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FMP-Met

METEOROLOGICAL UNCERTAINTY MANAGEMENT FOR FLOW MANAGEMENT POSITIONS

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Abstract

In this report a high-level summary of the FMP-Met project is presented. This document describes the Concept of Operations defined to support the decision-making process for Flow Management Positions (FMP) under adverse weather, the probabilistic methodologies developed to forecast sector demand, capacity reduction, sector congestion and traffic complexity, and the key results of the project, in particular the tool concept devised for FMP monitoring. The communication, dissemination and exploitation activities carried out are described as well. Moreover, the Technology Readiness Level (TRL) of FMP-Met is assessed. The potential benefits and the expected contribution to the ATM Master Plan are indicated, and the next steps for future development are identified. The main conclusions are: 1) the FMP-Met concept has been positively assessed by FMP experts and deserves further study, and 2) the goal of reaching TRL 1 at the end of the project has been achieved.

Table of Contents

List of Tables

List of Figures

1 Executive Summary

The FMP-Met project corresponds to the research topic "*Environment & Meteorology for ATM*", and focuses on the enhancement of Air Traffic Management (ATM) efficiency under adverse weather by integrating meteorological forecast uncertainty information into the decision-support tools used by Flow Management Positions (FMP). The FMP is an operational position that monitors the level of traffic in airspace sectors, adjusts the value of capacity in view of adverse weather conditions or other contingencies, and coordinates flow measures when an excess of demand over capacity is detected.

In this context, FMP-Met deals with the provision of probabilistic traffic and capacity reduction forecasts under convective weather, for a forecasting horizon of 8 hours (tactical traffic flow management), for en-route and Terminal Control Area traffic, to support the FMP process. Note, however, that the analysis of impact mitigation actions is not addressed in this project, for example, actions to resolve imbalances between demand and capacity.

FMP-Met proposes a **tool concept** which addresses the problem of how probabilistic traffic forecasts can be integrated into the FMP procedures. The **aim of the concept** is not to radically change the current FMP procedures, but to seamlessly integrate uncertainty information into the established procedures. Thus, the Concept of Operations developed is an evolution of the current practice, transitioning from deterministic predictions to probabilistic ones. The **overall objective** is to provide a probabilistic assessment of the impact of convective weather, up to 8 hours in advance, useful for FMPs (as the end users), intuitive and interpretable, to allow better-informed decision making.

The main **outcome** of the project is the development of probabilistic methodologies to forecast sector congestion (coming from the combination of probabilistic demand and capacity reduction) and traffic complexity to be used in conjunction with the tools currently employed by FMPs. The **novelty** of the FMP-Met concept is that it integrates weather information into the FMP tools, and uncertainty information into the FMP decision-making process under adverse weather, with a lead time of 8 hours. The new features can be easily incorporated in the form of a new tool layer added to the current layers. This concept also facilitates the consideration of other sources of uncertainty in addition to the meteorological one, such as the uncertainty in the take-off time and the uncertainty linked to the storm avoidance strategy.

These methodologies rely on the availability of three **supporting technical enablers**: 1) Probabilistic weather forecasts, 2) Probabilistic trajectory predictor, with storm avoidance, and 3) Probabilistic predictor of capacity reduction caused by thunderstorms. In FMP-Met, enablers developed in-house have been used, but the tool concept is very versatile, capable of using different implementations of the three underlying technical enablers.

The **overall conclusion** of this Exploratory Research project is that the concept proposed to enhance FMP decision-making process under adverse weather has potential and deserves to be explored further. Indeed, the FMPs' feedback is quite positive. They recognize that the FMP process under adverse weather can be operationally improved and that the FMP-Met concept developed in this project is a good first step.

The **potential benefits** that one could expect from the implementation of the FMP-Met concept are the following:

- Support to take anticipated, appropriate, and timely tactical flow measures under adverse weather (better-informed decision-making process for FMPs).
- Possibility of conducting a what-if analysis, to have a preliminary evaluation of the impact of measures to be taken, in terms of cost and effectiveness.
- Enhancement of ATM efficiency, which will ultimately reduce flight delays and improve passenger journeys.

The potential use of the tool concept developed in FMP-Met shows a main contribution to the following SESAR goal: **Improvement of the overall ATM system efficiency.** Indeed, an enhanced (better-informed) FMP process under adverse weather can lead the Air Navigation Services Providers to a better identification of the ATFCM (Air Traffic Flow and Capacity Management) measures to be implemented, thus improving the traffic throughput, and reducing delays.

The work carried out in the FMP-Met project has been validated. The **validation** has two parts: 1) Assessment of the probabilistic methodologies developed for traffic analysis under adverse weather in multi-sector scenarios. This assessment is performed comparing the FMP-Met predictions with results obtained using an advanced air traffic simulator taken as "reality". 2) Validation of the operational concept developed for tactical flow management under adverse weather, made by expert FMPs. The overall assessment is quite positive. Moreover, the analysis of the results and the FMPs' feedback has allowed to identify improvements for future development of the FMP-Met concept.

Furthermore, a **Maturity Assessment** has been performed; the Technology Readiness Level (TRL) of FMP-Met has been assessed. The level of satisfaction of all the maturity criteria evaluated leads to the conclusion that the assessment is positive, and, therefore, we can claim that the goal of reaching TRL 1 at the end of the project has been achieved.

The main step for the next R&D phase is the development of a **prototype tool,** in close collaboration with FMPs, implementing the FMP-Met concept. The goal will be to perform realistic simulations and to analyse operational feasibility, including human factors.

In this future development the following suggestions to improve the tool (made by the experts consulted) should be taken into account:

- addition of a Map View functionality, to have a better perception of the weather status and evolution, and
- addition of the What-If functionality, to evaluate beforehand the possible impact of measures to be taken.

2 Project Overview

2.1 Operational/Technical Context

As indicated in the Project Management Plan [1], the FMP-Met project corresponds to the research topic "*Environment & Meteorology for ATM*", and is fully aligned with the objectives of the SESAR 2020 Exploratory Research programme of securing

> "*the proper integration of existing and possible new meteorological products into ATM for example to reduce the vulnerability of the ATM system to local weather phenomena and to improve the prediction of 4D Trajectories and network forward planning to enable a minimisation of consequential weather-related delays*",

and also

> "*the incorporation of ensemble weather information into decision-support tools, adapted for different ATM stakeholders*".

Moreover, according to the topic description (Sub Work Area 1.3) described in the SESAR Single Programming Document 2019-2021 [17]:

> "*Research activities will study … how enhanced meteorological capabilities and their integration into ATM planning processes can be utilised for improving ATM efficiency and safety. This requires understanding of the potential of different types of weather-related information that could be used in ATM operations taking into account the inherent uncertainty of meteorological information*."

In line with the SESAR objectives just mentioned, FMP-Met focuses on the enhancement of Air Traffic Management (ATM) efficiency under adverse weather by integrating meteorological (MET) forecast uncertainty information into the decision-support tools used by Flow Management Positions (FMP). FMP is an operational position in the Area Control Centre (ACC) whose main role is to assist the ACC Supervisor to choose the best ATC sector configuration at the right time. FMPs monitor the level of traffic in airspace sectors, adjust the value of capacity in view of adverse weather conditions or other contingencies, and coordinate flow measures when an excess of demand over capacity is detected.

The presence of convective cells makes sector demand irregular and not easy to predict, increases traffic complexity and reduces sector capacity. Today, FMPs and ACC Supervisors tasked with Configuration Management brief themselves of relevant MET conditions on various MET-briefing systems other than CIFLO (CHMI for Flow Management Positions), and they must convert this information into impact on sector capacity and integrate it manually into the current Collaboration Human Machine Interface (CHMI). Risks here are many, from FMP officer not understanding the potential negative impact and causing an overload/over-delivery on sector, to overregulating weather with very low intensity. Furthermore, FMP actions to mitigate weather effects are often reactionary and too late, considered as the last option and applied when most flights are no longer subject to ATFCM measures. Hence, the provision of 1) an accurate prediction of the development of convective cells inside a sector, 2) a trustworthy forecast and characterisation of the future sector demand, and 3) a reliable estimation of the impact of the convective weather in the sector capacity, will support the FMP in taking anticipated, appropriate, and timely flow measures that, in turn, will increase the ATM efficiency and reduce delays.

2.2 Project Scope and Objectives

FMP-Met deals with the provision of probabilistic traffic forecasts under convective weather for a forecasting horizon of 8 hours (tactical traffic flow management), to support the FMP process. Note, however, that the analysis of impact mitigation actions is not addressed in this project, for example, actions to resolve imbalances between demand and capacity.

The key **research challenge** is the analysis of a traffic flow management problem with an extended time horizon, in which the levels of uncertainty are important and, therefore, a probabilistic approach is required. In this analysis different probabilistic weather forecast products have been used, with different lead times and coverage areas (the best products available at each time and location).

As indicated in the Grant Agreement [18], the **overall objective** is to provide a probabilistic assessment of the impact of convective weather, up to 8 hours in advance, coming from the combination of the probabilistic demand, complexity, and capacity reduction, useful for FMP (as the end user), intuitive and interpretable, to allow better-informed decision making.

To achieve this overall goal, the project has the following **specific objectives**:

1. Tailor multi-scale, multi-source convective weather information for FMP application.
2. Predict probabilistic aircraft trajectories using multi-scale convective weather information.
3. Translate convective weather forecasts into predictions of reduced airspace capacity.
4. Forecast multi-sector demand and complexity under convective weather.
5. Produce guidelines for the use of probabilistic forecasts for FMP application.

As a quantitative indicator of the **expected impact**, taking into account that a large percentage of the en-route air traffic delays are attributed to weather (21.2% in 2019, 3.6 million minutes, according to Eurocontrol's Performance Review Report 2019 [19]), if the methodologies developed in this project help to reduce the weather-dependent delays just by 5%, and if we consider that 1 minute of delay costs the ATM network roughly 100€, then savings of 18M€ per year could be achieved for the European air traffic system.

2.3 Work Performed

A schematic description of the FMP-Met project, including the input/output and the main tasks carried out, is given in Figure 1.

Two probabilistic **methodologies** have been developed for traffic analysis under adverse weather:

- sector demand,
- traffic complexity,

on which the tool concept for **FMP monitoring** is based. This tool, which requires the development of a probabilistic methodology to forecast sector congestion, is composed of 3 layers:

- Sector Configuration Monitor,
- Traffic Volume Monitor and
- Traffic Volume Analysis View.

These methodologies rely on the availability of three **supporting technical enablers**:

- Probabilistic weather forecasts.
- Probabilistic trajectory predictor, with storm avoidance.
- Probabilistic predictor of capacity reduction caused by thunderstorms.

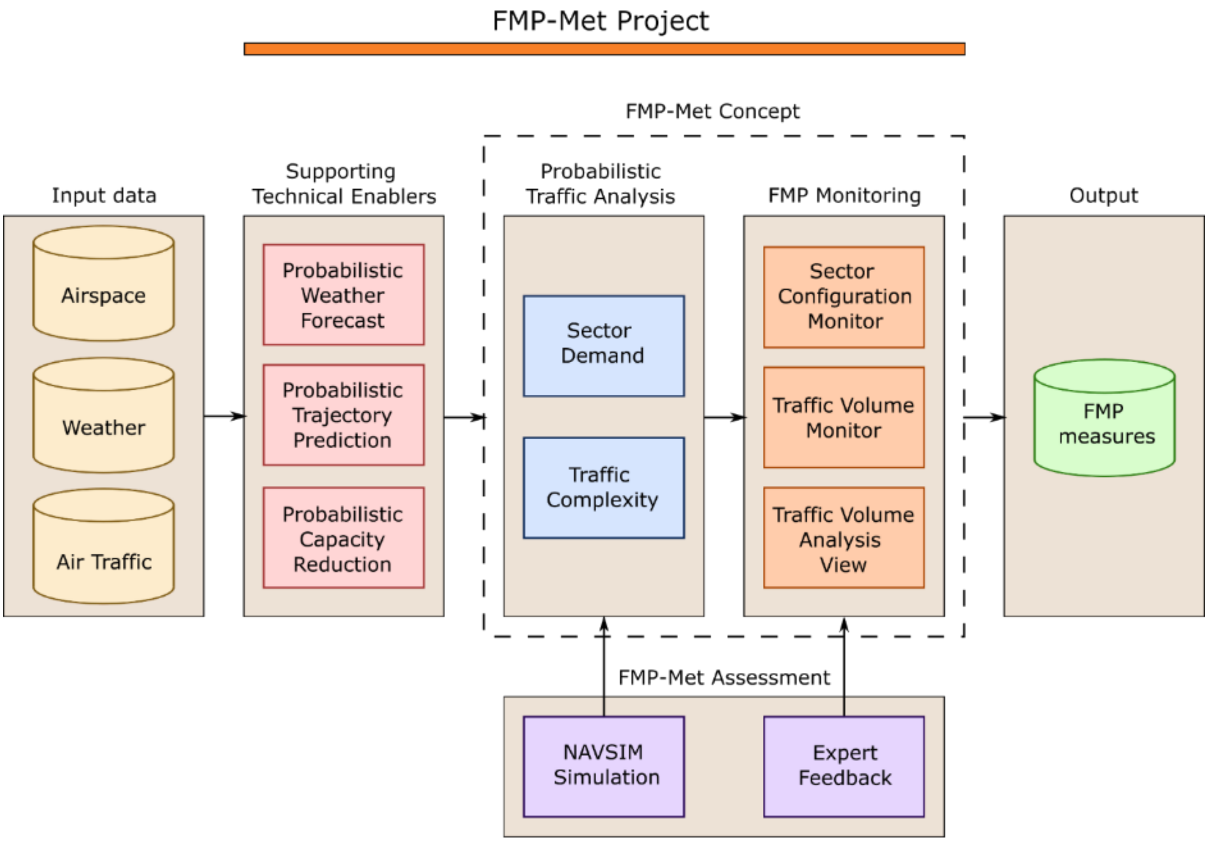

Figure 1: Structure of FMP-Met project.

The main elements depicted in Figure 1 are described next. (Note that the analysis of the FMP Measures to be taken based on the probabilistic predictions generated using the FMP-Met concept is beyond the scope of this project.)

2.3.1 Concept of Operations

The FMP-Met concept addresses the problem of how probabilistic forecasts of traffic load can be integrated into the FMP procedures. The **aim of the concept** is not to radically change the current FMP procedures, but to seamlessly integrate uncertainty information into the established procedures. The operational concept is described in deliverable D2.1 [3].

Nowadays, the Network Manager supports FMPs with current and anticipated air traffic demand via Eurocontrol's CHMI tool. These predictions are deterministic and based on data received from the flight-plan processing systems, airspace databases, live Air Traffic Control (ATC) data from Air Navigation Services Providers (ANSP), aircraft operator's position reports, and meteorological data from a weather service provider. Thus, the Concept of Operations developed is an evolution of the current practice, transitioning from deterministic predictions to probabilistic ones.

The integration of probabilistic information in the decision process is based on a decision support tool. In this project a **tool concept** is devised, which aims at giving a concise airspace overview to raise awareness for possible imbalances in demand and capacity. In addition, this tool will allow to test the impact of FMP measures informing the decision maker on the cost and effectiveness before taking the measure.

The **context of use** of the concept is the FMP process under adverse weather (thunderstorms), for en-route + Terminal Control Area traffic, for a time horizon of 8 hours (tactical phase).

Given the forecast look-ahead time of 8 hours, and the stochastic evolution of the atmosphere, the FMP predictions on sector demand and traffic complexity are affected by MET forecast uncertainty, so that a **probabilistic approach** becomes the appropriate one. The proposed tool is derived from existing concepts. The **novelty** in FMP-Met is that the weather impact is included in the traffic forecast used by the tool; in addition, since the forecast is probabilistic, it also includes uncertainty information.

2.3.2 Supporting Technical Enablers

The three **supporting technical enablers** are outlined next:

- Probabilistic weather forecasts. In this project MET uncertainty is quantified by a probabilistic prediction technique called Ensemble Weather Forecasting. Three types of forecasts are considered: ensemble nowcasts, limited-area Ensemble Prediction Systems (EPS) and global EPSs. The probabilistic weather forecasts used in the project are described in deliverable D3.1 [4].
- A probabilistic trajectory predictor, providing 4D trajectories with a measure of uncertainty. The trajectory predictor developed in the project captures not only the meteorological uncertainties, but also the uncertainty in the storm avoidance strategy and the uncertainty in the departure time for those aircraft that are still on ground. The probabilistic trajectory predictor used in the project is described in deliverable D4.1 [5]. A brief outline is given in Section 2.4.
- A probabilistic predictor of capacity reduction caused by thunderstorms, that is a probabilistic measure of the Available Sector Capacity, given, for example, as the ratio of the sector capacity under the given weather constraints to the maximum possible capacity of the sector without weather systems. The probabilistic predictor of capacity reduction used in the project is described in deliverable D6.1 [7].

2.3.3 Probabilistic Traffic Analysis

The probabilistic methodologies developed for traffic analysis under adverse weather are outlined next.

Sector demand

To forecast sector demand, a methodology to compute the probability distributions of the entry and occupancy counts for individual sectors has been developed (described in deliverable D5.1 [6]). The counts are determined from the probabilistic entry and exit times of all the aircraft that may cross the sector. These times are obtained from the probabilistic aircraft trajectories returned by the trajectory predictor developed in WP 4 (supporting technical enabler described in deliverable D4.1 [5]).

This methodology considers that the trajectories are predicted using different weather products, that multiple uncertainty sources are present, and that these uncertainties may be correlated or uncorrelated. It also considers climbing/descending trajectories that may enter/exit the sector not only by the lateral but also by the vertical limits. Although the methodology has been developed for ATC sectors, it can be applied to any generic airspace or traffic volume.

Sector congestion

To forecast sector congestion a methodology to compute the probabilistic sector overload has been devised (described in deliverable D5.1 [6]), which is the probabilistic difference of the entry and occupancy counts exceeding weather-dependent capacities. The weather-dependent capacities are derived from the capacity reductions determined in WP 6 (supporting technical enabler described in deliverable D6.1 [7]). Again, multiple uncertainty sources and their statistical correlations are considered.

The weather-dependent capacity for a given sector is obtained in terms of the nominal Monitoring Value (MV) and Occupancy Traffic Monitoring Value (OTMV) as follows

$$Wx\_MV = ASCR \cdot MV$$

$$Wx\_OTMV = ASCR \cdot OTMV$$

where *ASCR* is the Available Sector Capacity Ratio, a probabilistic variable defined as the ratio of the sector capacity under the given weather constraints to the maximum possible capacity of the sector without weather systems. The ratio is a non-dimensional value ranging between 0 and 1, where 0 represents a completely blocked airspace with no usable capacity and 1 represents an airspace without any weather-induced capacity reduction.

The probability of congestion of each individual sector is obtained from the probabilistic overload, which combines the probabilistic predictions of traffic forecast, *TF (TF* can be either the entry or the occupancy count) and weather-dependent capacity, *Wx_Cap* (*Wx_Cap* can be either the MV or the OTMV capacity). Thus, from *TF* and *Wx_Cap* the Relative OverLoad (*ROL*) is defined as

$$ROL = 100 \frac{TF}{Wx\_Cap} \; (\%)$$

and, from their probabilistic distributions, the *ROL* distribution is generated. In particular, the percentiles 50 and 95 of the distribution (Z_{50} and Z_{95}) are considered, which are used to define the probabilistic color code, as described in Section 2.4.

Traffic complexity

In FMP-Met the complexity distribution is obtained from the predicted probabilistic trajectories and takes into account the presence of the thunderstorm. The methodology (described in deliverable D6.1 [7]) is based on the PRU complexity model, defined by Eurocontrol's Performance Review Unit [20], enhanced by the introduction of a new complexity indicator describing the aircraft-to-weather interaction, aiming at accounting for the adverse effect of weather on complexity.

The weather interaction indicator represents all communication and coordination between the Air Traffic Control Officer (ATCO) and the aircraft concerning avoidance of convective weather. In this method, an aircraft is considered in weather interaction if it is inside a cell occupied by convective weather or bordering the convective weather. The analysis of the aircraft-weather interaction follows the same principle as the other indicators defined in the PRU method.

From all the complexity indicators one obtains the **complexity score** which provides a single complexity metric for the analyzed airspace. In FMP-Met we have developed a methodology to determine a probabilistic value of complexity score based on the ensemble of possible traffic scenarios.

2.3.4 FMP Monitoring

The three layers of the tool concept developed for FMP monitoring are outlined next (described in deliverable D2.1 [3]).

Sector Configuration Monitor

In the *Sector Configuration Monitor* the time evolution of the demand-capacity balance (DCB) is shown for all sector configurations of interest. For each sector configuration, the colors defining the expected traffic load are determined from the color state of the traffic volumes (TV) that constitute that configuration (the determination of the traffic volume's colors is given in Section 2.4.2) and they have the following meaning:

- Green: all TVs are in green state; that is, the traffic load is acceptable for all TVs.
- Yellow: at least one TV is in yellow state; that is, the traffic load for at least one TV is high but no action is required, or ATC measures are sufficient.
- Orange: at least one TV is in orange state; that is, the traffic load for at least one TV is very high.
- Red: at least one TV is in red state; that is, the traffic load for at least one TV is unacceptable.

The *Sector Configuration Monitor* is similar to the ATC Airspace Monitor in the CIFLO application. It allows to display an overview of the color state for various sector configurations at once. The main difference is related to how the color state is evaluated.

Traffic Volume Monitor

By selecting a specific sector configuration in the *Sector Configuration Monitor*, the *Traffic Volume Monitor* for the corresponding traffic volumes opens, displaying their traffic loads. The *Traffic Volume*

Monitor corresponds to the ATC Airspace Monitor in the CIFLO application, but based on probabilistic data.

Note that, to make use of the additional probabilistic information, the color code definition needs to be adapted; the scheme devised in this project is described in Section 2.4.2.

Traffic Volume Analysis View

To gain detailed insight into the situation in a specific TV, by selecting that TV in the *Traffic Volume Monitor* the *Traffic Volume Analysis View* can be opened. This view combines standard FMP information as available in CIFLO with additional probabilistic information, i.e. it extends the functionality of the Traffic Counts tool currently used in CIFLO. This layer relies on the computation of the stochastic distributions of the traffic counts and their differences with weather-dependent capacities (as described above).

The *Traffic Volume Analysis View* displays probabilistic distributions of traffic demand, sector congestion and traffic complexity. In FMP-Met 3 types of graphical representation have been selected (as described in deliverable D7.1 [8]):

A. Frequency plots (in fact, **frequency histograms**), showing specific *ROL* distributions for given time periods (see Figure 5 in Section 2.4.3).
B. Graphical displays known as **heat maps**, depicting the time evolution of the different parameters of interest. In these maps the color for each value represents the probability of obtaining that particular value; the darker the color, the higher the probability. The 5th, 50th and 95th percentiles can be indicated as well; the median represents the central value, and the difference between the 5th and 95th percentiles is a measure of the dispersion. This display integrates temporal and probabilistic information in one view (see Figure 6 in Section 2.4.3).
C. Complexity distributions depicted as **violin plots** for given time windows, representing the probabilistic complexity score (see Figure 7 in Section 2.4.3). The length of the violin plot is a measure of the dispersion. Distributions with small standard deviation result in short and wide violin plots, whereas cases with large standard deviation lead to elongated plots. Hence, wide sections of the violin plot correspond to high probability, and thin sections correspond to low probability. These displays depict the time evolution of the expected traffic complexity.

The innovation of these displays is that the impact of weather on the traffic is derived and displayed directly, without the need to consult and assess weather forecasts off-line.

While the color coding in the *Traffic Volume Monitor* is an indication of whether an action needs to be taken, the detailed information which can be derived from the distributions shown in the *Traffic Volume Analysis View* is meant to support the decision about which action should be taken.

2.3.5 Project Assessment

An assessment of the work carried out in the FMP-Met project has been presented in deliverable D7.1 [8]. It has 2 main parts:

1) Assessment of the probabilistic methodologies developed for traffic analysis, namely, sector demand and traffic complexity, under adverse weather in multi-sector scenarios. This assessment is performed comparing the FMP-Met predictions with NAVSIM simulations taken as “reality”.

2) Validation of the operational concept developed in the FMP-Met project for tactical flow management under adverse weather. This validation is based on FMPs’ feedback (expert opinion) via questionnaires, as outlined in Section 2.4.4.

Both the assessment and the validation are performed considering the same use case (see Appendix A), which corresponds to a day with strong convective activity. The overall assessment is quite positive. Furthermore, the analysis of the results and the FMPs’ feedback have allowed to identify improvements for future development of the FMP-Met concept.

2.4 Key Project Results

2.4.1 Unified framework for probabilistic trajectory prediction

A unified framework for probabilistic trajectory prediction under adverse weather for an extended horizon of 8 hours has been developed (described in deliverable D4.1 [5]). This framework considers the three types of probabilistic forecasts already mentioned (ensemble nowcast, limited-area EPS, and global EPS), two additional sources of uncertainty (uncertainty in the storm avoidance strategy and the uncertainty in the departure time for those aircraft that are still on ground), and integrates two trajectory predictors (TP): Short and Long-term TPs. The Short-term TP uses nowcast data and is capable of avoiding storm cells. The Long-term TP uses EPS data and does not avoid storm cells, because EPS does not provide storm cells but much larger areas where important convective activity is forecasted.

The procedure defines a decision tree (in the form of a block diagram) that univocally determines which TP (short or long) must be used, which MET product (nowcast, COSMO-D2, or ECMWF) has to be considered, and when to transition from one TP methodology to another, see Figure 2 (in this figure, NOWCAST TP corresponds to the short-term TP, and ECMWF-EPS TP and COSMO-D2-EPS TP to the long-term TP using ECMWF and COSMO EPS respectively).

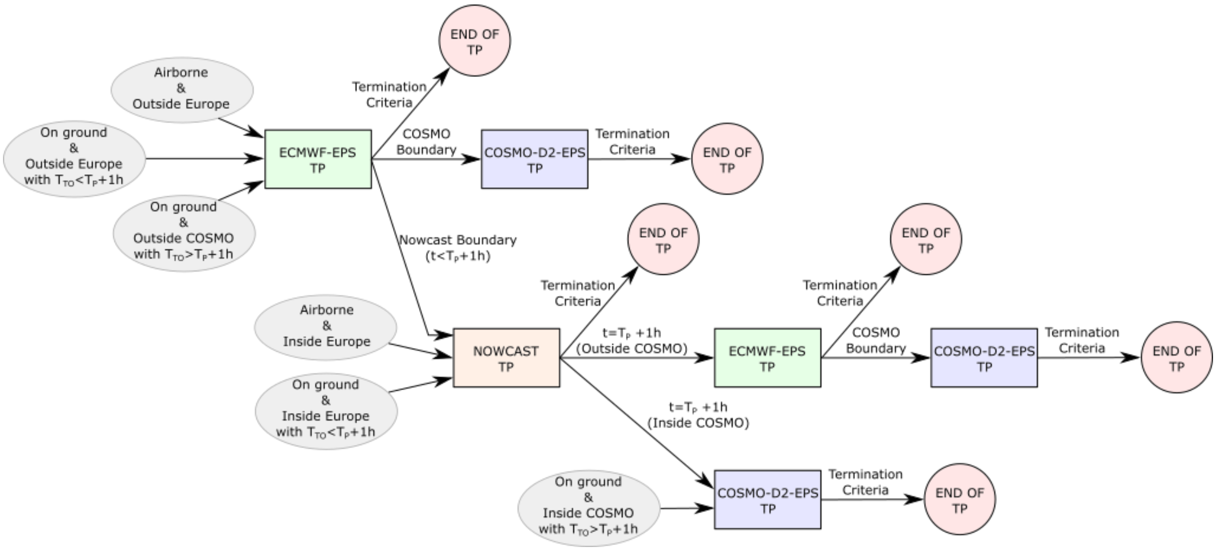

Figure 2: Unified framework for probabilistic trajectory prediction.

2.4.2 Final FMP-Met concept

The final FMP-Met concept defines a procedure to adapt the FMP monitor currently used to probabilistic input. The core of this procedure is a probabilistic color code used to determine the state of the expected traffic load, considering the standard ROL thresholds, namely 90%, 100%, and 110%. This probabilistic color code is based on two parameters of the *ROL* distribution: the percentiles 50 and 95 (Z_{50} and Z_{95}). The code is given by the 2-entry table shown in Figure 3, as described in deliverable D7.1 [8].

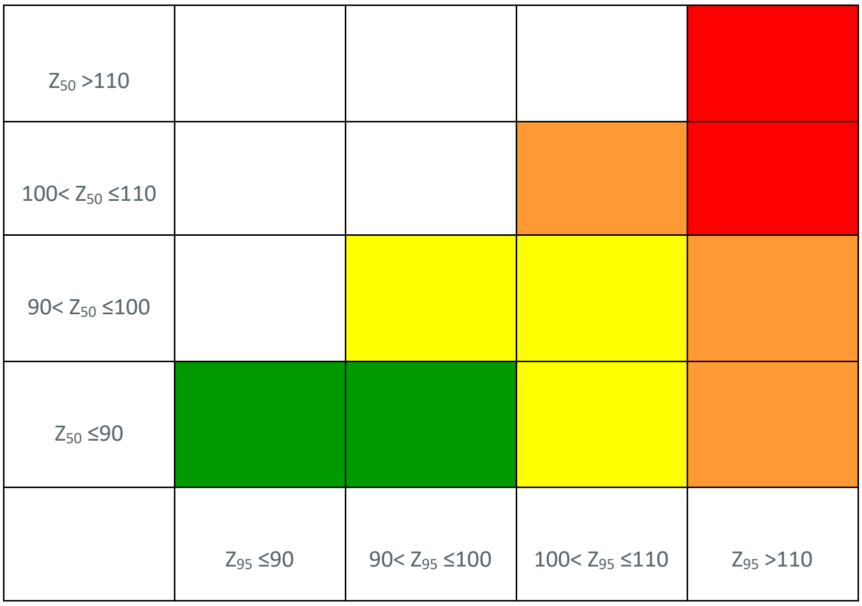

Figure 3: Probabilistic color code. ROL=100*TF/Wx_Cap (%).

This matrix defines the different scales of traffic load: 'acceptable traffic load' = green, 'high traffic load' = yellow, ' very high traffic load' = orange, and 'unacceptable traffic load' = red.

One can see that including the dispersion of the *ROL* distribution (off-diagonal cases) always makes the prediction more severe: green can become yellow and even orange, yellow can become orange, and orange can become red. This is because there is a fair chance that the relative overload in these off-diagonal cases is higher than the one predicted by Z_{50}.

2.4.3 Prediction results

The results presented in this section summarize the capabilities of the proposed probabilistic concept. Results are presented for configuration 10A1 (see Appendix A). The figures included below also show the graphical displays selected to present the probabilistic forecasted data.

Sector Configuration Monitor

The *Sector Configuration Monitor* displays an overall view of the color state of all the sector configurations of interest. It consists of the aggregation of the time evolution of all traffic loads like the top row for configuration 10A1 in Figure 4.

Traffic Volume Monitor

First, in Figure 4 we have the results obtained using the probabilistic coding developed in the project (the 2-entry table shown in Figure 3, which uses the percentiles Z_{50} and Z_{95} as input). Figure 4 shows results for the different sectors corresponding to the entry count for 1-hour periods, calculated every 20 minutes.

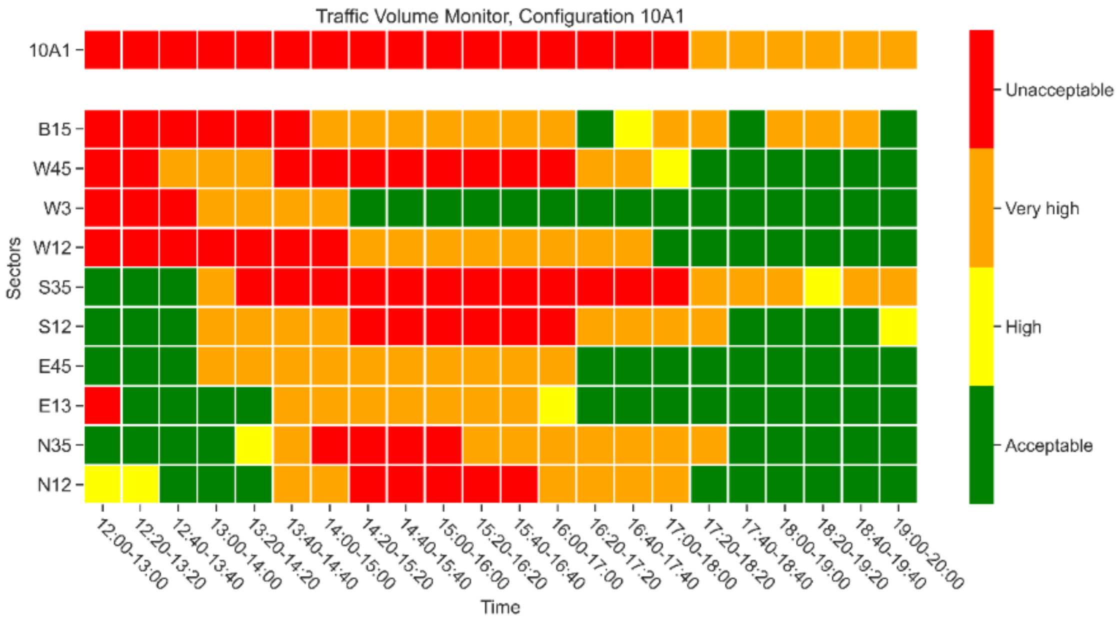

Figure 4: *Traffic Volume Monitor*. Probabilistic coding.

Traffic Volume Analysis View

Some features of the *Traffic Volume Analysis View* are described now. We present some examples which employ different graphical displays.

A.

First, Figure 5 shows two specific ***ROL* distributions** corresponding to the entry count for Sector B15 for two given time periods (each distribution is depicted as a **frequency histogram**):

1. From 15:00 to 16:00 – orange in Figure 4 (Z_{50}=74% and Z_{95}=208%).
2. From 16:20 to 17:20 – green in Figure 4 (Z_{50}=67.5% and Z_{95}=96.5%).

The values of Z_{50} and Z_{95} are the input to establish the color in the *Traffic Volume Monitor*. (The deterministic coding would give green in both cases.)

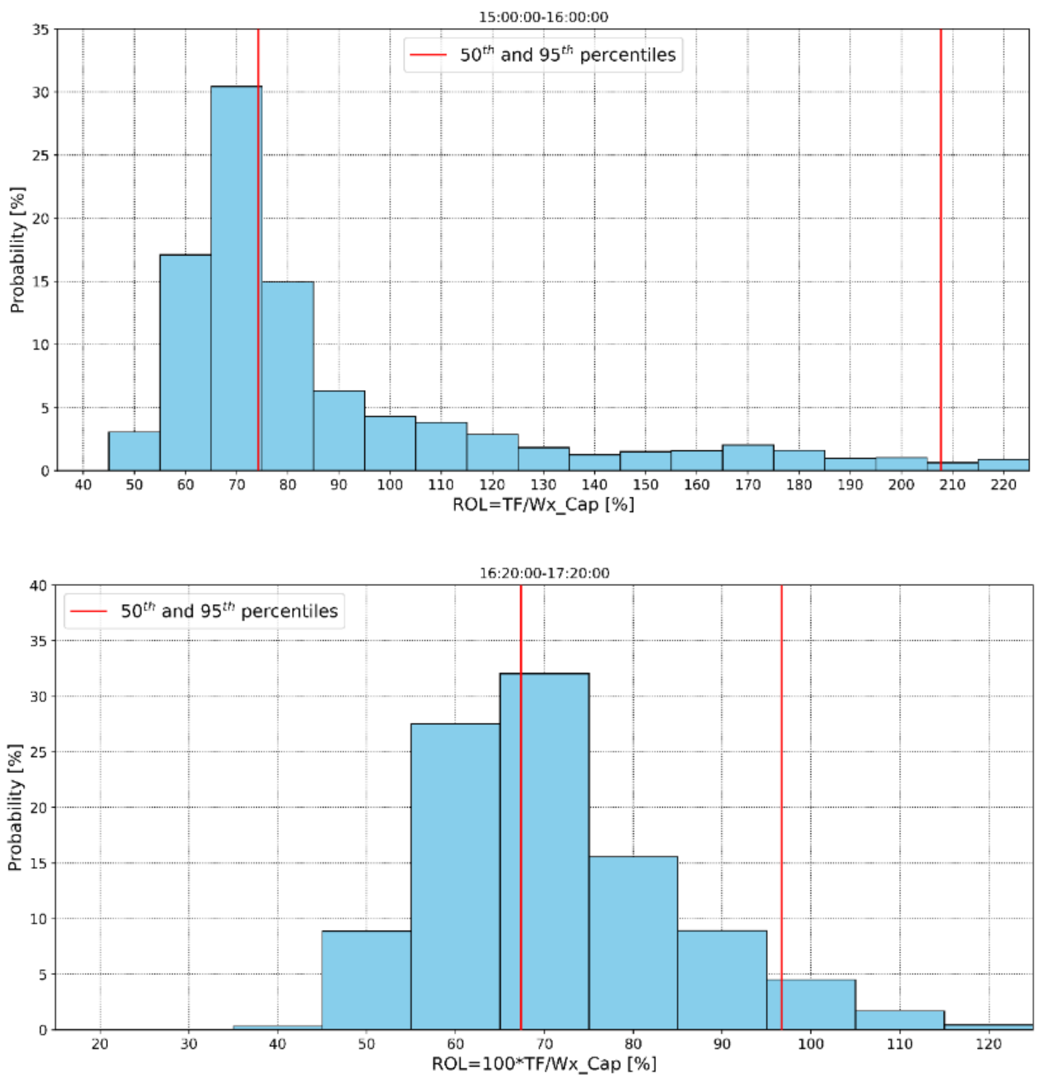

Figure 5: *Traffic Volume Analysis View*. *ROL* distributions for Sector B15.

B.

In this layer of the tool we can also present the **time evolution** of the different parameters of interest. In Figure 6 we present the evolution of the occupancy count between 12:00 and 13:00 for Sector B15, for time periods of 1 minute, according to usual practice.

The graphical display selected is as a **heat map**, where the color for each count value represents the probability of obtaining that particular value; the darker the color, the higher the probability. The 5th and 95th percentiles are represented as small black squares, and the 50th percentile (i.e., the median) as a small diamond. The median represents the central value, and the difference between the 5th and 95th percentiles is a measure of the dispersion. This display integrates temporal and probabilistic information in one view.

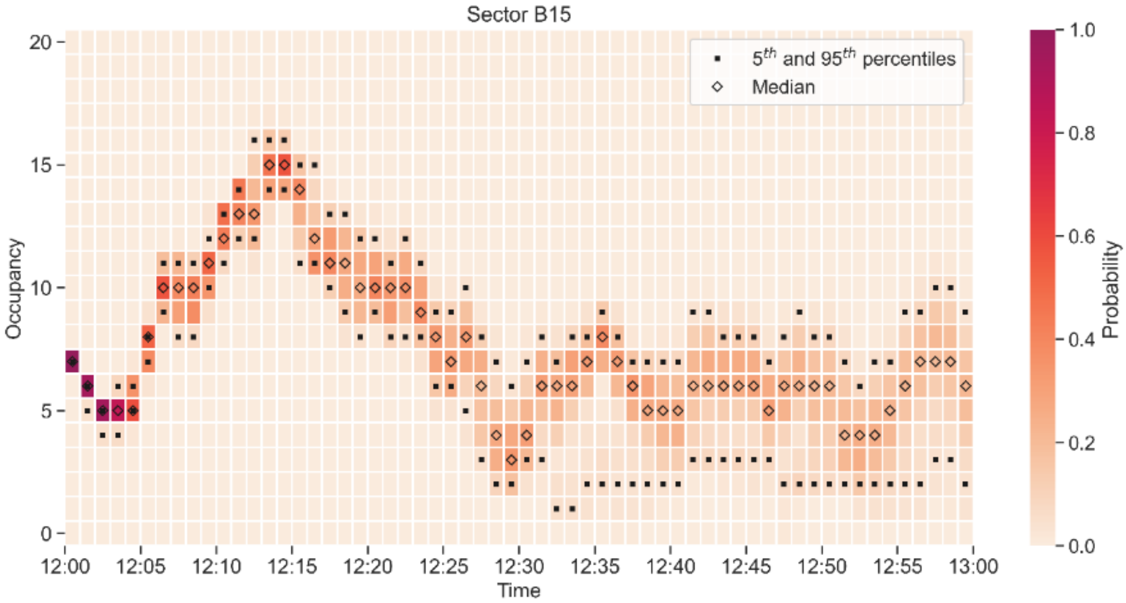

Figure 6: *Traffic Volume Analysis View*. Occupancy count evolution for Sector B15.

C.

Finally, we analyze the **expected traffic complexity**. An example of the evolution of the complexity score is shown in Figure 7, for Sector S35 between 12:00 and 20:00 hours, computed for 20-minute windows.

For each time window, the complexity distribution is depicted as a **violin plot**. As already indicated, the length of the violin plot is a measure of the dispersion (distributions with small standard deviation result in short and wide violin plots, and cases with large standard deviation lead to elongated plots). Hence, wide sections of the violin plot correspond to high probability, and thin sections correspond to low probability. Note that the area of all the violin plots in the figure is the same.

We can see high complexity scores for the distributions shown in the middle of the figure. In particular, the graph at t+240 (16:00h) has the complexity score being as low as 5 and as high as 20, which indicates a large standard deviation.

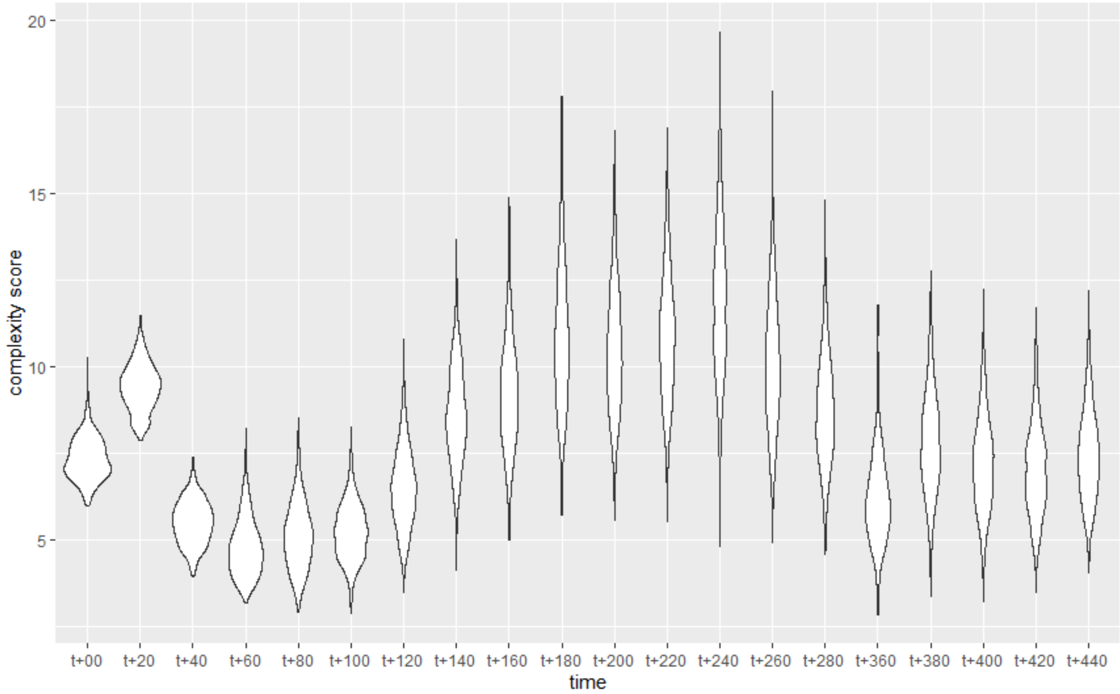

Figure 7: *Traffic Volume Analysis View*. Complexity evolution for Sector S35.

2.4.4 FMP expert feedback

Within FMP-Met a **validation exercise** was conducted with FMP experts from ACG and CCL, intended to validate the probabilistic operational concept developed in the project as described above. This exercise is outlined next.

The validation tool used to validate the FMP-Met concept is the **Judgmental technique (expert opinion)** via questionnaires. The validation results are **qualitative**. The goal has been to assess the usefulness of the proposed probabilistic concept for FMPs, that is, to know whether the new operational concept can become more useful than what they have today.

The exercise had **three steps**:

- First, the FMPs were briefed on the Operational Concept developed in FMP-Met.
- Second, the results of the simulations were presented to the FMPs.
- Third, the FMPs were asked to respond the questionnaire.

The questionnaire was discussed in several rounds of talks with the manager FMP, the deputy manager FMP, the ATM post-OPS expert and several simulation experts. The reply to the questionnaire was then reviewed and consolidated by the manager FMP. The questionnaire and the (anonymous) consolidated answers are included in deliverable D7.1 [8].

The main result is that the FMP-Met concept has been assessed positively. The FMPs recognized that the FMP process under adverse weather can be operationally improved and that the FMP-Met concept developed in this project is a good first step, which deserves to be explored further. The experts consulted were comfortable using the graphical displays selected for the tool concept developed. They also suggested improvements for future development (see Section 4).

2.5 Technical Deliverables

The technical deliverables included in the Grant Agreement [18] are briefly described in Table 1 (references to management deliverables can be found in Section 5 [2, 9-12]; all public deliverables are available in the project website [16]).

Table 1: Project Deliverables

Reference	Title	Delivery Date[1]	Dissemination Level[2]
Description			
D2.1	Concept of operations for weather-dependent probabilistic Flow Management	11/12/2020	Public
This document presents a Concept of Operations that integrates probabilistic forecasts of traffic load due to expected weather in flow management procedures to be used by the Flow Management Position (FMP). The core of the concept is an awareness-based approach to decision support. The focus is on the tactical phase (time range of 30 minutes to 8 hours before the sector entry time). A decision support tool concept is devised, which aims at giving a concise airspace overview to raise awareness for possible imbalances in demand and capacity, and also additional information to support decisions on measures to be taken. The aim of the concept is to seamlessly integrate uncertainty information in the established procedures (not to radically change the current FMP procedures).			
D3.1	Nowcast and EPS forecast products	14/12/2020	Public
This document describes the work done on weather provisioning and processing. This work has two main goals. The first is to produce a probabilistic convective weather forecast, to be used as MET data for the storm avoidance tool used in the project. The second is to provide and process Ensemble Prediction Systems to be used as MET data for trajectory prediction for long lead times (up to 8 hours). The document presents the requirements on the data of nowcasting and EPS, and concepts for data processing. Moreover, according to the requirements initially specified, the needed MET data sources are identified, and the necessary processing methods are defined.			

[1] Delivery data of latest edition

[2] Public or Confidential

D4.1	Trajectory prediction under adverse weather scenarios	19/05/2021	Public
In this deliverable a methodology to predict probabilistic aircraft trajectories using multi-scale convective weather information is proposed. The core of this deliverable is to effectively propagate uncertainties from a given current state up to look-ahead times of 8 hours. The challenge arises in integrating different MET products with different temporal scales (namely, Ensemble nowcasts, regional coverage EPS forecasts and global coverage EPS), and different sources of uncertainty. The deliverable addresses five main technical activities: Weather temporal interpolation, Short-Term Trajectory predictor, Long-Term Trajectory predictor, Uncertainty characterization, Unified framework to integrate Short and Long-Term TPs. Some examples are worked out using the integrated methodology.			
D5.1	Forecast of sector demand in multi-sector scenarios	18/11/2021	Public
This document presents the methodologies developed regarding the probabilistic prediction of sector demand and congestion when convective weather is forecasted. Firstly, a methodology to compute probabilistic forecasts of the entry and occupancy counts for individual sectors, which relies on the probabilistic aircraft trajectories returned by the TPs presented in D4.1. This methodology considers that multiple uncertainty sources may be present, and their statistical correlations. Secondly, a methodology to determine the probabilistic traffic overload of the sector, which considers the previous probabilistic counts and the weather-dependent capacities derived from the capacity reductions presented in D6.1. Results are shown for a realistic scenario, corresponding to a day with strong convective activity			
D6.1	Forecast of sector complexity and airspace capacity reduction in multi-sector scenarios	18/11/2021	Public
This deliverable presents the work carried out regarding methodologies to forecast airspace sector complexity and capacity reduction. The objective of this research is twofold: first, to analyse sector complexity under convective weather (provision of probabilistic forecasts of complexity metrics); second, to develop a methodology to forecast the reduction of airspace capacity under convective weather, taking into account the spatial extent and topology of the weather hazard and the traffic flow direction. Thus, the document addresses two main technical activities: Forecast of sector capacity reduction and Sector complexity analysis. Results are shown for the same scenario used in D5.1.			
D7.1	Evaluation and assessment of proposed methodologies	20/05/2022	Public
This deliverable presents the assessment of the work carried out in the FMP-Met project. It has 2 main parts: 1) Assessment of the probabilistic methodologies developed for traffic analysis, namely, sector demand and traffic complexity, under adverse weather in multi-sector scenarios. This assessment is performed comparing the FMP-Met predictions with NAVSIM simulations taken as “reality”. 2) Validation of the operational concept developed in the project for tactical flow management under adverse weather. This validation is based on FMPs’ feedback (expert opinion) via questionnaires. Both the assessment and the validation are performed considering the same use case. The overall assessment is quite positive. Furthermore, the analysis of the results and the FMPs’ feedback has allowed to identify improvements for future development of the FMP-Met concept.			

2.6 Communication, Dissemination and Exploitation

Different communication and dissemination activities have been carried out:

- construction of the FMP-Met website [16],
- Twitter and Research Gate profiles,
- presentation of posters at SID'20 and SID'21,
- participation in the 3rd Engage TC3 Workshop organized by SESAR (09/09/21),
- participation in ICRAT 2022 conference (in June 2022), presenting a paper,
- preparation of a contribution to SESAR ER4 Projects Results Brochure (June 2022),
- preparation of a leaflet describing FMP-Met final results (July 2022), to be included in SESAR 3 JU E-news (September issue).

Moreover, to coordinate and find synergies with other projects, several FMP-Met members have participated in the following workshops:

- ER/IR MET&ENV Workshop organized by the SJU (1/10/2020),
- 2nd ISOBAR Project Workshop (20/09/21),
- two joint ER4 MET/ENV SESAR projects workshops, held on 19/01/22 and 06/07/22.

The following papers have been produced during the timeframe of the project:

Conference papers:

- paper presented at the International Conference on Research in Air Transportation (ICRAT) 2022, June 2022 [13].
- paper prepared for the SESAR Innovation Days Conference 2022 (to be submitted in September 2022) [14].

Journal papers:

- paper prepared for the Transportation Research Part C: Emerging Technologies journal (to be submitted in October) [15].

Finally, with respect to exploitation, the *Meteorological Interpolation Toolbox for Optimization and Simulation* (METINTOS) library has been developed. The METINTOS library is an open-source product that contains all the optical flow functionalities described in WP4, including the capabilities to interpolate the described weather products (and eventually others). It is a python-based library hosted on GitHub under the following directory:

https://github.com/javiergarciaheras/metintos.

3 Links to SESAR Programme

3.1 Contribution to the ATM Master Plan

For the maturity assessment of the FMP-Met concept, a new OI Step is proposed:

DCB-xx01: Use of probabilistic weather forecasts to enhance FMP processes.

The aim of this OI is to enhance the decision-making process for FMPs under adverse weather, by integrating meteorological forecast uncertainty information into their currently used procedures.

The contribution of FMP-Met to this OI is summarized in Table 2.

Table 2: Project Maturity

Code	Name	Project contribution	Maturity at project start	Maturity at project end
DCB-xx01	Use of probabilistic weather forecasts to enhance FMP processes	The project contribution is the definition of a concept to integrate MET forecast uncertainty information into the procedures currently used by FMPs. The core of the new features to be incorporated into FMP tools is a probabilistic methodology to forecast sector congestion and traffic complexity under adverse weather in a time horizon of 8 hours.	Pre-TRL 1	TRL 1

The potential use of the tool concept developed in FMP-Met shows a main contribution to the following SESAR goal:

Improvement of the overall ATM system efficiency. An enhanced (better-informed) FMP process under adverse weather can lead the Air Navigation Services Providers to a better identification of the ATFCM measures to be implemented, thus improving the traffic throughput, and reducing delays.

3.2 Maturity Assessment

In this section the Technology Readiness Level (TRL) of FMP-Met is assessed. At the start of the project the positioning was Pre-TRL 1. In our previous work we had carried out research showing this level of achievement, as described in the Appendix B of the Project Handbook of SESAR 2020 Exploratory Research [21]: "*Fundamental exploratory scientific research investigating relevant scientific subjects and conducting feasibility studies looking for potential application areas in ATM, concentrating both on out-reach to other disciplines as well as educating within.*" Indeed, the application area found was FMP decision-making process when subject to the effects of convective weather.

Our goal was to reach TRL 1 at the end of the project. To achieve this level and the corresponding maturity we needed [21] "*to explore the transition from scientific research to applied research by bringing together a wide range of stakeholders to investigate the essential characteristics and behaviours of applications, systems and architectures. Descriptive tools are mathematical formulations or algorithms.*" In FMP-Met we have worked closely with stakeholders (FMP experts from ACG and CCL) and have delivered a concept tool that could enhance FMP decision-making process under adverse weather, providing support to take anticipated, appropriate, and timely tactical flow measures.

The TRL assessment performed in this document follows the layout proposed for ER Fund / AO Research Maturity Assessment. All the corresponding maturity assessment criteria are evaluated in Table 3.

The level of satisfaction of all the maturity assessment criteria evaluated leads to the conclusion that the assessment is positive, and, therefore, we can claim that the goal of reaching TRL 1 at the end of the project has been achieved.

Table 3: ER Fund / AO Research Maturity Assessment

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	The ATM problem addressed in this project is the enhancement of the decision-making process for Flow Management Positions (FMP) under adverse weather, by integrating meteorological forecast uncertainty information in their currently used procedures. Because the time window of interest in this traffic flow management problem is 8 hours, the main challenge is the need to analyse an extended time horizon in which the levels of uncertainty are important and, therefore, a probabilistic approach is required.
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Achieved	In the concept assessment provided by FMP experts (see TRL-1.12), they have indicated that in some Area Control Centres (ACC) convective weather is one of major challenges in Operations, especially in summer when their capacities and also Network capacities are exhausted. “Adverse weather will always increase Air Traffic Flow and Capacity Management (ATFCM) delays, and Air Traffic Control Officer (ATCO) workload as well.” Moreover, they have identified some drawbacks of the current process: • Today, FMP’s and ACC Supervisors tasked with Configuration Management brief themselves of relevant meteorological conditions on various separate (from CIFLO - CHMI for Flow Management Positions) MET-briefing systems, and they must convert this information into impact on sector Monitoring Value (MV) and integrate it manually into the current Collaboration Human Machine Interface (CHMI). Risks here are many, from FMP officer not understanding the potential negative impact and causing an overload/overdelivery on sector to overregulating weather with very low intensity.

			• Today, FMP actions on weather are often reactionary and too-late, considered as the last-option but with the best intentions applied when most airborne flights are no longer subject to ATFCM measures but Air Traffic Control (ATC). • In different ACCs different methods are used by FMPs to ascertain the impact of predicted (forecasted) weather to sector capacities, and in turn to choosing the optimal configuration. As a quantitative indicator of the expected impact, taking into account that a large percentage of the en-route air traffic delays are attributed to weather (21.2% in 2019, 3.6 million minutes, according to Eurocontrol's Performance Review Report 2019 [19]), if the methodologies developed in this project help to reduce the weather-dependent delays just by 5%, and if we consider that 1 minute of delay costs the ATM network roughly 100€, then savings of 18M€ per year could be achieved for the European air traffic system.
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 following weaknesses have been identified for the FMP-Met concept: • Only one use case has been analysed; more cases would be required to build trust in the concept. • The analysis is very demanding computationally (hence, some simplifications have been made: sampling, clustering). The FMP-Met concept is bound by the following constraints: • The concept is valid for en-route and approach phases. • The applicability of the concept is constrained to geographical areas where nowcast and local area model weather products are available.

TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Achieved	The FMP-Met concept has been defined and thoroughly described, including the required graphical displays, in deliverable D2.1 [3], and the corresponding assessment in deliverable D7.1 [8]. The concept has been summarised in Section 1.2. The probabilistic methodologies developed to forecast traffic congestion and traffic complexity, including all the mathematical details, are described and tested in deliverables D5.1 [6] (probabilistic traffic demand and congestion) and D6.1 [7] (probabilistic traffic complexity). The 3 underlying technical enablers considered in this project are described in deliverables D3.1 [4] (probabilistic weather forecast), D4.1 [5] (probabilistic trajectory predictor) and D6.1 [7] (probabilistic weather-induced capacity reduction).
TRL-1.5	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM MP Level?	Achieved	The potential use of the tool concept developed in FMP-Met shows a main contribution to the following SESAR goal: • **Improvement of the overall ATM system efficiency.** An enhanced (better-informed) FMP process under adverse weather can lead the Air Navigation Services Providers to a better identification of the ATFCM measures to be implemented, thus improving the traffic throughput, and reducing delays. This contribution is in line with the description of the topic "Environment and Meteorology for ATM" (Sub Work Area 1.3) of the SESAR Single Programming Document 2019-2021 [17]: "Research activities will study … how enhanced meteorological capabilities and their integration into ATM planning processes can be utilised for improving ATM efficiency and safety. This requires understanding of the potential of different types of weather-related

			information that could be used in ATM operations taking into account the inherent uncertainty of meteorological information.”
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 new capabilities offered by the FMP-Met concept are that it integrates • weather information into the FMP tools, and • uncertainty information into the FMP decision-making process. This concept also facilitates the consideration of other sources of uncertainty in addition to the meteorological one, such as the uncertainty in the take-off time and the uncertainty linked to the storm avoidance strategy. The concept has been developed so that the new features can be technically implemented, in the form of a new tool layer, added to the layers currently in use.
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Achieved	The main assumptions used in the development of the FMP-Met concept are the following: • The ensemble approach to quantify uncertainty (based on scenarios) is the right approach to integrate uncertainty information into the FMP process (this is the base for the statistical analysis). • The interaction-based PRU (Performance Review Unit) methodology to quantify traffic complexity is the right approach to account for the adverse effects of weather on complexity, through the addition of a new indicator for the aircraft-storm interaction.
TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and disbenefits identified? - Qualitative assessment on potential	Achieved	The following strengths, benefits and limitations have been identified: Strengths: • The concept developed considers

	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.		○ an extended time horizon (8 hours), using different probabilistic weather forecast products (with different lead times and coverage areas), ○ several sources of uncertainty (weather, take-off time, storm cell avoidance), ○ multi-sector scenarios, ○ 4-D trajectories and 4-D storms (Cloud Top Height, non-static meteorology with forecasts evolving over time). • The overall methodology is very versatile, capable of using different implementations of the three underlying technical enablers. Potential benefits: • Improved (better-informed) decision-making process for FMP under adverse weather. • Possibility of conducting a what-if analysis, to have a preliminary evaluation of the impact of measures to be taken Limitations: • Accuracy/reliability of the supporting technical enablers in capturing the real uncertainty, in particular the following factors: ○ The inherent variability of the forecasts, which may overestimate or underestimate the presence of the storm. ○ The limitation of the high-resolution EPS, which does not provide convective areas to avoid, and, linked to this, the lack of lateral deviations in the long-term trajectory predictor.

			• The positive assessment of the FMP-Met concept is limited by the fact that only one use case has been analyzed, although the concept potential has been clearly identified.
TRL-1.9	Have Initial scientific observations been reported in technical reports (or journals/conference papers)?	Achieved	The following papers have been produced during the timeframe of the project: Conference papers [13,14]: • Eduardo Andrés, Javier García-Heras, Daniel González, Manuel Soler, Alfonso Valenzuela, Antonio Franco, Juan Nunez-Portillo, Damián Rivas, Tomislav Radišić and Petar Andraši, "Probabilistic Analysis of Air Traffic in Adverse Weather Scenarios", International Conference on Research in Air Transportation (ICRAT) 2022, June 2022, pp. 1-8. • Anastasia Lemetti, Tatiana Polishchuk, Valentin Polishchuk, Alfonso Valenzuela, Antonio Franco, Juan Nunez-Portillo and Damián Rivas, "Probabilistic Analysis of Airspace Capacity in Adverse Weather Scenarios", SESAR Innovation Days (SID) Conference 2022 (to be submitted in September). Journal papers [15]: • Alfonso Valenzuela, Antonio Franco, Juan Nunez-Portillo and Damián Rivas, "Probabilistic Analysis of Tactical Flow Management under Adverse Weather", Transportation Research Part C: Emerging Technologies (to be submitted in October).
TRL-1.10	Have the research hypothesis been formulated and documented?	Achieved	The following hypotheses have been formulated: • The FMP process under adverse weather can be improved. • Information about weather uncertainty can improve current FMP decision-making process. • New features can be integrated into the tools currently used by FMPs.

			These hypotheses frame the FMP-Met concept (as described in deliverable D2.1 [3]) and are the base for the concept validation performed via FMPs' feedback (as shown in deliverable D7.1 [8]).
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	The following actions have been identified as possible future developments to improve the accuracy of the predictions: • Post-processing of high-resolution EPS to determine convective areas to be avoided (that is, to define no-fly zones). • Enhancement of the trajectory predictors with the capability of performing holdings. • Enhancement of the long-term trajectory predictor with lateral deviations, to avoid no-fly zones. The following actions have been identified (by the experts consulted) as possible future developments to improve the tool performance: • Addition of a Map View functionality, to have a better perception of the weather status and evolution. • Addition of What-If functionality, to evaluate before adopting a measure its possible impact.
TRL-1.12	Are stakeholders interested about the technology (customer, funding source, etc.)?	Achieved	The FMP-Met concept has been assessed positively by FMPs from ACG and CCL, by means of a validation exercise. This validation was based on FMPs' feedback (expert opinion) via questionnaires. The FMPs recognized that the FMP process under adverse weather can be operationally improved and that the FMP-Met concept developed in this project is a good first step, which deserves to be explored further. The experts consulted were comfortable using the graphical displays selected for the tool concept

			developed. They also suggested improvements for future development (see TRL-1.11).

4 Conclusion and Lessons Learned

4.1 Conclusions

The **overall conclusion** of this Exploratory Research project is that the concept proposed to enhance FMP decision-making process under adverse weather has potential and deserves to be explored further. Indeed, the FMPs' feedback is quite positive. They have recognized that the FMP process under adverse weather can be operationally improved and that the FMP-Met concept developed in this project is a good first step. Nonetheless, they have pointed out that it is difficult to make a solid assessment from the analysis of only one use case; hence, to build trust in the system more scenarios need to be evaluated. They have also suggested improvements for future development, see Section 4.3.

The **novelty** of the FMP-Met concept is that it integrates weather information into the FMP tools and uncertainty information into the FMP decision-making process under adverse weather, with a lead time of 8 hours. This concept also facilitates the consideration of other sources of uncertainty in addition to the meteorological one, such as the uncertainty in the take-off time and the uncertainty linked to the storm avoidance strategy.

The project results show that the **specific objectives** have been achieved:

1. Tailor multi-scale, multi-source convective weather information for FMP application: done in WPs 3 and 4.
2. Predict probabilistic aircraft trajectories using multi-scale convective weather information: done in WP 4.
3. Translate convective weather forecasts into predictions of reduced airspace capacity: done in WP 6.
4. Forecast multi-sector demand and complexity under convective weather: done in WPs 5 (demand) and 6 (complexity).
5. Produce guidelines for the use of probabilistic forecasts for FMP application: done in WPs 2 and 7.

The main **outcome** of the project is the development of a probabilistic methodology to forecast sector congestion and traffic complexity to be used in conjunction with the tools currently employed by FMPs. This methodology has led to the definition of a tool concept that could easily incorporate the new features, in the form of a new tool layer added to the layers currently in use.

The **potential benefits** that one could expect from the implementation of the FMP-Met concept are the following:

- Support to take anticipated, appropriate, and timely tactical flow measures under adverse weather (better-informed decision-making process for FMPs).
- Possibility of conducting a what-if analysis, to have a preliminary evaluation of the impact of measures to be taken, in terms of cost and effectiveness.
- Enhancement of ATM efficiency, which will ultimately reduce flight delays and improve passenger journeys.

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4.2 Technical Lessons Learned

The following technical lessons have been learned:

- The **ensemble approach** used to quantify uncertainty (based on scenarios) has proven to be an appropriate approach to integrate uncertainty information into the FMP process. However, the analysis for an extended horizon of 8 hours has required the use of three probabilistic MET products (each one defined by an ensemble) and two other sources of uncertainty (each one also defined by their respective ensembles). Hence, the number of possible scenarios to be considered in the statistical analysis grows exponentially, leading to extremely large computational costs.
- The capacity simulations have shown some discontinuities at the switching from nowcast to EPS forecast. It is clear that a **seamless weather product** with an outlook horizon of several hours (8 hours in our case) would lead to smoother predictions. We believe that further investigations are needed in order to develop such a high-quality weather product and use it for probabilistic capacity estimations. We identify the development of such a probabilistic seamless product as a topic for future MET research.
- Another problem found when making traffic predictions with a lead time of 8 hours is the difficulty in forecasting the storm avoidance (based on EPS weather products), which clearly affects the traffic flows. Although 8 hours is the time horizon of interest for FMPs, FMP experts have indicated that, for the adoption of ATCFM measures, the first 3-4 hours are more relevant. Therefore, efforts should be also directed towards the development of an accurate **nowcast product** with an outlook horizon of 3-4 hours, capable of identifying, within some uncertainty margin, convective cells to be avoided.

4.3 Plan for next R&D phase (Next steps)

The main step for the next R&D phase is the development of a **prototype tool,** in close collaboration with FMPs, implementing the FMP-Met concept. The goal will be to perform realistic simulations and to analyse operational feasibility, including computational efficiency.

In this future development the following suggestions to improve the tool made by the experts consulted should be taken into account:

- addition of a Map View functionality, to have a better perception of the weather status and evolution, and
- addition of the What-If functionality, to evaluate beforehand the possible impact of measures to be taken.

Likewise, the following actions required to improve the accuracy of the predictions should be considered (as identified in the assessment made using NAVSIM simulated reality):

- post-processing of high-resolution EPS to determine areas to avoid (no-fly zones),
- enhancement of the trajectory predictors with the capability of performing holdings,
- enhancement of the long-term trajectory predictor with lateral deviations, and
- enhancement of the overall ensemble approach to reduce the computational cost.

At this stage, the assessments or validations should consider comparisons with real traffic. To that end, with the involvement of ANSPs and/or Eurocontrol, access to the following information will be required:

- All the information needed to perform the predictions:
    - the last available weather forecasts (nowcast, limited-area EPS and global EPS),
    - the last position of the aircraft from the surveillance systems,
    - the last flight plan of all airborne aircraft (including the last ATC authorisations and instructions) and on-ground aircraft (including the last estimated or calculated take-off time), and
    - the current and scheduled airspace configuration.
- All the information related to the real development of the storm and air traffic for the next 8 hours:
    - atmospheric development according to weather radar,
    - aircraft positions obtained from the surveillance systems,
    - implemented ATFCM measures, and
    - actual airspace configuration and monitoring values.

Finally, following the experts' suggestion, the possibility of using Artificial Intelligence techniques must also be investigated, specifically addressing how these techniques could be incorporated into the ensemble approach that lies at the foundation of the FMP-Met concept.

5 References

5.1 Project Deliverables

[1] "FMP-Met Deliverable 1.1, FMP-Met Project Management Plan," Edition 00.02.01, July 2021.

[2] "FMP-Met Deliverable 1.3, TRL Assessment Report," Edition 00.01.00, June 2022

[3] "FMP-Met Deliverable 2.1, Concept of Operations for Weather-Dependent Probabilistic Flow Management," Edition 00.02.00, December 2020.

[4] "FMP-Met Deliverable 3.1, Nowcast and EPS Forecast Products," Edition 00.02.00, December 2020.

[5] "FMP-Met Deliverable 4.1, Trajectory prediction under adverse weather scenarios," Edition 00.01.00, May 2020.

[6] "FMP-Met Deliverable 5.1, Forecast of sector demand in multi-sector scenarios," Edition 00.01.00, November 2021.

[7] "FMP-Met Deliverable 6.1, Forecast of sector complexity and airspace capacity reduction in multi-sector scenarios," Edition 00.01.00, November 2021.

[8] "FMP-Met Deliverable 7.1, Evaluation and assessment of proposed methodologies," Edition 00.01.00, May 2022.

[9] "FMP-Met Deliverable 8.1, Dissemination plan," Edition 00.02.00, August 2020.

[10] "FMP-Met Deliverable 8.2, Communication plan," Edition 00.02.00, September 2020.

[11] "FMP-Met Deliverable 8.3, Exploitation plan," Edition 00.01.00, November 2020.

[12] "FMP-Met Deliverable 8.4, Data management plan," Edition 00.03.00, May 2022.

5.2 Project Publications

[13] Eduardo Andrés, Javier García-Heras, Daniel González, Manuel Soler, Alfonso Valenzuela, Antonio Franco, Juan Manuel Núñez, Damián Rivas, Tomislav Radišić and Petar Andraši "Probabilistic Analysis of Air Traffic in Adverse Weather Scenarios", International Conference on Research in Air Transportation (ICRAT) 2022, June 2022, pp. 1-8.

[14] Anastasia Lemetti, Tatiana Polishchuk, Valentin Polishchuk, Alfonso Valenzuela, Antonio Franco, Juan Manuel Núñez and Damián Rivas "Probabilistic Analysis of Airspace Capacity in Adverse Weather Scenarios", SESAR Innovation Days (SID) Conference 2022 (to be submitted in September).

[15] Alfonso Valenzuela, Antonio Franco, Juan Manuel Núñez and Damián Rivas, "Probabilistic Analysis of Tactical Flow Management under Adverse Weather", Transportation Research Part C: Emerging Technologies (to be submitted in October).

[16] Project website https://fmp-met.com

5.3 Other

[17] SESAR Single Programming Document 2019-2021 (SPD), 2019.

[18] Grant Agreement number: 885919 — FMPMet — H2020-SESAR-2019-2, 2020.

[19] Eurocontrol, Performance Review Report 2019, Performance Review Commission, 2019.

[20] Eurocontrol, Complexity Metrics for ANSP Benchmarking Analysis, Brussels, 2006.

[21] Project Handbook of SESAR 2020 Exploratory Research Call H2020-SESAR-2019-2 (ER4) (Programme Execution Guidance), Edition 03.00.00, March 2019.

Appendix A

For completeness, the use case considered in the project is described in this appendix.

A.1 Use case

To carry out the assessment of the methodologies and the validation of the FMP-Met concept, a use case developed within the Austrian airspace for June 12th, 2018, has been considered. This case corresponds to a day with high convection intensity. The prediction is performed **at 12:00 for the next 8 hours.** Figure 8 displays a snapshot of the actual thunderstorm situation at 12:30 (provided by on-ground weather radar). The scenario, in terms of airspace, weather and air traffic, is described in the following sections.

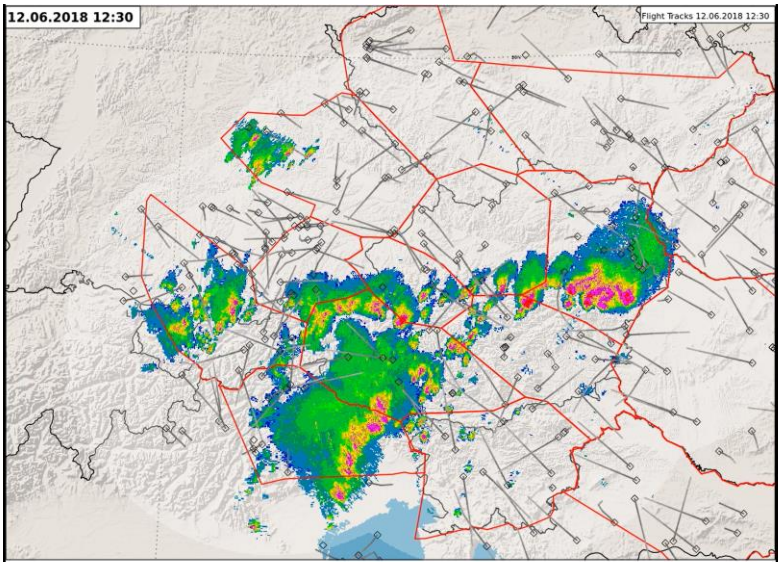

Figure 8: Thunderstorm on 12/06/2018.

Airspace

For AIRAC cycle 1806, the Austrian airspace under the control of the Wien Area Control Centre (ACC WIEN) is shown in Figure 9. It is divided into five geographical regions (B, E, N, S and W), and each region into five vertical layers:

- ACC WIEN B: B1, B2, B3, B4, and B5.
- ACC WIEN E: E1, E2, E3, E4, and E5.
- ACC WIEN N: N1, N2, N3, N4, and N5.
- ACC WIEN S: S1, S2, S3, S4, and S5.
- ACC WIEN W: W1, W2, W3, W4, and W5.

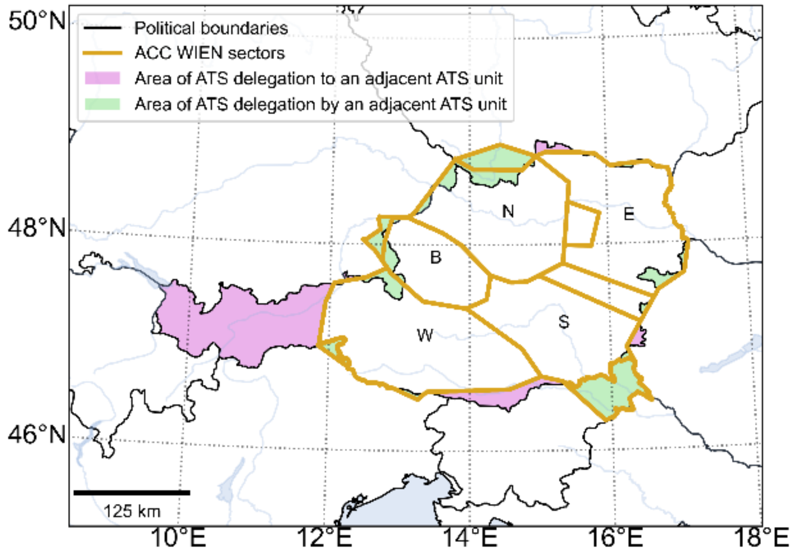

Figure 9: Geographical description of the Austrian airspace.

In total, 38 elementary volumes are used to define this airspace, which lead to near 60 possible different ATC sectors and 190 different sector configurations. For example, sector configuration 10A1 (the one initially scheduled at the prediction time) consists of ten ATC sectors: B15, E13, E45, N12, N35, S12, S35, W12, W3 and W45, which are formed as follows:

- B15, by all the elementary volumes from ACC WIEN B.
- N12, by the elementary volumes from N1 and N2.
- N35, by the elementary volumes from N3, N4 and N5.
- E13, by the elementary volumes from E1, E2 and E3.
- E45, by the elementary volumes from E4 and E5.
- S12, by the elementary volumes from S1 and S2.
- S35, by the elementary volumes from S3, S4 and S5.
- W12, by the elementary volumes from W1 and W2.
- W3, by the elementary volumes from W3.
- W45, by the elementary volumes from W4 and W5.

Weather forecasts

The three probabilistic weather forecasts considered in this use case, one ensemble nowcast and two EPS, are described next.

Ensemble Nowcast

Generated by AEMET, as described in D3.1 [4]. We consider the last available nowcast at the moment of the prediction; in this use case, the one generated at 11:45. It has been interpolated every 5 minutes and processed to identify the convective cells (at 38 dBz) and enlarged with a safety margin (13.5 NM). A common cloud top height for all the nowcast coverage area has been also provided: the flights can overfly them with a margin of 5000 ft. The number of members is 15, and they are statistically independent among them.

An example, corresponding to a prediction for 12:30, generated at 11:45, is depicted in Figure 10. The storm cells, already enlarged with a safety margin of 13.5 NM, are represented in red. The transparency in a particular location is related to the number of members that predict a storm cell to be in that very location (less transparent, more members).

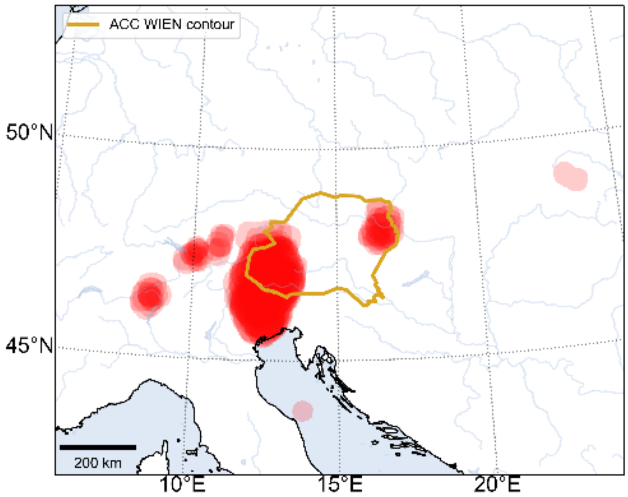

Figure 10. Nowcast generated at 11:45, prediction for 12:30.

ECMWF-EPS

Global EPS from the European Centre for Medium-Range Weather Forecasts (ECMWF). Downloaded by AEMET. The number of members is 50, and they are statistically independent among them. Convective areas are identified using two indicators: when the Total Totals is above 44 K, and the Convective Precipitation is above 0.

In this use case, the last available ECMWF-EPS is the one generated at 00:00. It has been interpolated every 15 minutes and processed to identify the convective areas (see D4.1 [5]).

COSMO-D2-EPS

Limited-area, high-resolution EPS. Purchased from the Fraunhofer Institute for Energy Economics and Energy System Technology (IEE). The number of members is 20, and they are statistically independent among them. Convective areas are identified using two indicators: when the Precipitation Intensity is above 5 mm/hour and when the Lifted Index is less than -4.

Also, a transition zone with unrealistic gradients has been identified in the contour of COSMO-D2-EPS coverage area, resulting from its boundary conditions during its generation. As a result, the outer 25 grid points on each side (about 50 km) have been discarded, being the coverage area of COSMO slightly downsized.

In this use case, the last available COSMO-D2-EPS is the one generated at 09:00. It has been interpolated every 15 minutes and processed to identify the convective areas (again, see D4.1 [5]).

Air Traffic

The historical traffic data has been retrieved from Eurocontrol's R&D Data Archive[3]. This application has been simplified by not considering the actual data, but the filed data: the positions of airborne aircraft at 12:00, the nominal take-off times, and the nominal routes to be followed are the ones given in their flight plans.

The traffic considered in the application consists of aircraft airborne at 12:00 or expected to take-off in the next 8 hours (including the uncertainty in the take-off time) which plan to cross the Austrian airspace plus a surrounding area of 50 NM. In this way, it is contemplated the possibility that some aircraft, flying close to the airspace of interest may be deviated into it because of the convective weather.

A total number of 2542 flights are considered in this application: 393 flights are airborne at 12:00, and 2149 flights are expected to depart in the next 8 hours. Their planned routes are shown in Figure 11.

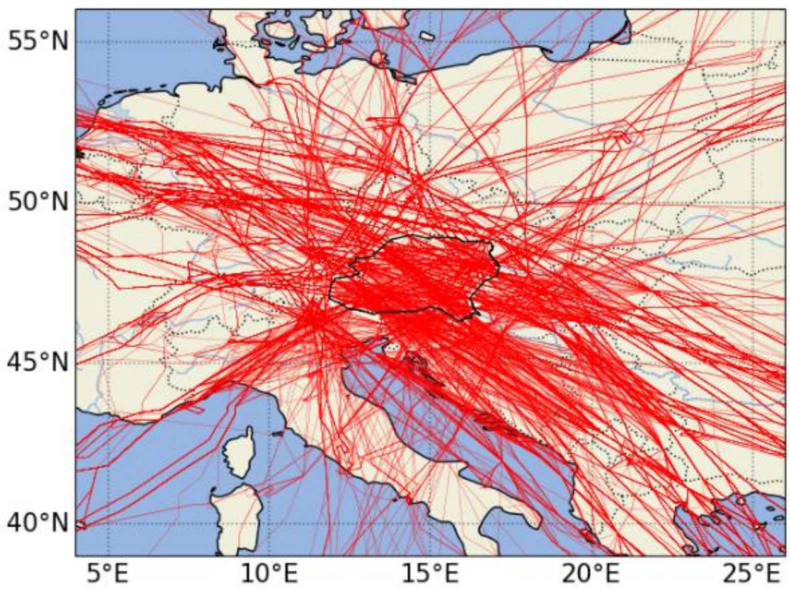

Figure 11: Planned routes of the flights considered in the application.

[3] https://www.eurocontrol.int/dashboard/rnd-data-archive

Appendix B

B.1 Acronyms and Terminology

Table 4: Acronyms and terminology

Term	Definition
ACC	Area Control Centre
ANSP	Air Navigation Services Provider
ASCR	Available Sector Capacity Ratio
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATFCM	Air Traffic Flow and Capacity Management
ATM	Air Traffic Management
CHMI	Collaboration Human Machine Interface
CIFLO	CHMI for Flow Management Positions
DCB	Demand-Capacity Balance
ECMWF	European Centre for Medium-Range Weather Forecasts
EPS	Ensemble Prediction System
FMP	Flow Management Position
MET	Meteorology
MV	Monitoring Value
OI	Operational Improvement
OTMV	Occupancy Traffic Monitoring Value
PRU	Performance Review Unit
ROL	Relative Overload
SESAR	Single European Sky ATM Research Programme
S3JU	SESAR3 Joint Undertaking (Agency of the European Commission)
TF	Traffic Forecast

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TP	Trajectory Predictor
TRL	Technology Readiness Level
TV	Traffic Volume
WP	Work Package
Wx_cap	Weather-dependent capacity

B.2 FMP-Met Consortium

Table 5: FMP-Met Consortium

Acronym	Definition
USE	Universidad de Sevilla
AEMET	Agencia Estatal de Meteorología
ACG	Austro Control GmbH
CCL	Croatia Control Limited
LiU	Linköping University
MetSol	MeteoSolutions GmbH
PLUS	Paris-Lodron Universität Salzburg
UC3M	Universidad Carlos III de Madrid
ZFOT	University of Zagreb