EXPLORATORY RESEARCH

SESAR JOINT UNDERTAKING

Evaluation and assessment of proposed methodologies

Deliverable ID:	D7.1
Dissemination Level:	PU
Project Acronym:	FMP-Met
Grant:	885919
Call:	H2020-SESAR-2019-2
Topic:	SESAR-ER4-05-2019 - Environment and Meteorology for ATM
Consortium Coordinator:	USE
Edition Date:	29/06/2022
Edition:	00.02.00
Template Edition:	02.00.05

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Authoring & Approval

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Rejected By - Representatives of beneficiaries involved in the project

Name and/or Beneficiary	Position / Title	Date

Document History

Edition	Date	Status	Name / Beneficiary	Justification
00.00.01	10/05/2022	Initial draft	USE, PLUS, ZFOT	New document
00.01.00	20/05/2022	First issue	USE, PLUS, ZFOT	Updated document

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00.02.00	29/06/2022	Second issue	USE	Reviewed document following SJU assessment report

Copyright Statement

FMP-Met

METEOROLOGICAL UNCERTAINTY MANAGEMENT FOR FLOW MANAGEMENT POSITIONS

This deliverable is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 885919 under European Union's Horizon 2020 research and innovation programme.

Abstract

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 FMP-Met 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, 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 has allowed to identify improvements for future development of the FMP-Met concept.

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1 Introduction[1]

1.1 The FMP-Met project

The **framework** for the FMP-Met project (Meteorological Uncertainty Management for Flow Management Positions) is the integration of meteorological (MET) forecast information into the decision-making process for Flow Management Positions (FMP) under adverse weather. Thus, FMP-Met deals with the provision of probabilistic forecasts of sector demand, sector complexity, and sector capacity reduction under convective weather for a forecasting horizon of 8 hours. Given the forecast lead time of 8 hours, the focus of the project is on the tactical flow management phase.

The **overall objective** is to provide the FMP with an intuitive and interpretable probabilistic assessment of the impact of convective weather on the traffic, up to 8 hours in advance, to allow better-informed decision making. To this end, a methodology to generate probabilistic predictions of demand-capacity balance to be used in conjunction with the tools currently used by FMPs has been developed.

The **potential impact** of this project, from the point of view of the overall efficiency of the Air Traffic Management (ATM) system, will be the improvement of the decision-making process in traffic flow management under convective weather. Indeed, the provision of an enhanced forecast of the future sector demand and complexity and of a reliable estimation of the impact of the convective weather on the sector capacity will support the FMP in taking anticipated, appropriate, and timely tactical flow measures, which consequently will lead to a reduction of delays.

1.2 The FMP-Met concept

The FMP-Met concept addresses the problem of how probabilistic forecasts of traffic and acceptable 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 (see D2.1 [1]).

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 (TMA) traffic, for a time horizon of 8 hours (tactical phase).

[1] The opinions expressed herein reflect the author's view only. Under no circumstances shall the SESAR3 Joint Undertaking be responsible for any use that may be made of the information contained herein.

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.

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

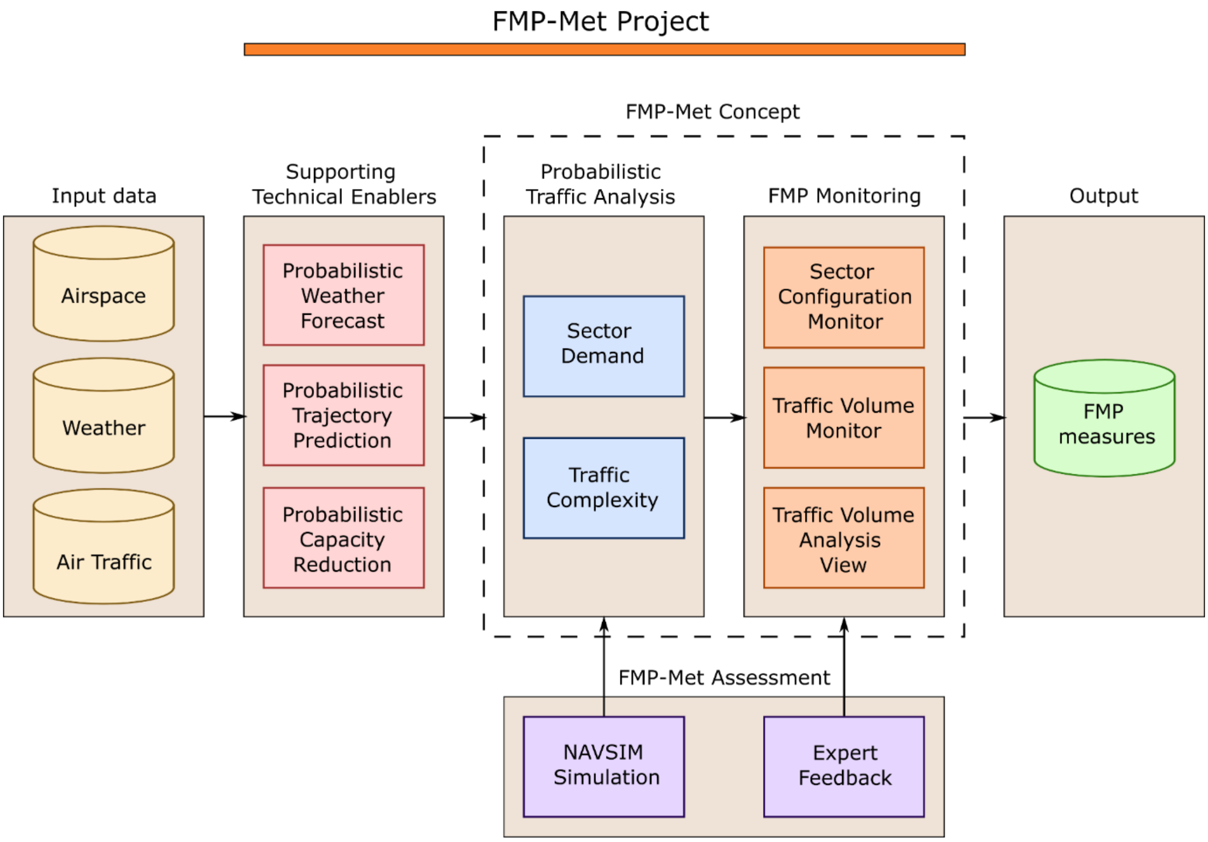

Figure 1. Structure of FMP-Met project

The FMP-Met concept relies on the availability of the following three **supporting technical enablers**:

- Probabilistic weather forecasts. In this project, MET uncertainty is quantified by a probabilistic prediction technique called Ensemble Weather Forecasting (EWF). Three types of forecasts are considered: ensemble nowcasts, and limited-area and global Ensemble Prediction Systems (EPS).
- A probabilistic trajectory predictor, providing 4D trajectories with a measure of uncertainty. The trajectory predictor developed in the project is capable of avoiding the storm cells and 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.
- 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.

Two probabilistic methodologies have been developed for traffic analysis under adverse weather: sector demand and traffic complexity (see D5.1 [2] and D6.1 [3], respectively), on which the tool concept for FMP monitoring is based. This tool is composed of 3 layers: Sector Configuration Monitor, Traffic Volume Monitor and Traffic Volume Analysis View.

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.

The assessment of the methodologies developed and of the concept as a whole has been the subject of WP 7, and it is reported in this deliverable.

1.3 Deliverable scope

This document presents the assessment of the work carried out in the FMP-Met project. It has 2 main parts (see the block diagram in Figure 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”, as described in Section 3.

- 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 described in Section 4.

The use case considered in both cases is the same (corresponding to a scenario with strong convective activity), and it is described in Section 2. Finally, in Section 5 some conclusions are drawn and improvements for future development are identified.

1.4 Acronyms and Terminology

Acronym	Description
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

BADA	Base of Aircraft Data
CB	Cumulonimbus
CDM	Collaborative Decision Making
CIFLO	Collaboration Human Machine Interface for Flow Management Positions
CNS	Communication, Navigation and Surveillance
CPDLC	Controller Pilot Data Link Communications
CPR	Correlated Position Report
CTH	Cloud Top Height
DCB	Demand-Capacity Balance
ECAC	European Civil Aviation Conference
ECMWF	European Centre for Medium-Range Weather Forecasts
EPS	Ensemble Prediction System
ERA5	ECMWF Reanalysis v5
ESA	European Space Agency
EWF	Ensemble Weather Forecasting
FIR	Flight Information Region
FMP	Flow Management Position
FMPO	Flow Management Position Officer
FPL	Flight Plan
MAE	Mean Absolute Error
MET	Meteorological
MV	Monitoring Value
OTMV	Occupancy Traffic Monitoring Value
PRU	Performance Review Unit
ROL	Relative Overload
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure Route
STAM	Short-Term ATFCM Measure
STAR	Standard Arrival Route
SWIM	Initial system-wide information management technology solution
TF	Traffic Forecast
TMA	Terminal Control Area
TP	Trajectory Predictor
TV	Traffic Volume
UAV	Unmanned Aerial Vehicle

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UAS	Unmanned Aerial System
UTC	Coordinated Universal Time
WP	Work Package

1.5 FMP-Met Consortium

Acronym	Description
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

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2 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 2 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.

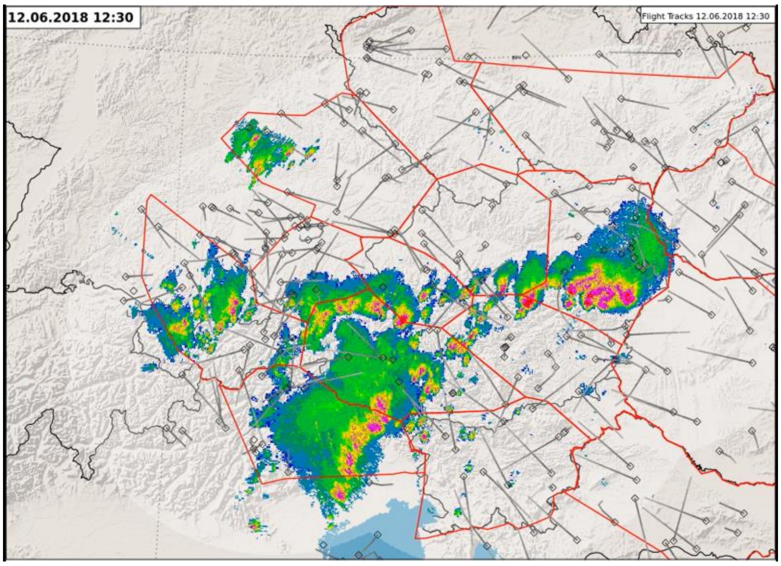

Figure 2: Thunderstorm on 12/06/2018

2.1 Airspace

For AIRAC cycle 1806, the Austrian airspace under the control of the Wien Area Control Centre (ACC WIEN) is shown in Figure 3. 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.

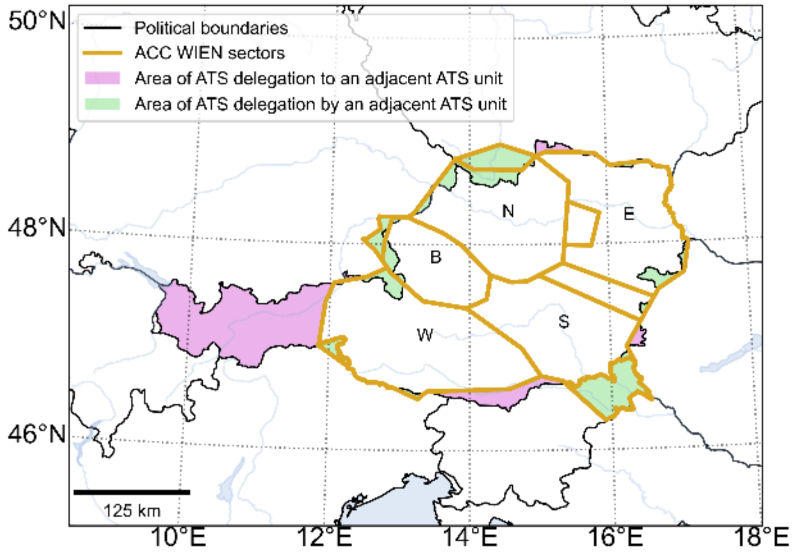

Figure 3: Geographical description of the Austrian airspace

In total, 38 elementary volumes are used to define this airspace, which lead to near 60 possible different Air Traffic Control (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.

2.2 Weather

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 nmi). 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 4. The storm cells, already enlarged with a safety margin of 13.5 nmi, 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).

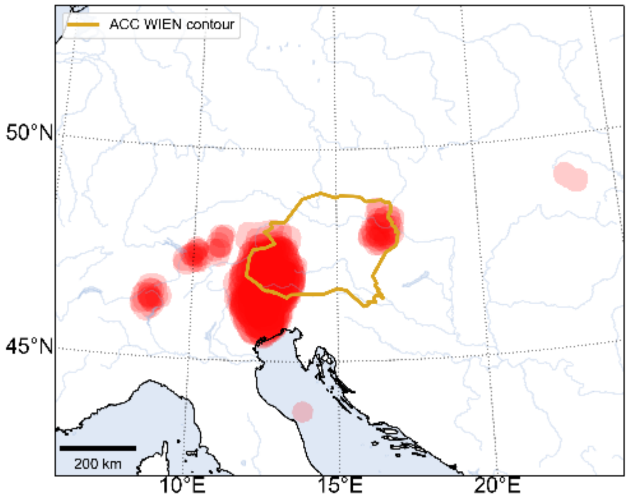

Figure 4. Nowcast generated at 11:45, prediction for 12:30.

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 Lifted Index is less than -4, and the Precipitation Intensity is above 5 mm/hour.

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]).

2.3 Air traffic

The historical traffic data has been retrieved from Eurocontrol's R&D Data Archive[2]. 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 nmi. 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 5.

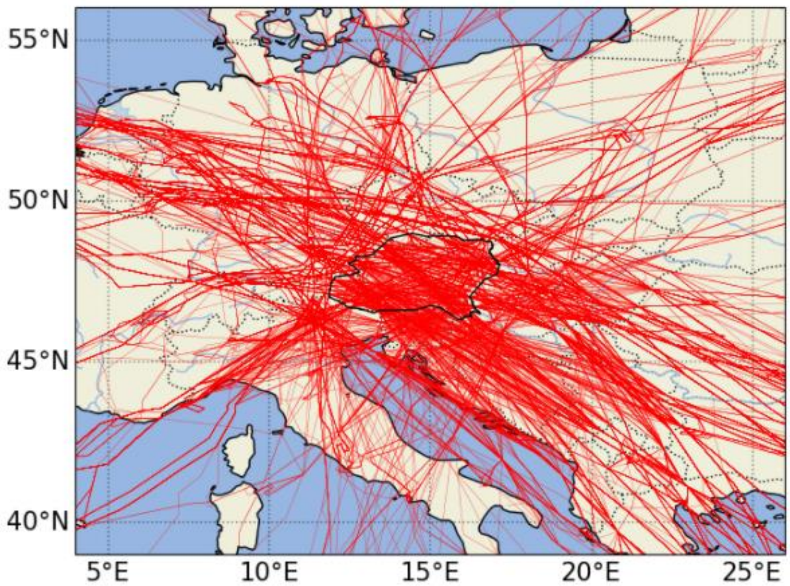

Figure 5. Planned routes of the flights considered in the application.

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

3 Assessment of methodologies

The main objective of this assessment is to answer the following question: **Is the reality well captured by FMP-Met predictions?** To answer this question, the FMP-Met consortium decided not to compare the FMP-Met predictions with recorded 4D flight tracks (e.g. CPR data) but with deterministic computations performed with a synthetic reality. This approach allows one to eliminate the potential impact of all non-weather-related events (e.g., direct routing between FIR boundaries, etc.) on the studied flight trajectories and to focus mainly on weather dependent limitations. Specifically, this synthetic reality is obtained from actual weather observations and traffic simulations performed with NAVSIM; see Figure 6.

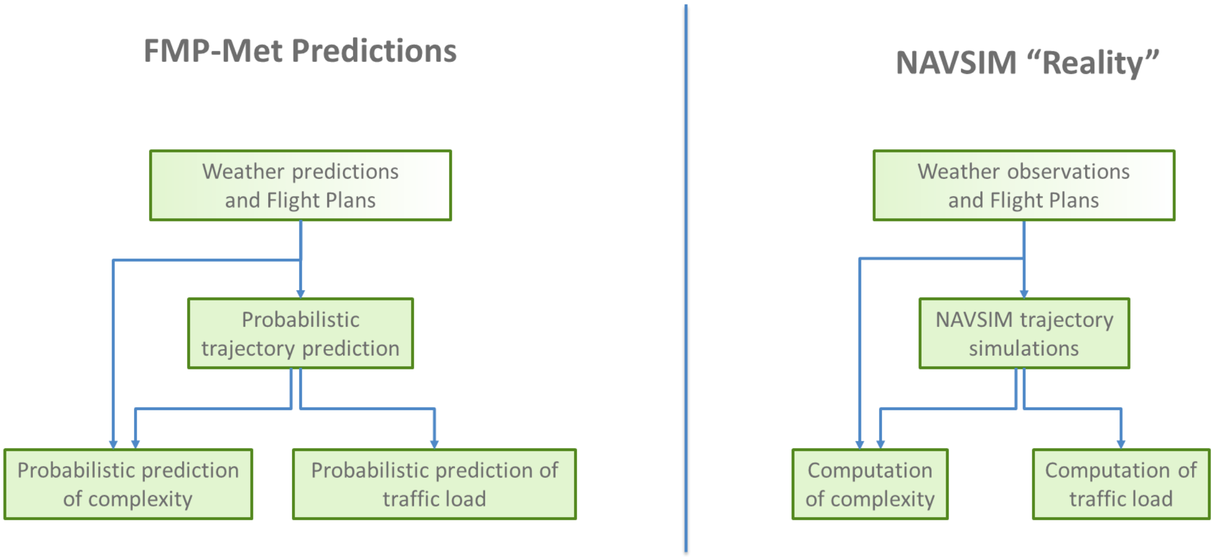

Figure 6. Overview of the assessment of methodologies.

The comparison between predictions and reality is presented in the following forms, which allow to assess the accuracy of the predictions in different ways:

- Superimposed graphical representations of prediction and reality, which allow for visual and comprehensible comparisons.
- The absolute error between the reality and the forecast median, which allows for evaluating the distance between the center of the prediction and the reality. The smaller, the better.

Notice that the expectation for the predictions is not to perfectly match the NAVSIM reality, since NAVSIM is a simulator and not the reality itself. Therefore, this section is more oriented toward determining if the results are reasonably accurate and, especially, toward identifying potential areas for further refinements.

The NAVSIM simulations are described next in Section 3.1, and the demand and complexity results in Section 3.2.

3.1 NAVSIM simulation

3.1.1 Introduction

NAVSIM is an ATM/ATC/CNS simulation framework and is used to simulate European and world-wide air traffic, based on specific reference days in the past (around 36.000 flights within 24 hours for Europe and 110.000 flights worldwide). It can be used as real-time and fast-time simulator, depending on the focus of the simulation project. NAVSIM allows accurate runway-to-runway and/or gate-to-gate simulation by integrating various sources of data like real air traffic traces extracted from Eurocontrol/ Network Manager data, worldwide flight scheduled data, or flight plan data. Thereby, NAVSIM is using worldwide navigation data and considers aircraft performances, Departure (SID), Enroute (i.e., airway system, Great Circle, or 4D-trajectory), Arrival (STAR), Approach and Final Approach.

NAVSIM enables the evaluation of future digital aeronautical communications, SESAR 4D-trajectory concepts, weather impact on ATM/ATC, wind-optimized routing, ATM performance, advanced Flexible Use of Airspace (aFUA), UAV/ UAS in non-segregated airspace, aircraft noise modelling, remote tower simulation, advanced airport operations and CDM/SWIM concepts, and future air traffic controller training featuring both voice and CPDLC communications. NAVSIM has been used and further developed in numerous national and international projects for human in-the-loop and system performance evaluations funded by Eurocontrol, EU's research and innovation funding programmes (FP6, FP7, H2020), European Space Agency (ESA), SESAR, Austrian Research Promotion Agency (FFG), Aviation Industry, etc. [6]-[13]. In recent years, NAVSIM has been applied for capacity and functionality assessment of current and future aeronautical communication systems and new ATM/ATC concepts in many European and national research projects. Especially in the context of the MET4LOWW project (2015-2018, [14]) –with Austro Control GmbH as consortium leader– NAVSIM has been adapted for simulation of air traffic scenarios with advanced arrival management and 4D trajectory optimization in TMA area under adverse weather situations (thunderstorms / Cb-cells, low visibility, strong wind, runway closures, etc., see [15]). Validation results within the MET4LOWW-project confirmed that NAVSIM shows very good agreement between simulation and actual flight tracks and ATCOs certified widely realistic behaviour of the simulator [8].

In WP7 NAVSIM has been used by PLUS to realistically simulate relevant air traffic with adverse weather situations considering the scenario described in Section 2. As a result of these simulations, the accuracy of the forecasts of demand and complexity under convective weather are evaluated.

3.1.2 NAVSIM simulations tasks & methodology

Simulation objectives & conditions to be met

The following main tasks have been defined to be carried out by NAVSIM based on a reference scenario with adverse weather situation (thunderstorms / Cb-cells) affecting the Austria Air Space and surrounding Flight Information Regions (FIRs) and available updated flight plan (FPL) data provided by Eurocontrol:

- Simulation / calculation of the 4D trajectory of all relevant flights in a "realistic" way:
  - being either already airborne at the beginning of the reference time period, or
  - take off during reference time period from a runway of the departure aerodrome until landing on a runway of the destination aerodrome or until end of reference time.

- Storing the resulting 4D trajectory as calculated by NAVSIM in electronically readable format to be further processed.

Relevant simulation input data & NAVSIM processing

The main input data provided to PLUS for the "realistic" flight simulation by NAVSIM for the simulation run were:

(i) Eurocontrol flight trajectories based on FPL updates.

(ii) Observation / nowcast data (5 minutes updates – 90 minutes ahead - every 15 minutes) with:

   a. AnalysisTime: "2018-06-12 12:00:00".

   b. Forecast: "0" (i.e., observation data, no forecast).

   c. Validity: "300" (time period during which data is valid: 300 seconds = 5 minutes).

   d. Polygon coordinates: list of latitude/longitude values describing the CB-polygon.

   e. The 95th percentile (CTH95p) of the Cloud Top Height (CTH) value (e.g. 10000 in meter).

(iii) ERA5 Grib data from ECMWF: hourly basis, 30 km grid, laterally divided into 16 sub-areas per 1 by 1 latitude/longitude degree field, and vertically divided into 37 different pressure value ranges, corresponding to 37 different altitude ranges:

   a. For the "realistic" simulation of flights by NAVSIM, the range of pressure levels from 1000 hPa down to 150 hPa was used. This corresponds to an altitude range from 364 feet up to 44302 feet (around flight level FL440) in a total of 25 (different) altitude ranges

All polygons in JSON format, were converted into convex polygons by NAVSIM. Consequently, weather deviation routing in NAVSIM is based on these convex polygons.

For a good optical discrimination between the weather observation / nowcast situation at different time periods, CBs are displayed in different colors: NAVSIM displays all polygons belonging to the same time slot in the same color; total of 12 different colors within 1 hour (see Figure 7).

Based on the actual True Air Speed in knots as available from the BADA performance data, the geographic position of the aircraft (latitude, longitude), the current altitude in feet, the current True Course and the current hour, the corresponding Ground Speed is calculated and applied to the overall calculation of the 4D flight trajectory for each flight.

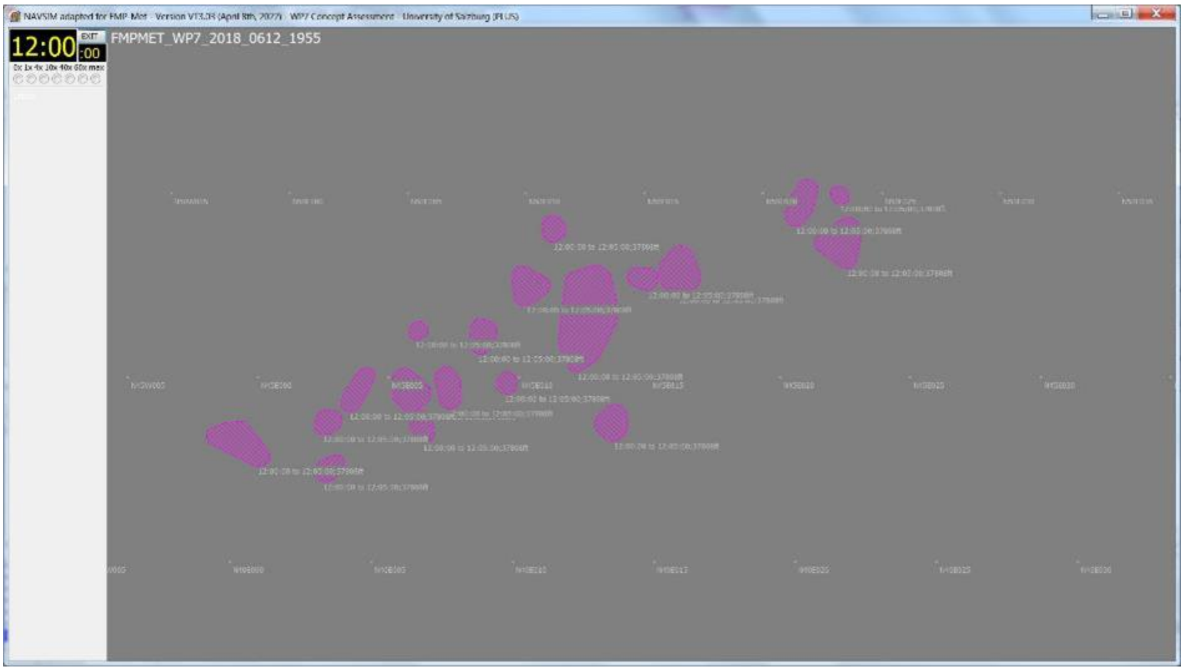

Figure 7: Converted JSON polygons within NAVSIM framework, color-coded 5 minutes timesteps.

Cb avoid modelling concept

In order to generate "realistic" 4D flight trajectory routes especially with regard to adverse weather situations as studied in the context of the FMP-Met project, an enhanced version of NAVSIM with the CbAvoid algorithm has been used. Based on the initial FPL reference trajectory (and its extension with additional intermediate waypoints), available Observation, Nowcast data and wind information contained in ECMWF/ERA5 data base, results were processed.

The developed NAVSIM CbAvoid modelling concept is based on the following functionalities and computation steps:

(1) Estimate "time over waypoint" for all original (and inserted waypoints) in initial FPL route.

(2) Check if any CB conflicts can be expected and indicate at what time and in which area.

(3) Simulate the entire flight from the initial aircraft position (airborne or take-off position) until landing on the destination runway, stepwise and

(4) Assuming a "pilot look ahead" behaviour of around 10 to 15 minutes (= 2 to 3 Nowcast update time slots), check at specified waypoints (original or intermediate) whether potential CB conflicts exist, taking into account current and expected altitude / Flight Level (FL) in "look-ahead" distance and Cloud Top Height (CTHp95) of all CBs ahead.

(5) If potential CB conflicts exist, for the weather deviation route segment ahead:

a. Identify a suitable waypoint ahead where the weather deviation route will start ("fix_pos_start") and a suitable waypoint ahead where the weather deviation route should end ("fix_pos_end"). Both the "fix_pos_start" and the "fix_pos_end" waypoints should be "clear of CB" during the entire time period until these waypoints will be reached / overflown.

b. Decide whether to perform a "left" turn or a "right" turn to avoid the CB conflicts ahead.

c. Based on current and upcoming valid Observation and Nowcast data, calculate an optimized weather deviation route which avoids the potential CB conflicts within the "look ahead" time window.

d. Insert the calculated weather deviation route (add additional "WX" waypoints and skip waypoints becoming obsolete due to the deviation route) into the existing reference trajectory until the (initial/extended) reference trajectory (FPL) route is reached again and keep the remaining route trajectory to the final waypoint (= destination runway).

e. Repeat the described CbAvoid algorithm from the beginning. Note that steps 1) to 5) are to be iteratively applied until a "CB conflict free" 4D flight trajectory route has been identified (or other constraints apply).

(6) If no CB conflicts exist, check the consistency of the weather deviation route and validate the 4D flight trajectory as calculated by NAVSIM / CbAvoid algorithm. Note that, in case no CB conflicts are detected at the first iteration, NAVSIM generates a 4D flight trajectory which corresponds to the initial FPL reference trajectory (additional intermediate waypoints included) taking into account aircraft performance and wind situation as resulting from step 1) above.

Note that, since FMP-Met predictions have not included the possibility of holdings, for consistency NAVSIM has been configured to not consider holdings in the simulations performed in this deliverable.

3.1.3 Simulation results and verification

In summary 2542 flights on June 12th, 2018, between 12:00:00Z and 20:00:00Z flying within the Austrian Airspace (plus an additional buffer zone) were analysed and simulated by NAVSIM. The resulting final 4D trajectory routes were generated, including weather deviation routes as required. The flights were simulated in all flight phases from Take-off (or airborne), Initial Climb, Enroute climb until Top of Climb, Enroute until Top of Descent, Enroute Descent, Arrival, Approach, Final Approach and Landing on the destination runway. Simulation results are available as csv files.

Figure 8 below shows some examples on how the combination of several different weather deviation routes are taken into account, depending on subsequent observation / nowcast data in 5 minutes time slots (relevant only when the aircraft actually arrives in the corresponding area, from which an "envelope" is constructed for generating a "smooth" 4D trajectory route to emulate a "realistic" flight/pilot behavior).

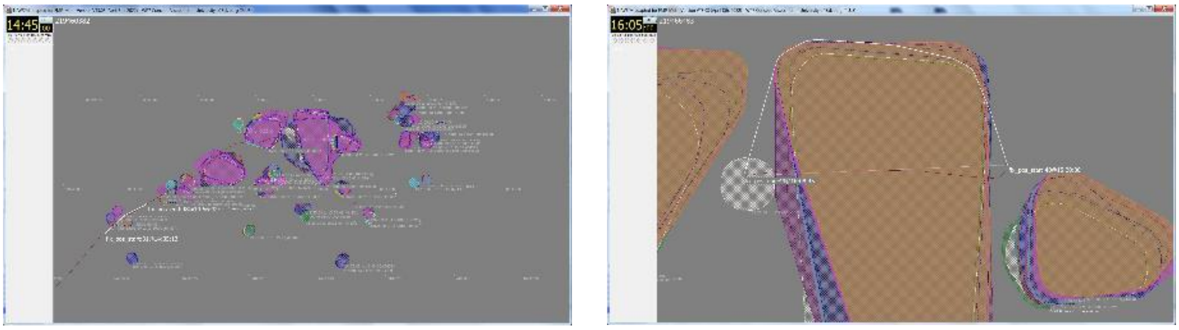

Figure 8: Examples of NAVSIM 4D flight trajectory calculation for all phases of flight based on FMP-MET input data and specifications

The following weather situations with an impact on the calculated 4D trajectories have been analyzed, applying appropriate NAVSIM algorithms to handle them:

(i) Airborne; no CB conflict(s) during the entire flight until landing on the destination runway.

(ii) No CB conflict(s) during the entire flight from take-off until landing on destination runway.

(iii) Both initial aircraft position (airborne or take-off) and destination runway are "clear of CB", but potential CB conflicts exist which must be avoided by calculation of appropriate weather deviation routes by NAVSIM.

(iv) The initial aircraft position (airborne or take-off) is not "clear of CB". In this case, no weather deviation route can be immediately calculated and therefore a "fly out of CB" functionality has been implemented in NAVSIM, which first simulates the flight along the initial FPL route until a CB conflict does not exist anymore. Then – outside the initial CB – the 4D trajectory to the destination runway is calculated (including possible weather deviation routes).

(v) The initial aircraft position (airborne or take-off) is "clear of CB", but CB conflicts, especially around the destination aerodrome, exist. In this case, for simplicity the solution adopted is that the destination-blocking CBs are neglected, and the flight is simulated along the initial FPL route.

(vi) The initial aircraft position (airborne or take-off) and the destination runway are relatively close to each other, both are not "clear of CB", and no CB conflict-free position along the FPL route can be found. In this special case, for simplicity the solution adopted is that the CBs are neglected, and the flight is simulated along the initial FPL route. This applies also to some cases in which no appropriate weather deviation route was found.

3.2 Results

3.2.1 Sector demand

The probabilistic methodology developed for sector demand analysis under adverse weather is described in D5.1 [2]. The results presented in this section are organised as follows. First, the occupancy and the entry counts are presented for the entire Austrian airspace, LOVV, considered as a whole and not fractioned into different sectors. Next, the counts are presented for two representative sectors of the sector configuration 10A1: sector W45 (one of the sectors with less accurate demand predictions) and sector E13 (one of the sectors with more accurate demand predictions). Finally, results are shown for all the sectors that constitute configuration 10A1.

Entire Austrian Airspace

The purpose of showing the demand for LOVV is to help in the understanding of the results. Since the spatial scale of the storm is quite large, these demand results help to understand if the flights are diverted, or not, to or from LOVV (and all its constituent sectors).

The occupancy count for LOVV and for the first hour (from 12:00 to 13:00) is shown in Figure 9. The probabilistic prediction of the occupancy is represented as a heat map, where the colour for each count value represents the probability of obtaining that particular value; the darker the colour, 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 black rhombus. The real occupancy count obtained from NAVSIM is represented as a blue inverted triangle.

In Figure 9, it can be observed that the prediction evolves over time as the reality does, increasing and decreasing as time progresses, and it is always close to the reality. In the beginning, the prediction is sharper (the dispersion is smaller) and, as the time horizon increases, the uncertainty increases. Regarding the statistical consistency, in 75% of the time intervals, the reality is encompassed by the closed interval defined by the 5th and 95th percentiles. Ideally, this percentage should be 90% (the probability of being between the two percentiles). Thus, the statistical consistency for this result is quite good.

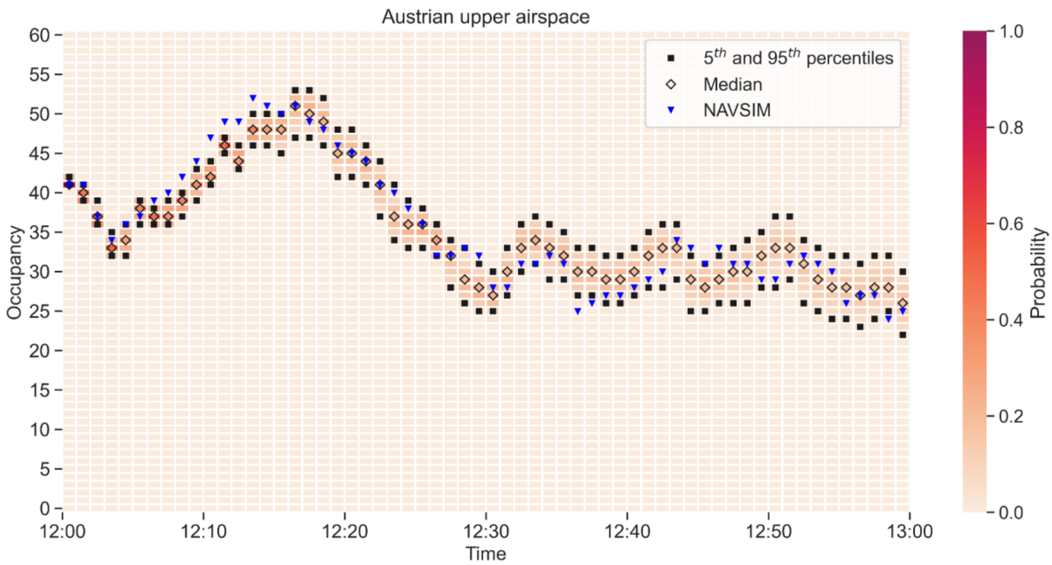

Figure 9. Occupancy count for LOVV; $\delta t = \Delta t = 1$ minute.

The entry count for LOVV and for the 8-hour time span (from 12:00 to 20:00) is presented in Figure 10. It can be seen that the entry is less accurate than the occupancy prediction. Prediction and reality are more separated, sometimes the reality is overestimated, but other times it is underestimated. The reality is encompassed by the 5-to-95 percentile interval in just 36% of the time periods.

One possible cause to explain this poorer performance lies in the long-term trajectory predictor (TP) developed in WP4, on which this entry count is mainly based. This long-term TP does not include lateral deviations, but only longitudinal deviations. Therefore, lateral diversions that may either prevent flights from entering the airspace, or lead outer flights into entering the airspace, are not predicted. Recall that lateral deviations were not included in this trajectory predictor because the high-resolution EPS, the meteorological product that provides the storm forecast for this predictor, does not provide areas to avoid (storm cells) but much larger areas where important convective activity is forecasted.

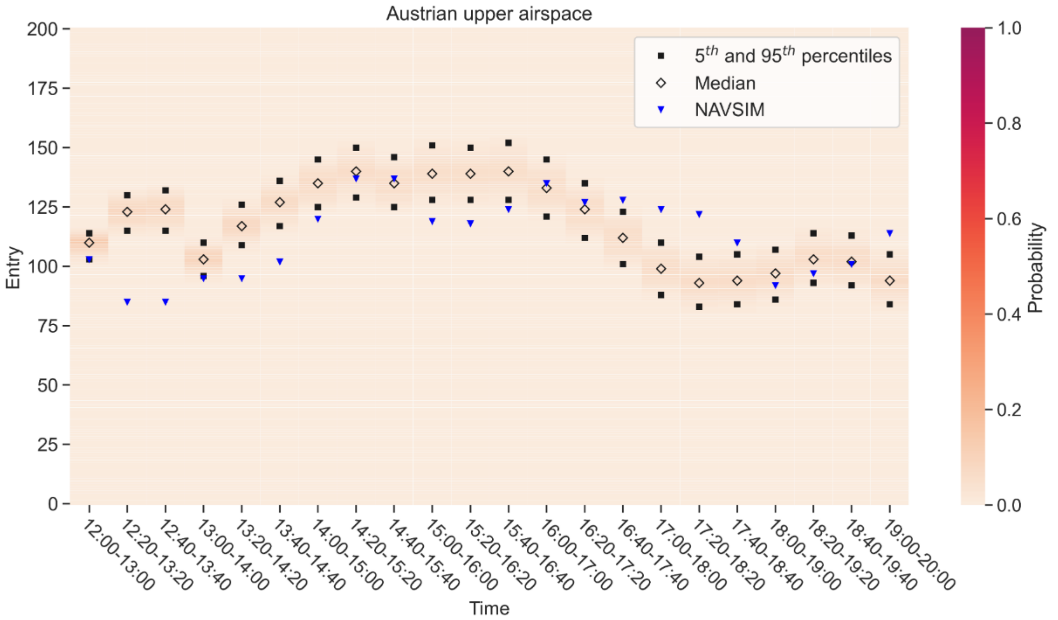

Figure 10. Entry count for LOVV; δt =20 minutes, Δt =1 hour.

Sectors W45 and E13

The occupancy and the entry counts of sector W45 are presented in Figure 11, top and bottom, respectively. Regarding the occupancy count, the larger inaccuracies are found in the first 25 minutes, when one or two aircraft were predicted to be in the sector, whereas the reality shows that there were between six and eight. In this case, the prediction estimated that the sector would be almost completely blocked, and therefore the flights diverted, but the reality was less severe. Two factors contributed to this situation: 1) the inherent variability of the nowcast, which in this case overestimated the presence of the storm, and 2) the safety margin of 13.5 nmi in the prediction, which may be conservative, since it led to an overlapping and merging of areas to avoid and, ultimately, to a blockage of the airspace.

Regarding the entry count, the largest differences are found between 13:00 and 16:00, where less aircraft than predicted entered the airspace. As before, one possible cause for this deviation is the lack of lateral deviation in the long-term trajectory predictor.

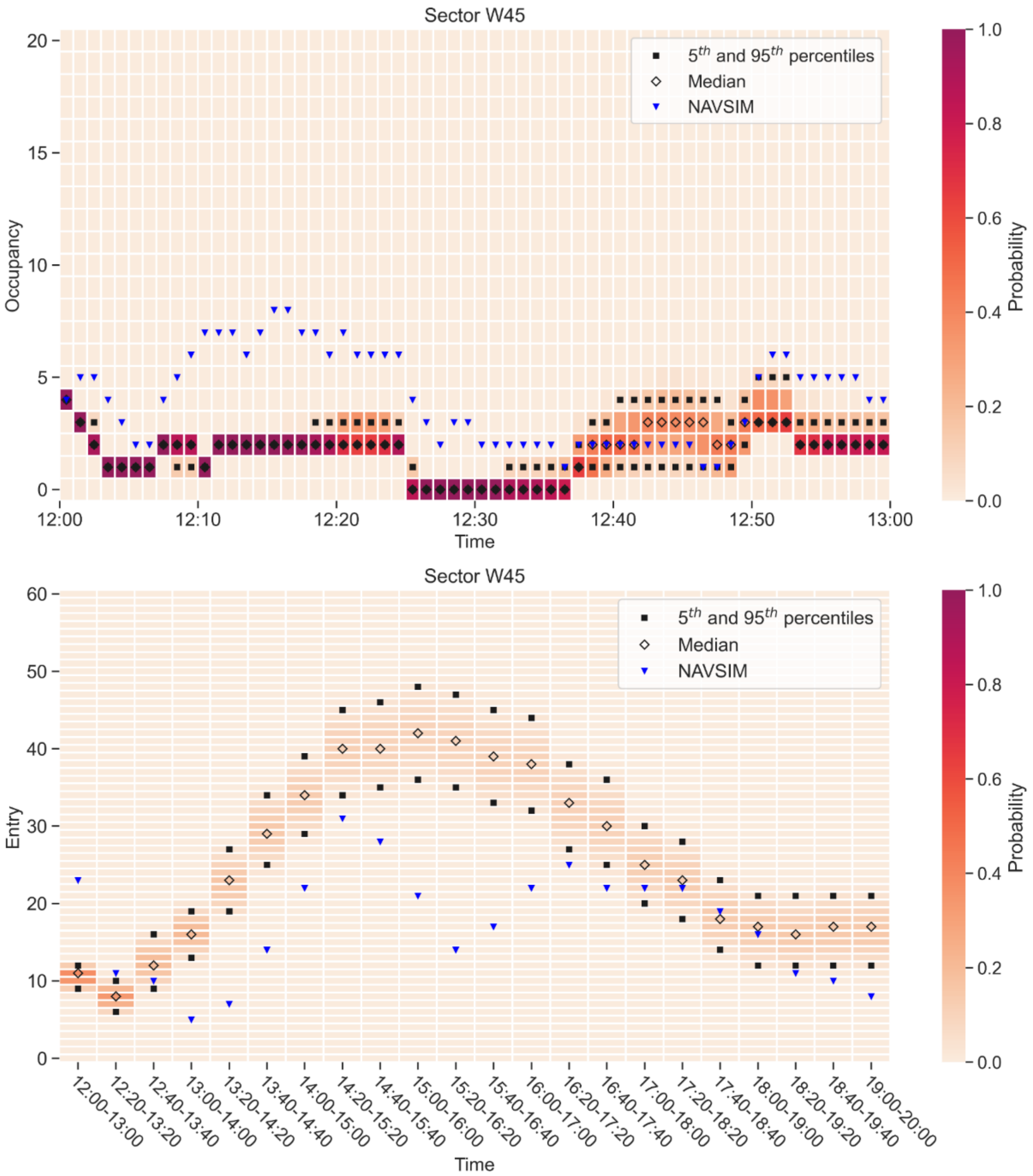

Figure 11. Sector W45. Top: occupancy count. Bottom: entry count.

The occupancy and entry counts of sector E13 are presented in Figure 12, top and bottom, respectively. The predictions for this sector are significantly better. Regarding the occupancy count, prediction and reality are always quite close. As for the entry count, the accuracy is quite good except for the time period between 16:00 and 17:20, where the real entry is larger than predicted.

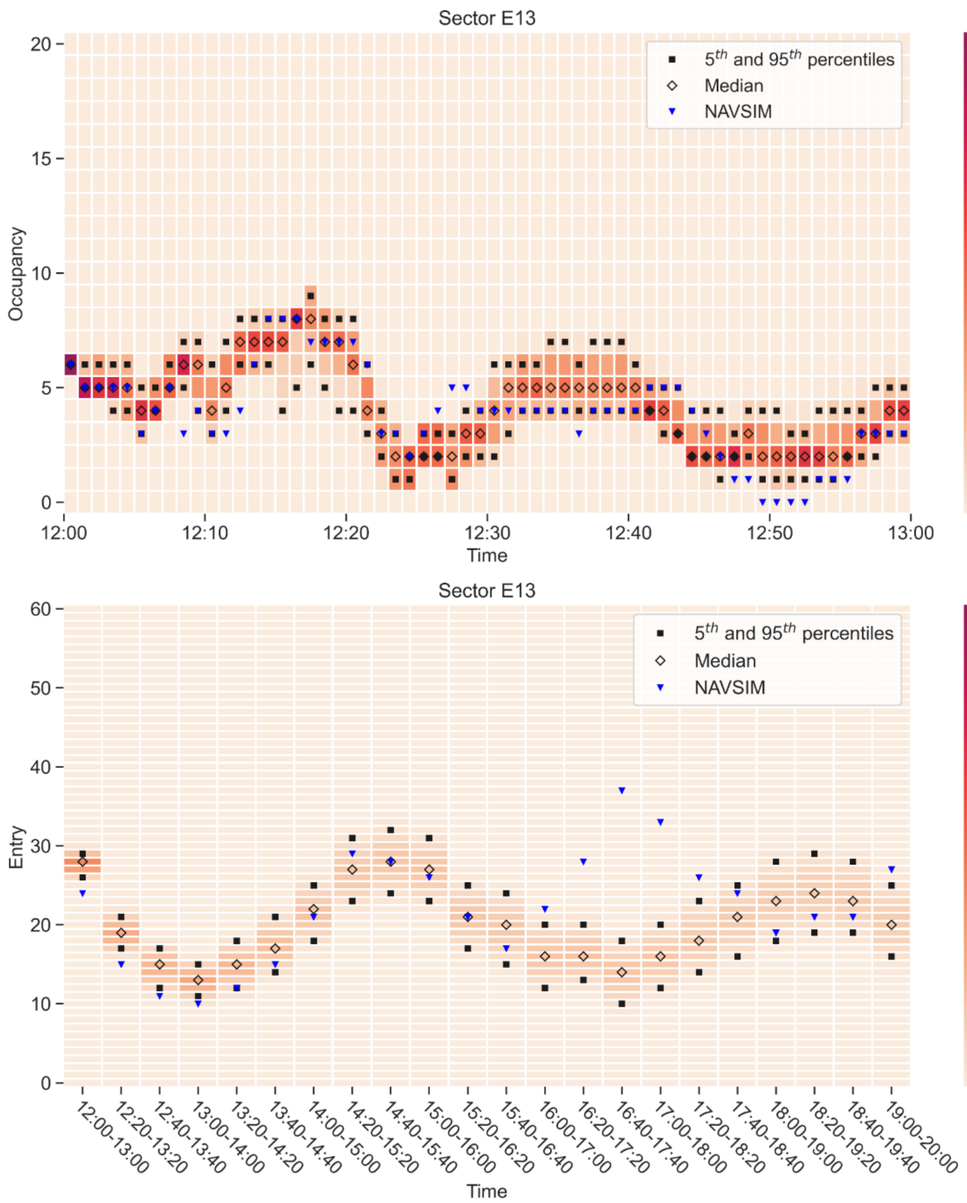

Figure 12. Sector E13. Top: occupancy count. Bottom: entry count.

All sectors from configuration 10A1

Table 1 shows the monitoring values for the entry and the occupancy counts for each sector of configuration 10A1 (for the 8 hours of prediction). The table also presents the non-dimensional Mean Absolute Errors (MAE between the median and the reality divided by the corresponding monitoring value) for each sector. The results for the occupancy and for the entry are very similar. The occupancy errors range between 8.5% and 32%, and the entry errors between 10 and 25%. Seven sectors for the occupancy and five sectors for the entry present an error below 15%. As a reference, in the CIFLO application, a 10% of the monitoring value represents one step in the colour code. Therefore, most of the prediction errors are between one or two colours.

Sector	Entry		Occupancy	
	MV	MAE/MV	Sustained OTMV	MAE/OTMV
B15	46	17%	10	32%
W45	48	21%	12	22%
W3	40	12%	9	13%
W12	42	25%	10	14%
S35	46	23%	12	13%
S12	40	12%	9	14%
E45	46	10%	11	8.5%
E13	50	10%	11	9.5%
N35	50	10%	13	14%
N12	43	19%	11	17%

Table 1. Monitoring values and non-dimensional Mean Absolute Errors for entry and occupancy counts and for each sector of configuration 10A1.

Conclusion

To the question 'Is reality well captured by the predictions of FMP-Met?' the answer is that the FMP-Met predictions capture the reality relatively well.

In Section 5 we identify some factors that may have limited the accuracy of the predictions and corrective actions as possible next steps. Also, we present some requirements to compare with real traffic in future phases of development.

3.2.2 Sector complexity

The methodology developed in the FMP-Met project for traffic complexity analysis (see D6.1 [3]) is based on the PRU complexity model, defined by Eurocontrol's Performance Review Unit [16], 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 ATCO and the aircraft concerning avoidance of convective weather. 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 the complexity score based on the ensemble of possible traffic scenarios.

To evaluate the predicted complexity scores generated using nowcast and COSMO-D2-EPS, they were compared to the complexity scores calculated based on NAVSIM trajectories and the real meteorology. A complexity score for the NAVSIM trajectories was calculated as a single score for each 20-minute time window, for each sector in the current sector configuration and for the entire LOVV as one sector. The NAVSIM complexity scores are shown as a red line that overlaps with the probabilistic complexity predictions, as shown in Figure 13 and Figure 14.

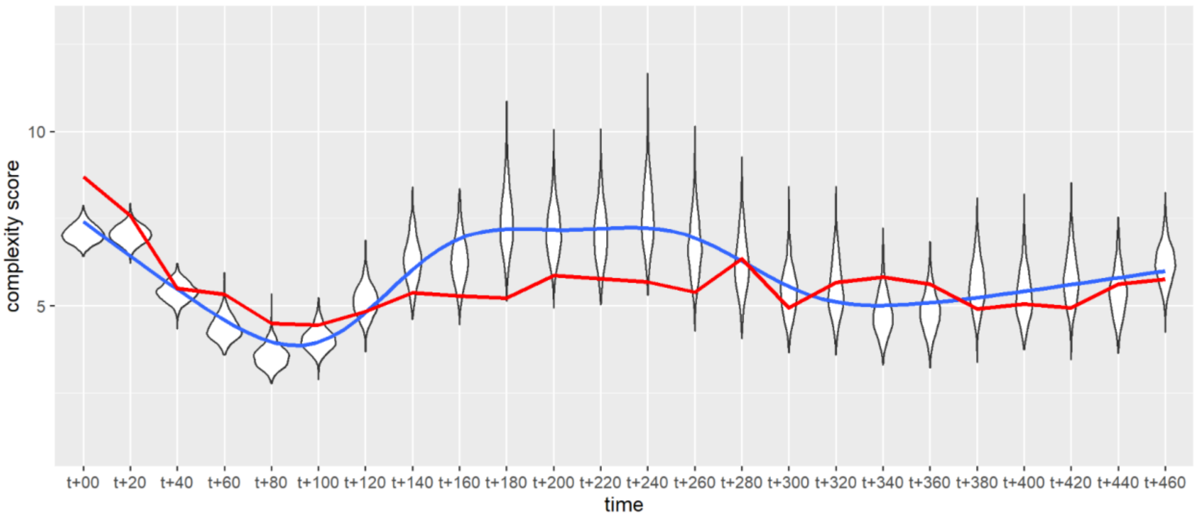

Figure 13 LOVV complexity score comparison

As can be seen in Figure 13, the NAVSIM complexity curve is shown as a red line over the calculated complexity values for LOVV from 12:00 to 18:00 on June 12th, 2018, while the blue line connecting the violin plots represents the complexity trend. Figure 13 shows that the NAVSIM complexity values, with slight variations, follow the trend line of the probabilistic complexity prediction. The initial decrease in complexity values from t+00 to t+80 is the same, followed by a slight increase and stagnation in complexity until t+260, where there is a fluctuation in complexity values. At t+380, the complexity value stabilizes and has an increasing trend. Comparing the complexity values and the trend line, it can be seen that the NAVSIM trajectories have higher complexity than predicted until time t+120. At t+120, the NAVSIM complexity is exactly like the blue trend line and by t+280 it is lower than predicted but still in the likely range (overlaps with the violin plots). At t+280 it is again exactly as the trend line, followed by overestimation and underestimation of predicted complexity. Finally, at t+380, the NAVSIM complexity is slightly lower than the predicted one but has the same increasing trend.

Figure 14 shows the NAVSIM complexity calculated for an opening scheme that involves five different sector configurations (notice that the traffic and complexity predictions can be performed for any sector configuration or opening scheme, scheduled or not). The NAVSIM complexity is compared to the predicted complexity values using the probabilistic trajectory predictions developed in FMP-Met. The five active configurations are 10A1 (12:00-14:30), 9A1 (14:30-17:00), 8S (17:00-18:00), 7WB1 (18:00-19:30), and 6WB1 (19:30-20:00). It can be seen that almost all NAVSIM complexity values fit within the predicted range. Sectors with dense distributions and small standard deviations, such as N12 and S12, also show a good overlap of predicted complexity with NAVSIM complexity results. In such sectors, the NAVSIM complexity is close to or slightly above the mean in most cases, while sectors with an elongated distribution and higher standard deviations, i.e. sector S35 from t+160 to t+260 and sector N35 from t+180 to t+280, show an overestimation of complexity compared to the NAVSIM results. There are some but very few cases where the NAVSIM complexity is outside the range predicted by the probabilistic prediction, such as in sector W3 at t+20 or W12 t+340. In these cases, the NAVSIM complexity value is always higher than the predicted complexity.

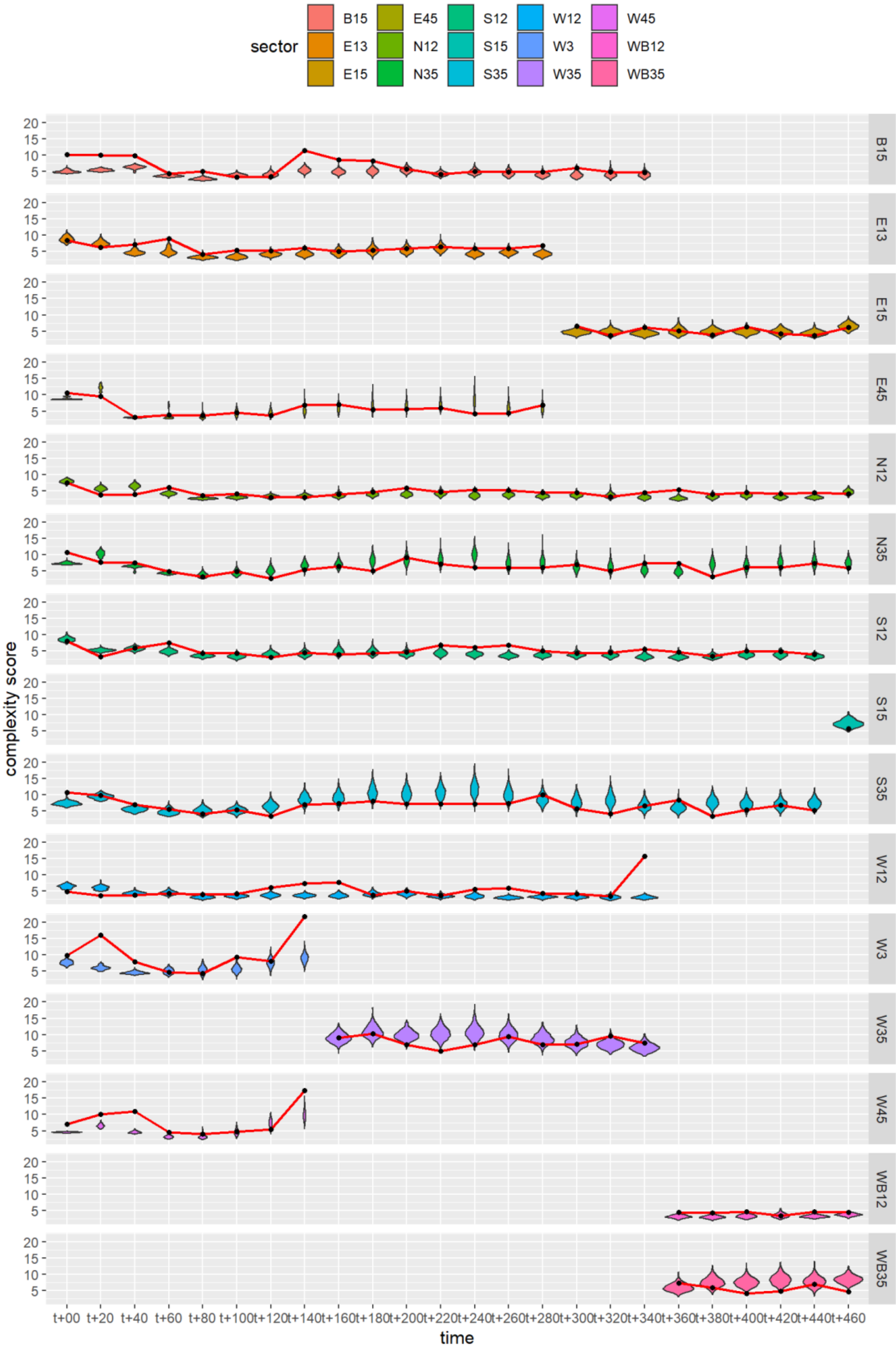

Figure 14 Complexity comparison per sector

Such a good overall agreement between predicted probabilistic complexity and NAVSIM complexity (so called reality) can also be quantified by computing the non-dimensional Mean Absolute Errors, which are defined as the MAE between the median and the reality divided by a reference value corresponding to the maximum value of NAVSIM complexity over the different time periods (referred to as NAVSIM_max). Results for each sector are presented in Table 2. Except for sectors S15 and WB35 (with a somewhat poorer prediction skill in relative terms) the non-dimensional MAE lies between 12% and 23%, confirming the trends seen in Figure 14.

Sector	NAVSIM_max	MAE/NAVSIM_max
B15	10.8	18%
E13	8.9	16%
E15	6.5	16%
E45	10.6	12%
N12	7.5	16%
N35	10.7	15%
S12	8.1	15%
S15	5.7	27%
S35	10.7	20%
W12	7.5	21%
W3	21.7	20%
W35	10.2	19%
W45	17.3	18%
WB12	4.9	23%
WB35	7.5	30%

Table 2. Maximum value of NAVSIM complexity score and non-dimensional Mean Absolute Errors for complexity scores for each sector.

4 Concept validation

This section addresses the validation of the FMP-Met concept performed with the assistance of expert FMPs. First, the information about the concept provided to the FMPs, prior to the validation exercise, is presented in Sections 4.1 and 4.2; then, the exercise itself, including the questionnaire, is described in Section 4.3; and, finally, the FMPs feedback is collected in Section 4.4.

4.1 Reference scenario

The reference scenario is the current approach and tools used by FMPs. This approach is based on deterministic analyses that do not include weather effects. Moreover, the impact on the traffic and on the sector capacity needs to be estimated by the FMP based on external MET information, outside the main FMP tool; the capacity value is manually adjusted according to the expected weather by the user.

This reference scenario will be used as a basis of comparison to assess the benefits of the operational improvement addressed by the project.

For completeness, some features of the current approach used by FMPs are briefly described next. The FMP Monitor window in CIFLO (Figure 15) is used to display and monitor the declared sector configurations through the day. This window is used to quickly identify situations where Traffic Forecast (TF) comes close or intersects the capacity (Monitoring Value, MV) line of any Traffic Volume (TV) in the declared Daily Sector Configuration Plan. By looking at the FMP Monitor, a FMP can easily identify such an overload situation.

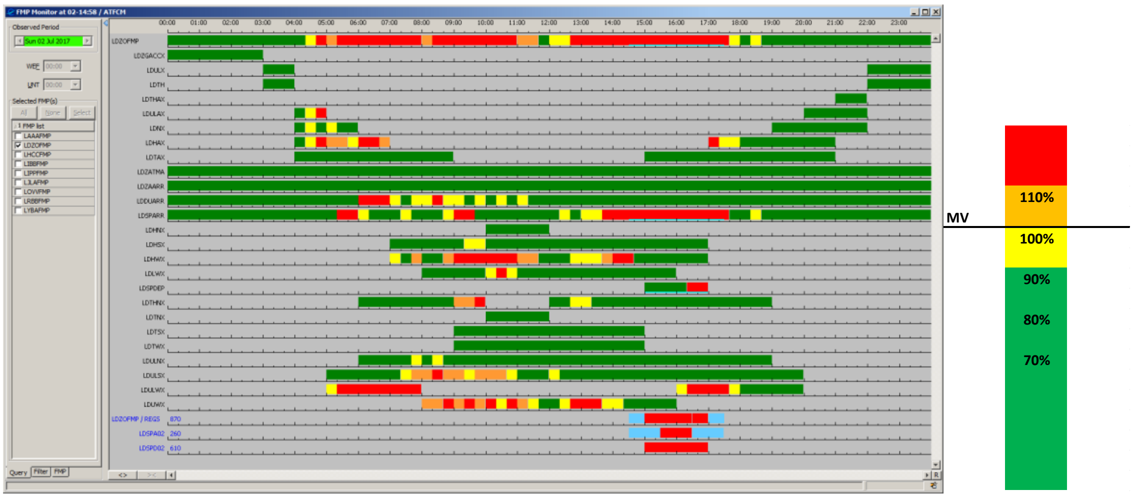

Figure 15: FMP Monitor and color code definition.

In the current approach, the colors used in the CIFLO application at FMP positions throughout European Civil Aviation Conference (ECAC) area have the following meaning, as a function of the monitoring value:

- Green: traffic load is acceptable, up to 90% of defined threshold (MV).
- Yellow: traffic load is high, between 90% and 100% of MV.
- Orange: traffic load is very high, between 100% and 110% of MV.
- Red: traffic load is unacceptable, over 110% of MV.

While these functions enable the FMP to identify periods of high load–weather intersection, some drawbacks of the current process can be identified:

- Today, FMP's and ACC Supervisors tasked with Configuration Management brief themselves of relevant meteorological conditions on various separate (from CIFLO) MET-briefing systems, and they must convert this information into impact on sector MV and integrate it manually into the current 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 flights are no longer subject to ATFCM measures but ATC (flights are airborne).
- 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.

4.2 Solution scenario (FMP-Met approach)

As already indicated, the integration of probabilistic information in the decision process is based on a decision support tool. The proposed tool is derived from existing concepts. The **novelty** in FMP-Met is that the weather impact is included in the traffic forecast and the forecasted capacity used by the tool. In addition, the forecasts of traffic and capacity are probabilistic and hence also include uncertainty information.

The tool devised in this project has three **main layers**:

- Sector Configuration Monitor
- Traffic Volume Monitor
- Traffic Volume Analysis View

4.2.1 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 are determined from the color state of the traffic volumes that form that configuration (the determination of the traffic volume's colors is given below) and they have the following meaning:

- Green: if all traffic volumes are in green state; that is, if the traffic load is acceptable for all traffic volumes.
- Yellow: if at least one traffic volume is in yellow state; that is, if the traffic load for at least one traffic volume is high but no action is required, or ATC measures are sufficient.

- Orange: if at least one traffic volume is in orange state; that is, if the traffic load for at least one traffic volume is very high.
- Red: if at least one traffic volume is in red state; that is, if the traffic load for at least one traffic volume is unacceptable.

An example of the *Sector Configuration Monitor* showing the time evolution for the next 180 minutes in 5-minute intervals for selected Austrian sector configurations (2A, 5A, 5B, …) is shown in Figure 16. Note that, although the forecasting horizon is 8 hours, the decision support tool will allow the user to restrict the time window for visualization to shorter forecasting horizons.

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. More details on how the colors are defined are given below.

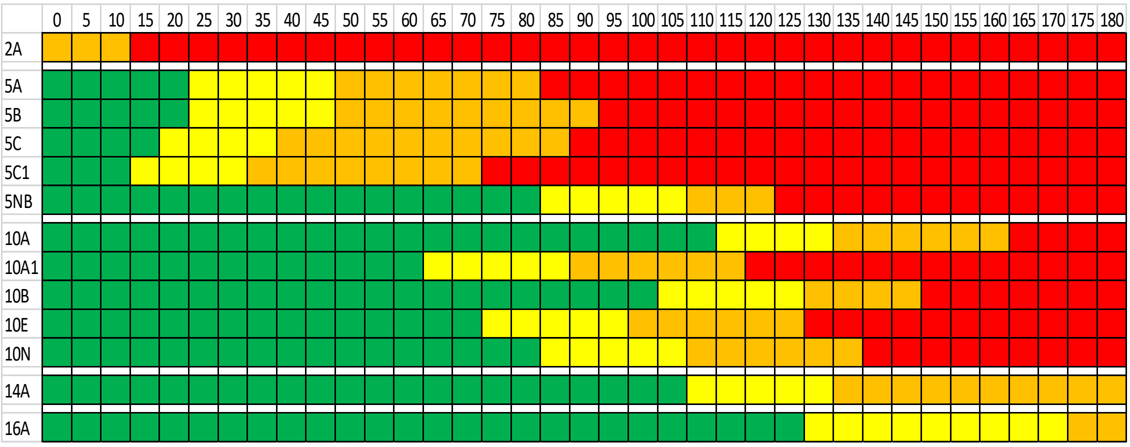

Figure 16: Schematic of the Sector Configuration Monitor.

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

An example of the *Traffic Volume Monitor* showing the time evolution for the next 180 minutes in 5-minute intervals for the traffic volumes of the Austrian sector configuration 10A is shown in Figure 17, where B15, W45, W3, … are the corresponding traffic volumes.

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 below.

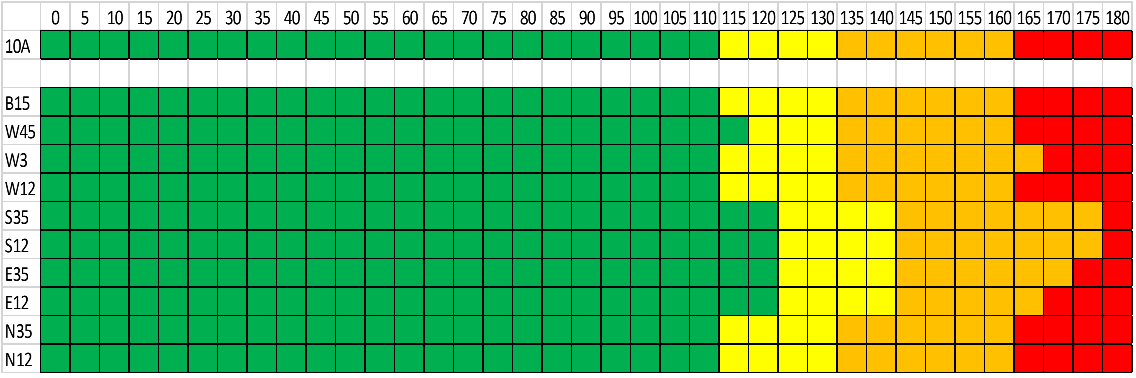

Figure 17: Schematic of the Traffic Volume Monitor.

4.2.3 Traffic Volume Analysis View

To gain detailed insight into the situation in a specific traffic volume, by selecting it 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.

Traffic demand and sector congestion

In FMP-Met we have developed methodologies that provide 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 Occupancy Traffic MV - OTMV).

The weather–dependent capacity for a given sector is obtained in terms of the nominal MV and OTMV as follows

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

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

where *ACSR* 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.

From *TF* and *Wx_Cap* we define the Relative OverLoad (*ROL*)

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

and from their probabilistic distributions we generate the *ROL* distribution, and, in particular, we consider the percentiles 50 and 95 of the distribution (Z50 and Z95), which are used to define the probabilistic color code, as described in Section 4.2.4.

Sector complexity

Finally, we can also analyze the **expected traffic complexity**, which can be seen as additional information to "demand – capacity" that supports the decision-making process. For example, peaks in the "demand – capacity" distributions can be assessed to be more/less problematic by looking at the corresponding expected 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 is based on the PRU complexity model, defined by Eurocontrol's Performance Review Unit, 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 ATCO and the aircraft concerning avoidance of convective weather. In this method, an aircraft is considered in weather interaction if it is located in 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.

Graphical displays

In FMP-Met we have selected 3 types of representation:

A. Frequency plots (in fact, **frequency histograms**), showing specific *ROL* distributions for given time periods (see Figure 23 below).
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 24 below).
C. Complexity distributions depicted as **violin plots** for given time windows, representing the probabilistic complexity score (see Figure 25 below). The length of the violin plot is a measure of the dispersion. Distributions with small standard deviation result in short and wide violin plots. On the other hand, 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 or not 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.

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4.2.4 Probabilistic color code

To define the probabilistic color code we consider 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 18.

The colors below the diagonal are closely related to the aversion to the uncertainty, hence, they are subject to **further analysis** and corroboration by expert FMPs.

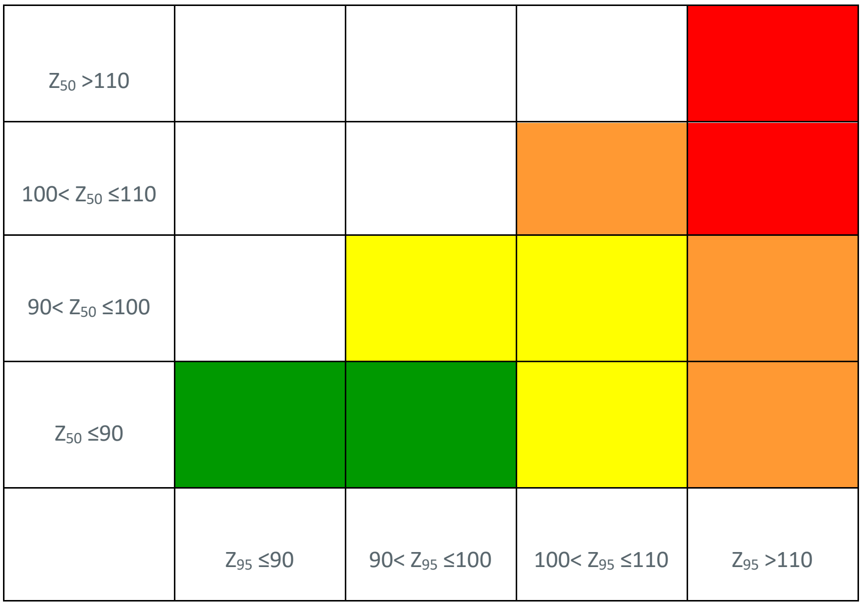

Figure 18: Probabilistic color code. ROL=100*TF/Wx_Cap (%).

If we want to compare this probabilistic code with the deterministic one currently used, we can emulate current practice considering only one parameter of the distribution: Z_{50} (that is, the median). This can be shown as a 1-entry table (Figure 19). Note that using Z_{50} as input leads to results where weather effects are taken into account (but not the uncertainty in the weather prediction), because the presence of the thunderstorm has been considered in the calculation of both *TF* and *Wx_Cap*.

We 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}.

Z_{50} >110				
100< Z_{50} ≤110				
90< Z_{50} ≤100				
Z_{50} ≤90				
	Z_{50} ≤90	90< Z_{50} ≤100	100< Z_{50} ≤110	Z_{50} >110

Figure 19: Reference deterministic color code (used for comparison). ROL=100*TF/Wx_Cap (%).

4.3 Validation exercise

This section describes the validation exercise conducted with FMP experts from ACG and CCL.

4.3.1 Validation procedure

This validation exercise is intended to validate the probabilistic operational concept developed in FMP-Met as described in Section 4.2.

The validation tool used to validate the FMP-Met concept is the **Judgmental technique (expert opinion)** via questionnaires. The questionnaire is included in Section 4.3.3. The validation results will be **qualitative**. The goal is 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.

4.3.2 Simulation results

The results presented in this Section aim at

1) presenting the capabilities of the proposed probabilistic concept, and
2) providing the basis to perform a qualitative comparison between the FMP current procedure and the new one proposed in the FMP-Met project.

Results are presented for the three layers of the envisioned tool, for **configuration 10A1**.

Traffic Volume Monitor

First, in Figure 20 we have the results obtained using the probabilistic coding developed in the project (the 2-entry table shown in Figure 18, which uses the percentiles Z_{50} and Z_{95} as input). This coding includes weather impact and forecast uncertainty. Figure 20 (and Figure 21 and Figure 22 below) show results for the different sectors corresponding to the entry count for 1-hour periods, calculated every 20 minutes.

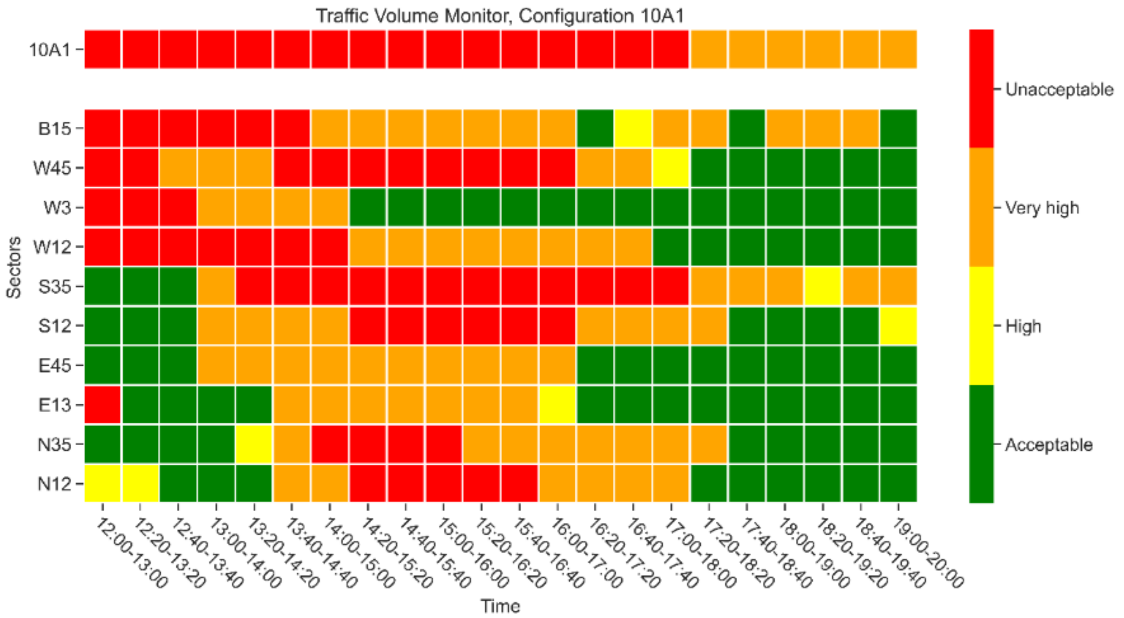

Figure 20: *Traffic Volume Monitor*. Probabilistic coding (including weather impact and forecast uncertainty).

Next, **for comparison**, we present two additional results obtained using deterministic codings:

- Figure 21 – deterministic coding (1-entry table shown in Figure 19, which uses the percentile Z_{50} as input). This coding includes weather impact, but does not include forecast uncertainty.
- Figure 22 – the same deterministic coding used in Figure 21, but applied to the nominal traffic and the nominal MV, without taking into account the impact of the thunderstorm (without

storm avoidance and without capacity reduction) and without the other sources of uncertainty.

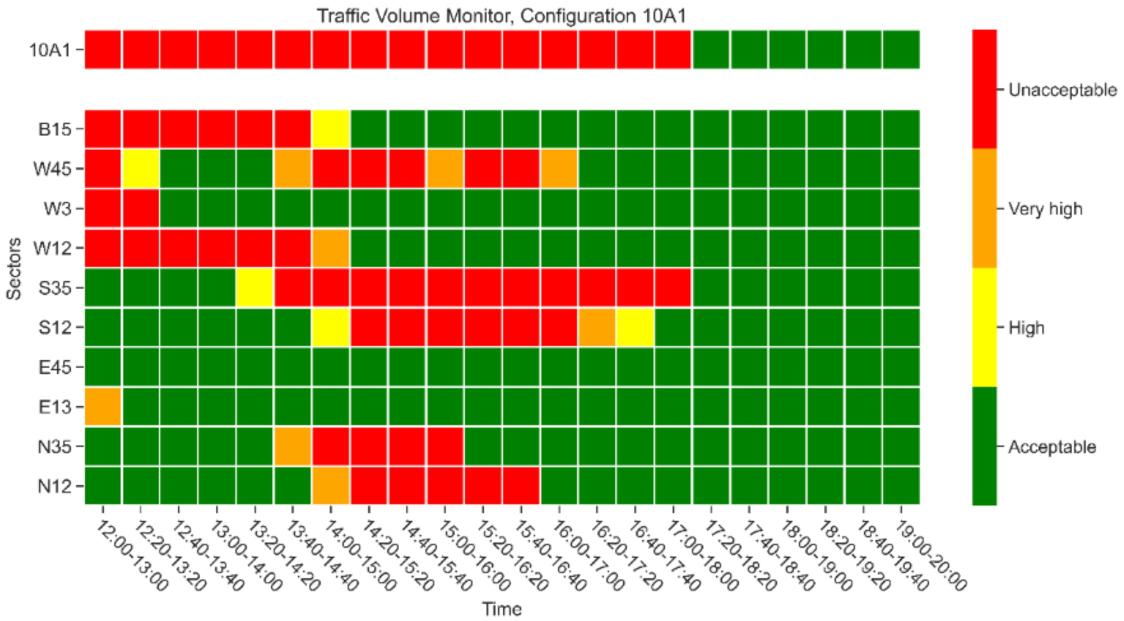

Figure 21: *Traffic Volume Monitor*. Deterministic coding including storm impact, without forecast uncertainty.

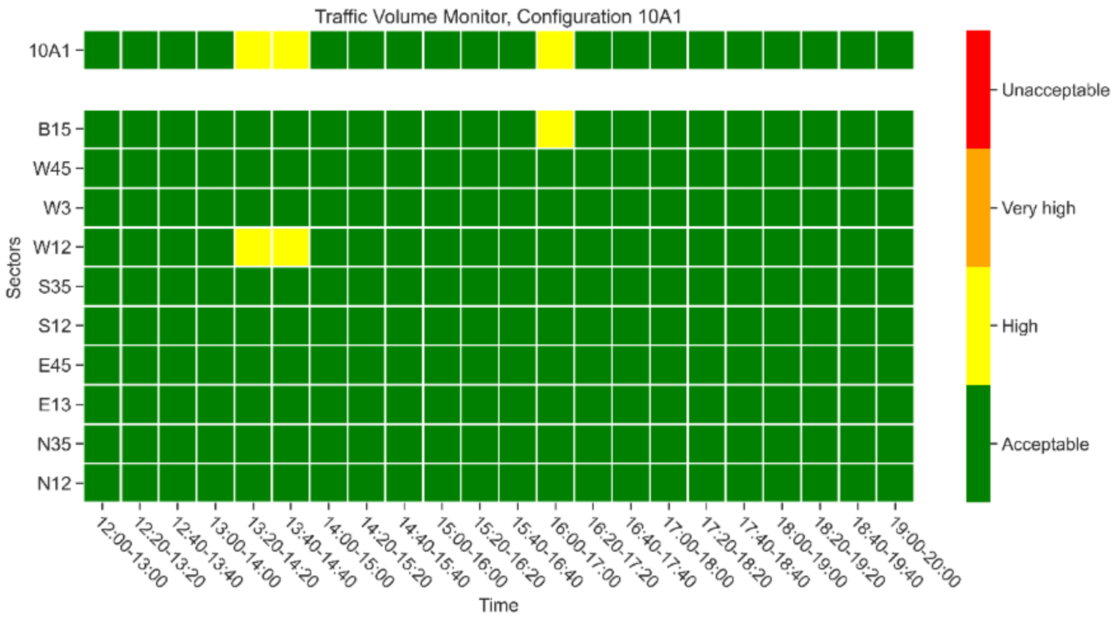

Figure 22: *Traffic Volume Monitor*. Nominal traffic, without weather effects and without other uncertainty sources.

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 23 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 20 (Z_{50}=74% and Z_{95}=208%).
2. From 16:20 to 17:20 – green in Figure 20 (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.)

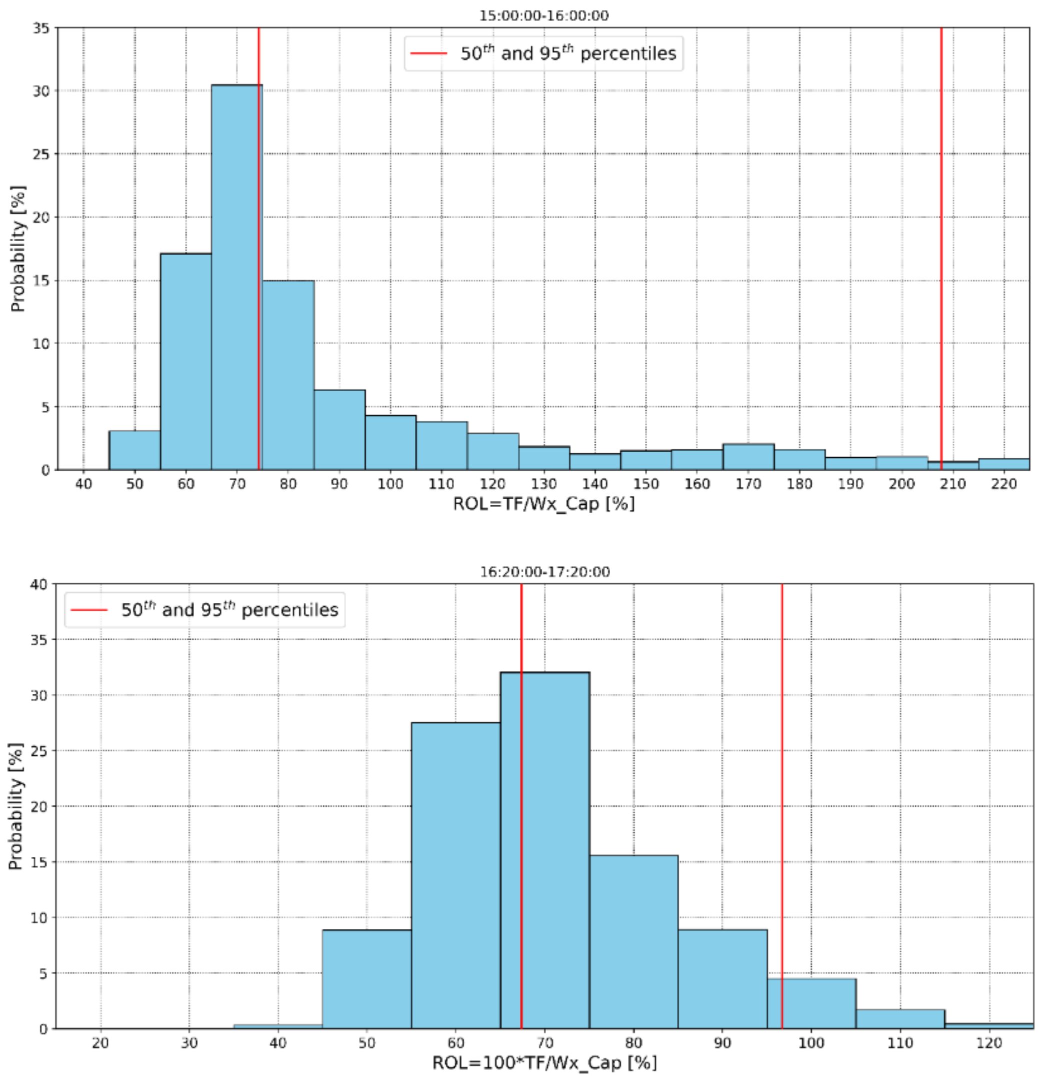

Figure 23: *Traffic Volume Analysis View*. *ROL* distributions for Sector B15.

B.

In this layer of the tool we can also present the **time evolution** of the different parameters of interest. In Figure 24 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.

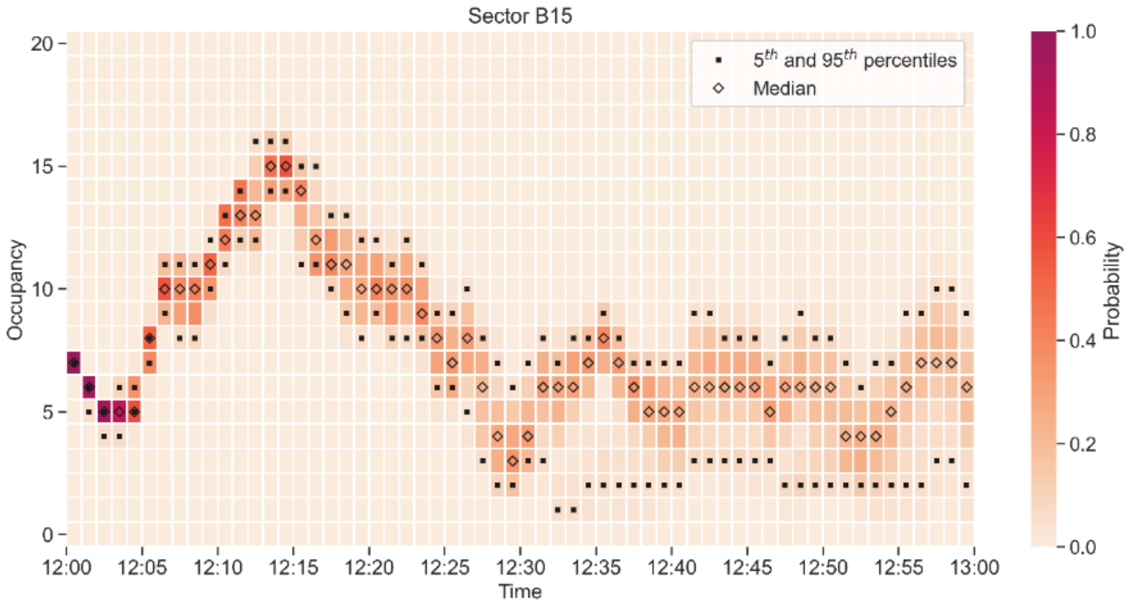

Figure 24: *Traffic Volume Analysis View*. Occupancy count evolution for Sector B15.

C.

Finally, we analyze the **expected traffic complexity**. An example of the evolution of the complexity score is shown in Figure 25, 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.

In Figure 25, 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.

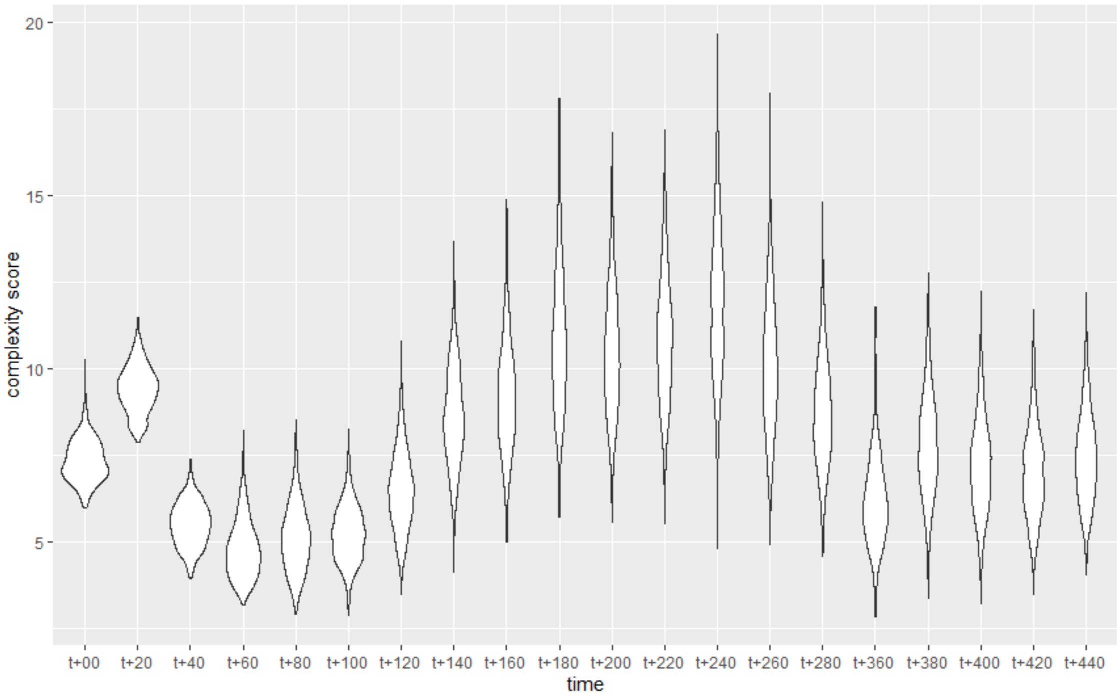

Figure 25: *Traffic Volume Analysis View*. Complexity evolution for Sector S35.

4.3.3 Questionnaire

The questionnaire presented to the FMPs read as follows:

Taking into account that results/potential benefits are based on the assumption that the accuracy of the severe weather detection and prediction is operationally acceptable, please answer the following questions:

1. *In your opinion, can the FMP process be operationally improved by integrating adverse weather information? On the traffic and on the sector capacity? Just on one of them? On anything else?*

2. *In your opinion, can the FMP process be operationally improved by integrating probabilistic information into the traffic and capacity forecasts?*

3. *Would the concept proposed in FMP-Met improve the situational awareness of the FMP in adverse weather conditions?*

4. *Would the concept proposed in FMP-Met lead to improved decision making? Would it lead to more timely planning, anticipating the decision making? Would it help to decide more appropriate ATFCM measures? Would it lead to improved Flow Management?*

5. *Would the proposed enhancements help reduce the negative effects of adverse weather? To what extent?*

6. *Are the graphical displays proposed clear and easy to interpret? Would you feel comfortable using them?*

7. *All in all, do you find the proposed probabilistic concept for FMPs useful? In your opinion, does it deserves further effort to produce a functional prototype of the new tool? What functionalities would you like to see in this prototype?*

8. *Finally, please add any additional comment, thought or new idea that you may have.*

4.4 FMPs' feedback

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. ACG and CCL have provided the following (anonymous) consolidated answers and comments.

#1.

In your opinion, can the FMP process be operationally improved by integrating adverse weather information? On the traffic and on the sector capacity? Just on one of them? On anything else?

Yes, definitely on both, traffic and sector capacity, these two components always have to be considered together (to consider sector capacity alone is not useful without demand). In addition, we also see the influence of weather on complexity as very relevant.

Can the FMP process be operationally improved by integrating adverse weather information?

It must be improved; in our ACC convective weather is one of major challenges in Ops, and it correlates with summer when our capacities and also Network capacities are exhausted.

On the traffic and on the sector capacity?

Yes, ideally on level of individual flights, but also on sector level, and further for configuration level.

Just on one of them? On anything else?

People tend to think they need a map to better comprehend, visualize and make estimates themselves of the development of adverse weather. Probably it would be good to have possibility to jump quickly from the Monitor Views into Map view.

#2.

In your opinion, can the FMP process be operationally improved by integrating probabilistic information into the traffic and capacity forecasts?

Yes, these concepts seem to be useful. We would be curious to study these methods over a longer time period, so that we can evaluate the benefits more thoroughly.

After explaining the number of trajectories which you calculated just for the chosen date (moment) there was some disbelief present from the FMPO. Then again, since there is a mean (average) value which is along the lines of expected (what we are used to see) it is definitely worth exploring. We understand (we think) that recent achievements in AI and big data roaming enable the system to learn and possibly improve further with time. If that is the case, then it is definitely worth exploring further.

#3.

Would the concept proposed in FMP-Met improve the situational awareness of the FMP in adverse weather conditions?

Yes, if concepts and tools are graphically well prepared and thus easy to understand and comprehend, they will increase awareness automatically.

Most FMPO think concept is OK but not necessary for Configuration Monitor. In our ACC we have many possible combinations of lateral and vertical elementary sectors but we somehow always run the same ones. The concept is best applied in monitoring Sector Load (TV Analysis View) and changes to it driven by adverse weather. (this is possibly due to FMPO looking at things in map view by default when it regards the weather – Where is it and where is it moving? If you talk to them in config. view, probably they don't immediately know sector composition and they miss the information where the weather is).

#4.

Would the concept proposed in FMP-Met lead to improved decision making? Would it lead to more timely planning, anticipating the decision making? Would it help to decide more appropriate ATFCM measures? Would it lead to improved Flow Management?

That's difficult to assess from one case study. In principle yes, but it strongly depends on the quality and reliability of the system. Operational FMPs have to build trust in these systems. We have to use such tools over a longer period to build trust in the system.

Would the concept proposed in FMP-Met lead to improved decision making?

Not sure, have to see. We are all worried about the look ahead time and the size of dispersion. We are looking at 2-3 hours in advance and making decisions then, if the dispersion there is very large, we don't have use for this information.

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Would it lead to more timely planning, anticipating the decision making?

Yes, in certain situations when the weather is deteriorating and the Tool shows continuous high risk we would make sure to extend the action horizon.

Would it help to decide more appropriate ATFCM measures?

Yes, if there is What-If, but in the TACT phase the measures are either a Regulation or a STAM. If the TL predictions would show a recognizable pattern in accuracy, they would for sure lead to less restrictive rates being used on protective regulations.

Would it lead to improved Flow Management?

It could lead to improvements in efficiency and accuracy of actions in flow management. New info is always welcome.

#5.

Would the proposed enhancements help reduce the negative effects of adverse weather? To what extent?

Negative effects of adverse weather will always be there. Adverse weather always will increase ATFCM-delays (we would need a more proper metrics to assess the increased resilience due to these tools). However, we would expect that these concepts will decrease the negative economic impact over a longer time period and to have a positive effect on ATCO workload as well. To answer these questions the average effect of applying the method on many cases needs to be evaluated.

Probably they would help to the extent of their accuracy. If that can be further improved with time through machine learning, we are wasting time here then…☺

#6.

Are the graphical displays proposed clear and easy to interpret? Would you feel comfortable using them?

Yes, the color-coded dashboards are clear and easy to understand. It's very important to get a clear idea of the expected impact of weather on traffic flows. The time-series are not that intuitively understandable, they probably need more training.

Are the graphical displays proposed clear and easy to interpret?

The ones explained in the document are clear and easy.

Would you feel comfortable using them?

Yes, no problem.

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#7.

All in all, do you find the proposed probabilistic concept for FMPs useful? In your opinion, does it deserve further effort to produce a functional prototype of the new tool? What functionalities would you like to see in this prototype?

Yes, definitely. As already said, it would be very interesting to investigate the performance of the tools in different traffic and weather conditions. The proposed presentation is a very good first step. Tools for What/If analysis would be desirable.

All in all, do you find the proposed probabilistic concept for FMPs useful?

Yes, we think it is worth exploring further, as it is a very different approach to the current "exact" guess of the Traffic Demand/Load, but if the results are comparable on same scale we definitely think it is worth exploring. Volatility of Traffic Load is very different at different parts of the Network so probably not all ANSP have the issue of Predictability.

In your opinion, does it deserve further effort to produce a functional prototype of the new tool?

Yes, we would like to test the prototype.

What functionalities would you like to see in this prototype?

Flight list of ad-hoc created Object. Draw a cloud/area of convection on Map and get flight list of flights penetrating the area now, or in 3 hours ahead.

Show known/expected location of Jet stream and turbulence with FL information – because normally AO's descend/climb very quickly (change sector and sector load) once they hit area of turbulence.

#8.

Finally, please add any additional comment, thought or new idea that you may have.

As already mentioned, What/If analysis tools could be very helpful.

Perhaps, you could experiment with alternative presentations, that possibly could enhance the intuitive comprehensibility.

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5 Conclusions and next steps

NAVSIM simulations have provided a positive assessment of the probabilistic methodologies for traffic analysis developed in this project, within the limitations inherent to both the predictions and the simulated reality. Taking into account that the expectation was not to perfectly match the NAVSIM reality, since NAVSIM is a simulator and not the reality itself, the results are promising and encourage further developments.

Several factors have been identified that may limit the accuracy of the predictions:

- 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 areas to avoid.
- The absence of holdings in the trajectory predictors, in cases where the traffic and weather situation calls for this measure.
- The lack of lateral deviations in the long-term trajectory predictor.
- The safety margin used in the predictions, which was obtained from the literature as a reference value, may be conservative as, in this use case, it has led to a blockage of the airspace in some time periods.

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 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.
- Refinement of the safety margin and using data from Europe.

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, which deserves to be explored further. Nonetheless, they have pointed out that with only one use case analysed it is difficult to make a solid assessment; indeed, to build trust in the system more scenarios need to be evaluated.

The experts consulted are comfortable using the graphical displays selected for the tool concept developed, and identify as a possible improvement the addition of a Map View functionality, to have a better perception of the weather status and evolution. They are also very much interested in the What-If functionality to be included in a future development of the tool.

Likewise, 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.

In posterior phases of development, when the concept is considered to be more mature, the assessments or validations should consider comparisons with real traffic. To that end, the ANSP or Eurocontrol should be monitoring the weather and, at a certain time instant, when an adverse weather situation is determined to occur, activate the retrieval and storage of:

- All the information needed to perform the predictions:
  - the last available weather forecasts (nowcast, global EPS, and high-resolution 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.

6 References

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

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

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

[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] García-Heras, J., Soler, M., González-Arribas, D., Eschbacher, K., Rokitansky, C.-H., Sacher, D., Gelhardt, U., Lang, J., Hauf, T., Simarro, J., Valenzuela, A., Franco, A., and Rivas, D. (2021). "Robust flight planning impact assessment considering convective phenomena," Transportation Research Part C: Emerging Technologies, 123, 102968, https://doi.org/10.1016/j.trc.2021.102968.

[7] Hirtl, M., Arnold, D., Baro, R., Brenot, H., Coltelli, M., Eschbacher, K., Hard-Stremayer, H., Lipok, F., Maurer, C., Meinhard, D., Mona, L., Mulder, M. D., Papagiannopoulos, N., Pernsteiner, M., Plu, M., Robertson, L., Rokitansky, C.-H., Scherllin-Pirscher, B., Sievers, K., Sofiev, M., Som de Cerff, W., Steinheimer, M., Stuefer, M., Theys, N., Uppstu, A., Wagenaar, S., Winkler, R., Wotawa, G., Zobl, F., and Zopp, R. (2020). "A volcanic-hazard demonstration exercise to assess and mitigate the impacts of volcanic ash clouds on civil and military aviation," Nat. Hazards Earth Syst. Sci., 20, 1719–1739, https://doi.org/10.5194/nhess-20-1719-2020.

[8] Kern, Ch., Steinheimer, M, Kerschbaum, M., Rokitansky, C.-H., Eschbacher, K., and Zobl, F. (2018): Learnings from ATM-KPIs - MET-potentials for arrival- and departure management, MET4LOWW Workshop, Vienna International Airport, Austria, 11 April 2018.

[9] Kerschbaum, M., Steinheimer, M., C.-H. Rokitansky, and K. Eschbacher (2018a); MET-Potenziale für das Arrival und Departure Management (MET4LOWW), FFG Take-off Projekt, 2018: 8, https://open4aviation.at/de/projekte/met4loww.php.

[10] Kerschbaum, M., Steinheimer, M., C.-H. Rokitansky, K. Eschbacher, and Zobl, F. (2018b): Probabilistische MET-Informationen für die Kapazitätsoptimierung im Arrival- und Departure-Management (PROB4LOWW), 2019: 9, https://open4aviation.at/de/projekte/prob4loww.php.

[11] Plu, M., Scherllin-Pirscher, B., Arnold Arias, D., Baro, R., Bigeard, G., Bugliaro, L., Carvalho, A., El Amraoui, L., Eschbacher, K., Hirtl, M., Maurer, C., D. Mulder, M., Piontek, D., Robertson, L., Rokitansky, C-H., Zobl, F., and Zopp, R. (2021): An ensemble of state-of-the art ash dispersion models: towards probabilistic forecasts to increase the resilience of air traffic against volcanic eruptions, . 5 Okt 2021, in: Natural hazards and earth system sciences: NHESS. S. 1-32: 3, https://doi.org/10.5194/nhess-2021-96.

[12] Rokitansky, C.-H., Ehammer, M., and Gräupl, T. (2007): Newsky - building a simulation environment for an integrated aeronautical network architecture. In: 1st CEAS European Air and Space Conference, Berlin, Germany. CEAS, Brussels, Belgium, 2007, pp. 611–618. https://doi.org/10.1109/DASC.2007.4391905.

[13] Rokitansky, C.-H., Eschbacher, K., Mayr, M., and Zobl, F. (2018a), "Advances in ATM simulation by using global flight simulation framework NAVSIM", SESAR Innovation days 2018, pp. 49-50.

[14] Rokitansky, C.-H., Eschbacher, K., Zobl, F., Kallus, W., and Schmidt, R. (2018b), "Intelligent Airport Operations and Advanced Arrival Management Algorithms & Decision Support Tools," in Aviation Psychology in Austria 2018, ed. Kallus.

[15] Steinheimer, M., and Rokitansky, C.-H. (2016): "Air Traffic Management and Weather: the Potential of an Integrated Approach", Proceedings INAIR 2016, Nov. 2016.

[16] EUROCONTROL, «Complexity Metrics for ANSP Benchmarking Analysis,» Brussels, 2006.