Quarterly Journal of the Royal Meteorological Society*, Vol. 141, No. 691, pp. 2289-2299, 2015.

[42]"NextGen Weather - Weather Delays," [Online]. Available: https://www.faa.gov/nextgen/programs/weather/faq.

[43]C. Wanke, M. Callaham, D. Greenbaum and A. Masalonis, "Measuring Uncertainty in Airspace Demand Predictions for Traffic Flow," *AIAA Guidance, Navigation, and Control Conference*, Austin, TX, 2003.

Appendix A

A.1 Glossary of terms

Term	Definition	Source of the definition
Convection risk	Integral along the route of the probability of convection.	TBO-Met context
Deviation trajectory	Revised trajectory devised to avoid storm cells.	TBO-Met context
DIVMET	Storm-avoidance tool used in TBO-Met	Ref. [32]
Entry count	Number of flights entering the sector during a selected time period.	Adapted from the Hourly Entry Count definition given in Eurocontrol Experimental Centre Note No 15/07
Ensemble Prediction System	Numerical weather prediction system that allows the estimation of the uncertainty in a weather forecast as well as the most likely outcome	World Meteorological Organization No. 1091
Nowcast	Weather analysis and forecast for the next few hours.	World Meteorological Organization No. 1198
Occupancy count	Number of flights inside the sector during a selected time period.	Eurocontrol Experimental Centre Note No 15/07
Predictability	Dispersion of a predicted magnitude	TBO-Met context
Pre-tactical level	Temporal framework from some months up to three hours before departure	TBO-Met context
Tactical	Temporal framework from a few hours before operation to the moment of operation	TBO-Met context

Table 16: Glossary

A.2 Acronyms and Terminology

Term	Definition
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATFCM	Air Traffic Flow and Capacity Management
ATM	Air Traffic Management
BADA	Base of Aircraft Data
BDT	Business Development Trajectory
cp	Convection penalty
DCB	Demand and Capacity Balancing
dp	Dispersion penalty
ECMWF	European Centre for Medium-Range Weather Forecasts
EPS	Ensemble Prediction System
GLAMEPS	Grand Limited Area Model-EPS
MAT	Maturity Assessment Tool
Met	Meteorology
N	Number of members of the EPS
NEST	Network Strategic Tool
OI	Operational Improvement
p_c	Probability of convection
RBT	Reference Business Trajectory
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking
TBO	Trajectory Based Operations
t_f	Flight time
TMA	Terminal Manoeuvring Area

TRL	Technology Readiness Level
VS	Validation Scenario
WP	Work Package

Table 17: Acronyms and terminology

Appendix B Maturity Assessments

In this Appendix, the individual maturity assessments made for the three research topics addressed in the project are included, which are related to the three new OIs proposed in TBO-Met (described in Section 3.1). Thus, the assessment for trajectory planning, related to AUO-XX01 (Use of probabilistic forecasts to generate more predictable trajectories at mid-term planning level), is in Table 18; the assessment for storm avoidance, related to AUO-XX02 (Use of probabilistic weather information to enhance trajectory prediction under thunderstorm activity), in Table 19; and Table 20 contains the assessment for sector demand, related to DCB-XX01 (Use of probabilistic weather forecasts to enhance sector demand prediction).

Table 18: Exploratory Research Fund / Maturity Assessment for Trajectory planning

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? Where does the problem lie?	Achieved	A major challenge for Trajectory-Based Operations is the existence of significant uncertainties in the models and systems required for trajectory prediction. In particular, weather uncertainty has been acknowledged as one of the most relevant ones [38]. One of the **ATM problems** addressed in TBO-Met at the trajectory scale is the generation of more predictable trajectories considering the uncertainty of weather predictions. The **exploratory concept** developed in TBO-Met for this problem is a stochastic optimization methodology capable of trading-off cost-efficiency and predictability and/or exposure to convective risk.
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Achieved	In the past, some initial efforts have been made to quantify the effects of meteorological uncertainties on the flight duration. For example, in the IMET project (part of Work Package E of the SESAR Programme), the duration of a flight with fixed Mach number and flight level was calculated for each ensemble member

			of an EPS [39]. As a reference, a standard deviation of 4.4 minutes was obtained for a 400-minute flight when forecasted 30 hours in advance. The optimization algorithm developed in TBO-Met shows that it is possible to reduce the effects of the meteorological uncertainties. In particular, it quantifies and is able to reduce the time dispersion and the convective risk, see Deliverable 4.1 [9]. This reduction comes from an increase in the flight time and in the fuel consumption. As an example, for an Airbus 330 and for a particular flight forecasted 6 hours in advance, the algorithm shows that it is possible to reduce the dispersion in the arrival time by approximately 1.25 minutes at the toll of 500 kg of extra fuel burnt.
TRL-1.3	Are potential weaknesses and constraints identified related to the exploratory topic/solution under research? - The problem/challenge/ need under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others.	Achieved	The main constraint that apply to the topic under research is that the problem is **restricted to the mid-term planning level**, i.e., in this context from a few days to several hours before departure. It affects to all airspace users at any geographical location. No potential weaknesses affecting the ATM problem under research have been identified.
TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Achieved	The concept has been defined and thoroughly described, including mathematical details and preliminary results, in Deliverable 4.1 [9]. The concept can be summarized as follows: development of an optimal control methodology to solve trajectory-planning problems considering meteorological uncertainty. Different trade-offs between predictability, convective risk, and cost

			efficiency can be made. State-of-the-art forecasts from EPS are used as input data for the wind field and convective risk. With this methodology the uncertainty can be quantified and reduced by proposing alternative routes.
TRL-1.5	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM Master Plan Level?	Achieved	The results show two contributions to SESAR goals: • **Improvement of the overall ATM system efficiency.** As stated in SESAR's ATM Master Plan [40] (Section 3.3.4, which deals with predictability), SESAR performance ambition aims to reduce the size of the arrival-time window from approximately 5 minutes to 2 minutes. This will have a beneficial effect on the reduction of the buffer times the airlines factor into schedules in order to increase their robustness to tactical time variations leading to strategic delay costs. Most of this reduction is expected to come from taxi-time and arrivals in Terminal Manoeuvring Areas. The proposed methodology shows that some reduction is also achievable for the en-route phase at the mid-term planning level. • **Increase in capacity**. As shown in Deliverable 5.2 [13], reducing the time dispersion or the convective risk of the individual trajectories also reduces the dispersion of the sector demand. Thus, if the sector demand is more predictable, smaller safety buffers can be considered when establishing declared sector capacities; therefore, declared sector capacities can be increased.
TRL-1.6	Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities? - What are these new capabilities?	Achieved	In the trajectory-scale at the mid-term planning, the new capability developed in TBO-Met is the **reduction of the unpredictability of the trajectory and its exposure to convective areas**. This reduction is done by quantifying the uncertainty and the exposure, and including them in the process of flight planning. The technical implementation is possible, as it has been shown in the project. It would require the modification of the flight planning tools used by the users to,

	- Can they be technically implemented?		first, include the uncertainty costs in the objective function, and second, to adapt the optimization strategies to the consideration of probabilistic weather forecasts.
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Achieved	The exploratory concept is based on the physical assumption that the probabilistic weather forecast provides a representative sample of the possible future states of the atmosphere (see Deliverable 4.1 [9]). Other assumptions are: • The availability of a probabilistic forecast composed of a given number of equally-probable members. • The unique source of uncertainty is the meteorological uncertainty.
TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and disbenefits identified? - Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be that quantitative information already exists, in which case it should be used if possible.	Partial – Non Blocking	**Two strengths** of the exploratory concept have been identified: first, the **quantification of the trajectory uncertainty** due to weather and, second, **the tailoring of the uncertainty reduction for each flight according to the user's preferences**. The amount of uncertainty reduction can be chosen by the airspace user by selecting the appropriate relative weight of the uncertainties in the operation costs, similarly to what is done today with the cost index and the time costs. The following **benefits** have been identified: • Reduction of the expected flight time and expected fuel consumption uncertainties. • Reduction of fuel reserves. • Reduction of airline's buffer times allocated to increase its robustness.

			• Increase of declared sector capacities. However, the following **disbenefit** arises: • Increase of expected flight time and expected fuel burnt. At this stage of development, the proposed methodology has three **identified limitations**: • Raw meteorological input data has been used. However, biases and dispersion errors often occur in forecast ensembles: they are usually underdispersive and, as a consequence, uncalibrated [41]. Therefore, statistical post-processing, that is, calibration, can be beneficial. • The methodology is only suitable for free flight concept. Its adaptation to a structured airspace, e.g. the one conceived in the free route concept with entry and exit points between airspaces, would require an adaptation of the formulation of the optimization problem. • Meteorological forecasts are not considered to evolve over time, i.e., a fixed snapshot of the forecasted status of the atmosphere is considered for the whole duration of the flight.
TRL-1.9	Have Initial scientific observations been reported in technical reports (or journals/conference papers)?	Achieved	Besides Deliverable 4.1 [9], the following conference/journal papers with methodological approaches, modelling, and initial results have been published ([25], [26] and [27]): D. González-Arribas, M. Soler, and M. Sanjurjo, “Wind-Based Robust Aircraft Route Optimization using Meteorological Ensemble Prediction Systems,” *6th SESAR Innovation Days*, Delft, The Netherlands, 2016.

			D. González-Arribas, M. Soler, M. Sanjurjo-Rivo, J. García-Heras, D. Sacher, U. Gelhardt, J. Lang, T. Hauf, and J. Simarro, "Robust Optimal Trajectory Planning under Uncertain Winds and Convective Risk," *ENRI International Workshop on ATM/CNS*, Tokyo, Japan, 2017. D. González-Arribas, M. Soler, and M. Sanjurjo, "Robust Aircraft Trajectory Planning under Wind Uncertainty using Optimal Control," *Journal of Guidance, Control, and Dynamics*, Vol. 41, No. 3, pp. 673-688, 2018. These papers can be found in the project website [31].
TRL-1.10	Have the research hypothesis been formulated and documented?	Partial – Non Blocking	The hypotheses were reported in Deliverable 4.1 [9], they read as follows: • Aircraft performance is based on BADA 3 models. • Constant barometric altitude is considered for the flight. • Constant Mach speed is considered for the flight. • No routing constraints are imposed (free flight concept). • Meteorological forecasts are not considered to evolve over time.
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	To bring current research to higher technological levels, the following research is considered to be needed in the future: • The inclusion of other sources of uncertainty different from the meteorological one, e.g., on aircraft dynamics. • The use of calibrated Ensemble Prediction Systems obtained through statistical post-processing techniques, for instance Ensemble Model Output Statistics.

			• The enrichment of aircraft performance modelling, e.g., considering BADA 4, which accounts for compressibility effects. • The consideration of structured airspaces. • The consideration of three-dimensional flights, including thus variable barometric altitude. This would allow the computation of complete flights. • The consideration of meteorological forecasts that evolve over time, e.g., to consider a series of snapshots of the forecasted status of the atmosphere for the whole duration of the flight.
TRL-1.12	Are stakeholder's interested about the technology (customer, funding source, etc.)?	Achieved	Throughout the course of TBO-Met Project, partners have attended several conferences (e.g., SESAR Innovation Days), workshops (e.g., Electronic Navigation Research Institute Workshop), congresses (e.g., World ATM Congress), among others. The following stakeholders have shown interest about the algorithms/tools developed in TBO-Met: • Pilots • Air Traffic Controllers • Airlines • Met Offices • Air Navigation Services Providers • Airborne System Designers • Ground System Designers

			These expressions of interest have been somehow informal and we ambition to channel them upwards towards higher maturity levels.

Table 19: Exploratory Research Fund / Maturity Assessment for Storm Avoidance

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? Where does the problem lie?	Achieved	A challenging aspect of aircraft trajectory prediction at short-term level is the avoidance of hazardous convective weather regions, more commonly referred to as storms or thunderstorms. Thus, one of the **ATM problems** addressed in TBO-Met at the trajectory scale is the short-term trajectory prediction under thunderstorm activity. The **exploratory concept** developed in TBO-Met for this problem is a probabilistic trajectory predictor with storm avoidance, taking into account the uncertainty in the location of the convective cells (modelled as stochastic no-fly zones).
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Partial – Non Blocking	The inherently uncertain nature of thunderstorms causes major safety risks. In addition to increased safety risks, thunderstorms are also a leading cause of reduced time and cost efficiencies. From 2008 to 2013, inclement weather caused 69% of system-impacting delays (delays greater than 15 minutes), as recorded in the OPSNET Standard "Delay by Cause" Reports [42]. Within those weather delays, thunderstorms emerging from atmospheric instabilities were responsible for around 25%, turning them into the leading cause of flight delays in the US airspace. The methodology developed in TBO-Met allows to quantify the effects of the thunderstorm uncertainty, see Deliverable 4.2 [10]. As an example, short-term trajectory prediction has been used to forecast, for a particular scenario and with tens of minutes in advance, the expected delay due to crossing an area with active storms. In the case study, three different routes were considered, subject to the same thunderstorm activity; the standard deviation of the delay ranged between 22 and 149 seconds.

TRL-1.3	Are potential weaknesses and constraints identified related to the exploratory topic/solution under research? - The problem/challenge/ need under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others.	Achieved	The main constraint that applies to the topic under research is that, in terms of time, the problem is **restricted to the short-term level**; in this context, this is equivalent to tens of minutes before encountering the storm hazard. Besides this constraint, no weaknesses have been identified related to the exploratory topic under research.
TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Achieved	The concept has been defined and thoroughly described, including mathematical details and preliminary results, in Deliverable 4.2 [10]. It can be summarized as the development of a probabilistic trajectory predictor with storm avoidance, taking into account the uncertainty in the location of the convective cells (modelled as stochastic no-fly zones). Deterministic Nowcasts are used as input data for the location and size of the convective cells. The uncertainty in the location of the cells is modelled synthetically. The output is an ensemble of deviation trajectories that avoid the possible storm realizations and reattach to the original reference route.
TRL-1.5	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM Master Plan Level?	Partial – Non Blocking	The main contribution of the algorithm developed in TBO-Met for stochastic trajectory prediction with storm avoidance is in the areas of **safety** and **operational-efficiency** because, by using this algorithm, the involved stakeholders, airspace users and ANSPs, would be better informed and, therefore, better prepared, some minutes in advance, to face the effects of an evolving thunderstorm field. It can be said that this is an indirect contribution.

TRL-1.6	Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities? - What are these new capabilities? - Can they be technically implemented?	Achieved	The results obtained in TBO-Met related to the storm avoidance problem underpin an innovative capability, namely, **the short-term forecasting of the possible deviation trajectories** that an aircraft might follow to avoid a set of storm cells. On one hand, this innovative capability paves the road for a more proactive way of facing a thunderstorm field, as more information for decision support is known in advance. On the other hand, it is a basic building block for more accurate, short-term, traffic analyses. The technical implementation is possible, as it has been shown in the project. In fact, an already implemented tool (DIVMET) has been modified, first, to generate multiple thunderstorm field scenarios based on a deterministic Nowcast and, second, to compute a number of possible deviation trajectories (one per each scenario of convective cells). In fact, if a probabilistic Nowcast were available, the original and well-stablished DIVMET tool (without modifications) could be applied as many times as Nowcast members, to obtain the ensemble of deviation trajectories.
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Achieved	The following assumptions have been used in the definition of the exploratory concept: • The location of the convective cells is the unique source of uncertainty. • Availability of a Nowcast providing the position and size of the convective cells. • Availability of a model defining how the cell position uncertainty evolves with lead time.
TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and disbenefits	Partial – Non Blocking	**Two strengths** of the exploratory concept have been identified. On one hand, the methodology allows for the **quantification of the uncertainty of the forecasted aircraft trajectory** when affected by thunderstorms; this is based on the notion

	identified? - Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be that quantitative information already exists, in which case it should be used if possible.		that the trajectory predictor provides a probabilistic trajectory. On the other hand, the methodology also allows to **forecast traffic uncertainty** in the short term. The **benefit** identified is the possibility to take **more informed decisions** as to when and how to avoid the storms. This idea applies, first, to the airlines and pilots, as they would have a better picture of the possible scenarios that they would encounter when avoiding the thunderstorm field; and second, to the ANSPs and Network Manager, as they can use the output of the methodology in order to forecast sector demand in the short term. The following **limitations** have been identified: • In terms of geographical location, the studies are restricted to the Spanish airspace, because the Nowcasts used in TBO-Met have been provided by AEMET (Spanish Met Office). • The prediction time horizon is defined by the Nowcast forecast horizon. • The analysis (including the convective cell description and the avoidance strategy devised) is 2-D, because only 2-D information about the convective cells can be extracted from the Nowcasts. • Instead of a probabilistic Nowcast, a synthetic uncertainty model is added to a deterministic Nowcast to characterize the location of the convective cells.
TRL-1.9	Have Initial scientific observations been reported in technical reports (or journals/conference papers)?	Partial – Non Blocking	The methodological approach, the modelling, and initial results were published in Deliverable 4.2 [10]. Additionally, a conference paper will be presented at ISSA 2018, in which the effects in the sector demand are analysed [30]:

			A. Valenzuela, A. Franco, D. Rivas, D. Sacher, J. García Heras, M. Soler, "Effects of Weather Uncertainty in Sector Demand at Tactical Level," *accepted for the International Symposium on Sustainable Aviation 2018,* Rome, Italy, 2018.
TRL-1.10	Have the research hypothesis been formulated and documented?	Partial – Non Blocking	The hypotheses were reported in Deliverable 4.2[10]. They read as follows: • Elliptical convective cells are considered. • Constant barometric altitude is considered. • Constant ground speed is considered. • A 2-D avoidance strategy is considered. • No operational constraints are considered.
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	To bring current research to higher technological levels, the following research is considered to be needed in the future: • The inclusion of other sources of uncertainty different from the location of the convective cells. • The improvement of thunderstorm uncertainty modelling, e.g., extracting probabilistic fields by using probabilistic Nowcasts. • In case of the availability of Nowcasts providing 3D storm cells, the consideration of vertical avoidance manoeuvres. •The consideration of operational environment constraints, such as preventing the deviation trajectories from entering into restricted or reserved airspaces or the fulfilment of time constraints at specific fixes.

TRL-1.12	Are stakeholder's interested about the technology (customer, funding source, etc.)?	Achieved	As already indicated, airspace users and ANSPs would benefit from the innovative methodology developed in TBO-Met for short-term trajectory prediction under thunderstorm activity. In general, they are very much interested in the storm avoidance problem, as indicated in the TBO-Met Survey [8] and informally at the Steering Board meetings, because there is a real need for enhanced (more efficient) avoidance strategies. On the other hand, the interest of the ANSPs should come from the possibility of improving the accuracy of short-term traffic analyses.

Table 20: Exploratory Research Fund / Maturity Assessment for Sector Demand

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? Where does the problem lie?	Achieved	An improved traffic predictability thanks to the elaboration of a probabilistic demand will help the ANSPs and the Network Manager in their planning and monitoring needs. The **ATM problem** addressed in TBO-Met at the traffic scale is the quantification of sector demand uncertainty considering the uncertainty of weather predictions. The **exploratory concept** developed in TBO-Met for this problem is an ensemble-based stochastic methodology to predict sector demand based on the uncertainty of the individual trajectories.
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Partial – Non Blocking	In the past, the effects of uncertainties on the sector demand prediction were quantified in an aggregated way, considering all significant components of uncertainty together, without distinction of the different uncertainty sources, see for example [43]. The particular contribution of the meteorological uncertainty was assessed only in a qualitatively way, being recognized as one of the main sources of uncertainty that affect the ATM system [38]. The methodology developed in TBO-Met allows to quantify the effects of the meteorological uncertainty. Results are presented in Deliverable 5.2 [13] for applications concerning the pre-tactical and the tactical phases. Next, as a reference, some quantitative results are summarized. In the pre-tactical phase, only considering wind uncertainties, dispersions on the entry time as large as 7 minutes have been obtained for predictions made one day in advance. The dispersion in the entry and the occupancy count depends on the

			duration of the time periods chosen for the analysis, maximum values of 5 flights have been obtained for 1-minute duration. In the tactical phase, considering uncertain thunderstorms, dispersions much larger than in the pre-tactical analysis have been found; as large as 19 minutes in the entry time, for predictions made 10 minutes before the aircraft enters the sector. Maximum dispersions of 4 flights have been found in the occupancy count for predictions made 15 minutes in advance and duration of the time periods of 1 minute.
TRL-1.3	Are potential weaknesses and constraints identified related to the exploratory topic/solution under research? - The problem/challenge/ need under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others.	Achieved	The main **weakness** identified related to the ATM problem addressed in TBO-Met is that the current solutions to the problem, which are based on the use of time constraints and the consideration of safety buffers, are somewhat inefficient. No potential constraints affecting the ATM problem under research have been identified.
TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Achieved	The concept has been defined and thoroughly described, including mathematical details and preliminary results, in Deliverables 5.1 [12] and 5.2 [13]. The concept can be summarized as follows: a methodology to assess the uncertainty of sector demand when meteorological uncertainty is taken into account. The methodology has been developed to analyse the uncertainty of sector demand (probabilistic sector loading) in terms of the uncertainty of the individual

			trajectories. The approach is based on the statistical characterization of the entry and occupancy counts.
TRL-1.5	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM Master Plan Level?	Achieved	Related to the methodology developed to obtain a probabilistic demand, the fundamental research results show two contributions to SESAR goals (see Deliverables 5.1 [12] and 5.2 [13]): • Increase in capacity. If sector demand probabilistic predictions are available, ANSPs can reduce the capacity buffers they factor in order to protect themselves from over-deliveries (when the actual number of aircraft that enter a regulated sector during a particular period exceeds the declared capacity); therefore, declared sector capacities can be increased. • Improvement of the overall ATM system efficiency. An improved traffic predictability thanks to the elaboration of the probabilistic demand, can lead the Network Manager and the ANSPs to a better identification of the Air Traffic Flow and Capacity Management measures to be implemented, thus improving the traffic throughput.
TRL-1.6	Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities? - What are these new capabilities? - Can they be technically implemented?	Achieved	The results obtained in TBO-Met confirm that it is possible to **compute probabilistic sector demand forecasts**, from a set of individual trajectories that take into account uncertain weather, such as winds, convective areas or storm cells. This new capability can be seen as a basic pillar for the innovative concept of probabilistic Demand-Capacity Balancing. The technical implementation is straightforward because it only requires, first, to apply current tools to compute deterministic demand forecasts as many times as individual members of the probabilistic weather forecast (either Ensemble Prediction Systems or Nowcast), and second, to perform a statistical

			characterization of the results. Therefore, no ground-breaking development is needed.
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Achieved	The main assumption (or pre-condition) made in the exploratory concept is the **availability of an ensemble of trajectories** for each flight; this is the base for the statistical analysis. This assumption was stated in Deliverable 5.1 [12]. The underlying trajectory predictor that computes the trajectories has to provide one trajectory for each possible weather realization. All the trajectories are considered to be equally probable.
TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and disbenefits identified? - Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be that quantitative information already exists, in which case it should be used if possible.	Partial – Non Blocking	Two **strengths** of the innovative concept have been identified: on one hand, the methodology developed to obtain a probabilistic demand is **quantitative** and, on the other hand, it is a **versatile methodology** in the sense that any underlying trajectory predictor can be considered (the one developed in TBO-Met or any other). The following **benefits** have also been identified: • A better understanding of the uncertainty propagation from the trajectory scale to the traffic scale (scientific benefit). • An improvement on sector demand predictability. • Benefits for the stakeholders: support for better-informed decision making (ANSPs – support for dynamic sector configuration, Network Manager – support for better Demand-Capacity Balancing). The methodology developed to obtain a probabilistic sector demand has an **identified limitation**: The analysis is restricted to one sector. However, the methodology is suitable to be extended to perform a multisector analysis.

TRL-1.9	Have Initial scientific observations been reported in technical reports (or journals/conference papers)?	Achieved	The methodological approach and different analyses were published in Deliverables 5.1 [12] and 5.2 [13]. Additionally, two different publications have been presented at international conferences and a third one is in preparation. The methodology to obtain a probabilistic demand from the uncertainty of the individual trajectories was presented at EUCASS 2017 [28]: A. Valenzuela, A. Franco, D. Rivas, “Sector Demand Analysis under Meteorological Uncertainty,” *7th European Conference for Aeronautics and Space Sciences*, Milan, Italy, 2017. The pre-tactical analysis considering aircraft trajectories subject to wind uncertainty was presented at SESAR Innovation Days 2017 [29]: A. Valenzuela, A. Franco, D. Rivas, J. García Heras, M. Soler, “Effects of Reducing Wind-Induced Trajectory Uncertainty on Sector Demand,“ *7th SESAR Innovation Days*, Belgrade, Serbia, 2017. These papers can be found in the project website [31]. The tactical analysis considering aircraft trajectories subject to uncertain storms is analysed in the following conference paper [30]: A. Valenzuela, A. Franco, D. Rivas, D. Sacher, J. García Heras, M. Soler, “Effects of Weather Uncertainty in Sector Demand at Tactical Level,“ *International Symposium on Sustainable Aviation 2018,* Rome, Italy, 2018.
TRL-1.10	Have the research hypothesis been formulated and documented?	Partial – Non Blocking	The research hypotheses for the development of the general methodology are collected in Deliverable 5.1 [12], and the hypotheses of its adaptation to tackle the tactical problem are collected in Deliverable 5.2 [13]. The following research hypotheses have been considered:

			• Only the en-route operating environment has been considered. However, the extension of the methodology for probabilistic sector demand prediction to TMA or airport environments would be straightforward. • The ATC sector geometry is fixed and does not change with time; therefore, the effects of opening/closing sectors are not analysed. • At pre-tactical phase, trajectories are considered to cross the ATC sector only once. At tactical phase, the deviation trajectories may cross the same sector multiple times to avoid convective regions within the sector; in that case, the entry and exit times are considered to be the time to the first entry and the time to the last exit, respectively.
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	Three main lines of further scientific research have been identified to be necessary: • **Extension to the TMA,** considering climbing/descending trajectories which may enter/exit the sector not only by the lateral boundaries but also by the upper and lower limits. • **Multi-sector analysis,** that is, the extension of the methodology developed in TBO-Met considering several sectors at once. • **Variable sector configuration,** to take into account that the ATC sectors can be opened and/or merged.
TRL-1.12	Are stakeholder's interested about the technology (customer, funding source, etc.)?	Achieved	As previously mentioned, ANSPs and the Network Manager would benefit from the innovative methodology developed in TBO-Met. They have shown rather informally (at the Steering Board meetings, at workshops and conferences, and in other contexts) very much interest on having the capability of forecasting probabilistic sector demand. Another evidence of the interest of the stakeholders is the fact that another project in the H2020 Exploratory Research call deals with building probabilistic traffic

			predictions: COPTRA, participated by Boeing Research and Technology Europe, Catholic University of Louvain, Istanbul Technical University, CRIDA and Eurocontrol.