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Copyright Statement

COPTRA

COMBINING PROBABLE TRAJECTORIES

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Abstract

This document describes the conclusions of the COPTRA project based on quantitative and qualitative results. In this document, by considering both trajectory and traffic level uncertainties, demand and capacity balancing (DCB) problem in air traffic management (ATM) is described and cascade methodology to solve the considered problem is introduced. Then, validation process for the DCB algorithms are explained with examples and the possible operational implementation of the project output is discussed. Finally, general evaluation of the COPTRA project is given.

Table of Contents

List of Tables

List of Figures

1 Executive Summary

SESAR and their advanced operational functionalities such as Trajectory Based Operations (TBO) will bring together many different improvements that allow the uncertainty of trajectory prediction to be better managed and reduced. Improvements include downlinking of the Extended Projected Profile from the flight to enrich ground trajectory predictions, sharing of detailed information on the ground through SWIM, the submission of more detailed flight plan information, the use of 4D contracts during the flight, increasing adoption of Airport Collaborative Decision Making (CDM), and so on.

COPTRA has focused on developing an efficient methodology to estimate air traffic demand probabilistically by using flight trajectory predictions within a Trajectory Based Operations (TBO) environment. This objective is detailed with three sub-objectives developed through three research work packages: a) define the concept of probabilistic trajectory prediction (WP02); b) define the probabilistic traffic concept and study how it can be constructed by combining probabilistic trajectories, using the probabilistic trajectory definition (WP03); and c) apply probabilistic traffic to Air Traffic Control (ATC) planning (WP04). COPTRA addresses a very specific aspect of TBO related to the ability to support demand-capacity balancing as well as air traffic planning through the identification and management of prediction uncertainty (both at trajectory and traffic levels) as expressed in the S2020 advanced Demand & Capacity Balance (DCB) concept.

COPTRA develops trajectory prediction uncertainties and describes the individual trajectory predictions through stochastic definitions (WP02). In WP03, probabilistic occupancy counts and their time-based behaviours are obtained through a stochastic queuing network model and a graph model at the network level. WP02 results are taken as input in WP03. Afterward, the output of WP03 is used for the identification of critical flights and balancing demand and capacity in a probabilistic way (WP04).

In WP02, COPTRA concentrates on the characterization of trajectory prediction uncertainty sources. The proposed approach monitors deviations between predicted and actual trajectories and defines the uncertainties that cause these deviations regarding probabilistic distributions. The primary sources of trajectory prediction uncertainty that have been considered are initial aircraft mass; initial time; cruise altitude; cruise speed; and top-of-descent location (measured as the flown distance from the departure point). Quantification of the uncertainties associated with individual aircraft trajectory predictions is based on the application of the Polynomial Chaos (PC) theory. The method relies on univariate polynomial descriptions of the sources of uncertainty affecting the trajectory prediction process that is used to determine the multivariate polynomial expansions that represent the variability of the predicted aircraft state variables. Aircraft trajectory prediction uncertainty can be described as the estimated amount or percentage by which a predicted trajectory may potentially differ from the actual trajectory. Main advantages of this solution are four: explicit representations of the uncertainty sources are not required; polynomial expansions are easily obtained; it does not imply any modification of the original definition of the Trajectory Predictor (TP) specification; and it can apply to different models by just using a different input sampling.

At the network level (WP03), COPTRA first obtains the probability that, at any given time, a flight is within a sector; second, it computes the distribution of the probabilistic occupancy counts by combining the individual probability distributions computed in WP02. To solve this problem, COPTRA proposes two approaches. The first one utilizes graph theory and big data analytics to process available data set and identify critical flights. In the second one, COPTRA develops a queueing network model mimicking the dynamics of the uncertainty propagation in European air traffic network.

The operational application of COPTRA approach is studied in WP04. To do so, WP04 (a) injects probabilistic traffic predictions into DCB prototype tools (existing prototypes were adapted to demonstrate the benefit of using and conveying probabilistic traffic predictions); and (b) measures improvements regarding traffic prediction accuracy. WP04 builds on the results of WP02 in terms of probabilistic trajectory predictions and on WP03 for the combination of probabilistic trajectory predictions into probabilistic traffic predictions (in the form of occupancy count distributions). Results were generated through the performance of five validation exercises: Exercises 1 and 2 studied the viability of using probabilistic traffic prediction to improve occupancy count predictions (objective b.). Exercises 3 and 4 studied the potential impact of probabilistic traffic prediction on DCB and ATC planning processes by considering the detection of hotspot situations in a probabilistic setup (objective a. and b.). Exercise 5 researched how probabilistic traffic predictions can be (visually) conveyed to the local traffic manager. The exercises measured the improvement in prediction accuracy.

Further research is needed to evaluate systematically the theoretical properties, the possibilities for improvement, and the practical implementability of the developed models. COPTRA provides algorithms and models to that end.

COPTRA’s broad goal was to build probabilistic models for the prediction of sector occupancy and demand of the European air traffic network taking into account the uncertainty in planned flight trajectories. Several key challenges have been singled out: (a) the characterization of uncertainties on the individual trajectories and possibly managing them; (b) the development of accurate models for the uncertainty in the European air traffic network; (c) the study of control strategies for providing optimal aircraft trajectories within a TBO environment; and (d) the integration of these tools into the current ATM system.

These areas overlap as, e.g., the uncertainty in air traffic network can be linked to the choice of a control strategy, and the integration of a model providing pertinent information to a controller can serve to better control the status of the whole air traffic network. Following are potential future research needs in the scope of COPTRA that will lead to further operational improvements:

- Improved uncertainty estimation through model-driven state estimation based on machine learning and hybrid estimation theory
- Applying/Comparing/Connecting several mathematical models, which have applications to other modes of transportation and strong theoretical foundation
- Elaboration of fast algorithms and heuristics, backed up with theoretical analysis, able to provide control strategies leading to near-optimal solutions
- Defining air traffic complexity metric and integrating into demand and capacity balancing
- Applying network resiliency and integrating into air traffic network flow management through “network stability.”

- Developing advanced visualization techniques to present relevant information in an efficient way

2 Project Overview

2.1 Operational/Technical Context

The prediction of future air traffic situations is central ATC planning. Its uses range from Air Traffic Controller (ATCo) workload management to ensure capacity, to helping the setup of flow management measurements when the demand cannot be accommodated.

Different methods are used to generate forecasts for different time horizons to support relevant decisions; the basic question always being "how can the demand be met?" Long-term answers might be "build a new control centre" and "train some new controllers" and so on. The medium-term question might be answered by managing the controller leave roster and planning the "sector opening scheme." The time-frame of the main concern of this work is the ATC planning horizon (about 90 mins.), with a mix of activated airborne flights (Reference Business Trajectory (RBT) available) and flights still in planning (Strategic Business Trajectory (SBT) available). It is however intended that the scheme developed in this work will generally apply to all time-frames.

Trajectory Based Operations (TBO) brings together many different improvements that allow the uncertainty of trajectory prediction to be better managed and reduced. These include downlinking of the Extended Projected Profile from the flight to enrich ground trajectory predictions, sharing of detailed information on the ground through SWIM, the submission of more detailed flight plan information, the use of 4D contracts during the flight, increasing adoption of Airport Collaborative Decision Making (CDM), and so on.

Predicting occupancy counts is central to ATC planning and DCB: the predicted values are used to choose the right airspace sectorisation or decide on necessary regulations. Today, however, the uncertainties on the inputs of counting process (like take-off time) make the count predictions highly volatile.

Many sources of uncertainty exist in ATM leading to non-optimal preventive actions (increased margins or buffers).

In [14], Irvine details the Capacity buffer theory that states that sector capacity is set to control the probability of occupancy counts exceeding the peak acceptable level. The theory establishes a direct link between count uncertainty and sector capacity. This stresses for the need manage better uncertainty and to find ways to make it explicit.

One major source of uncertainty is related to the actual off-block and take-off times, which can be offset for numerous reasons. Delay data is extensively collected and documented (see, e.g., EUROCONTROL's Central Office for Delay Analysis [15]).

When predicting sector occupancy counts, uncertainty also comes from the differences between the flight planning information (used to predict sector occupancy) and the way the flights are eventually flown.

2.2 Project Scope and Objectives

COPTRA proposes an efficient method to forecast air traffic probabilistically by using flight trajectory predictions within a Trajectory Based Operations (TBO) environment. This objective is detailed with three sub-objectives that form three research work packages:

1. Define the concept of probabilistic trajectory prediction (WP02).
2. Define the probabilistic traffic concept and study how it can be constructed by combining probabilistic trajectories, using the probabilistic trajectory definition (WP03).
3. Apply probabilistic traffic to Air Traffic Control (ATC) planning (WP04).

COPTRA addresses a very specific aspect of TBO related with the ability to help demand-capacity as well as traffic planning through the identification and management of prediction uncertainty (both at trajectory and traffic levels) as expressed in the S2020 advanced Demand & Capacity Balance (DCB) concept. The added value that this deliverable brings into the SESAR 2020 programme is mainly the provision of a probabilistic trajectory predictor and a traffic uncertainty propagation framework to the S2020 PJ09.01 “Advanced Demand and Capacity Balance”, including an assessment of how integrating trajectory uncertainty models into existing tools. Furthermore, a project added-value output will be the provision of traffic prediction based on probabilistic traffic situations to S2020 PJ09 (Network Prediction and Performance).

2.3 Work Performed

The scope of the COPTRA is to propose an efficient method to build probabilistic traffic forecasts based on flight trajectory predictions within a TBO environment. This objective can be detailed as defining and predicting the concept of probabilistic trajectories (WP02), defining the concept of probabilistic traffic situation by using probabilistic trajectory definition, studying how probabilistic traffic situations can be built by combining probabilistic trajectories (WP03) and applying probabilistic traffic situations to ATC planning (WP04).

In Figure 1, the methodological structure of the COPTRA project is given. First, nominal individual trajectories are predicted by using the actual Flight Plan. On the other hand, physical uncertainties in single flight level are obtained. Therefore, by using these two outputs, prediction of individual trajectories is made stochastically which takes place under WP02. In WP03, occupancy count distributions are generated with uncertainty analysis by using stochastic queuing network model and graph model at the network level. WP02 results are taken as input in WP03. Afterwards, the output of the WP03 is used for the identification of critical flights and the determination of probabilistic demand capacity balancing.

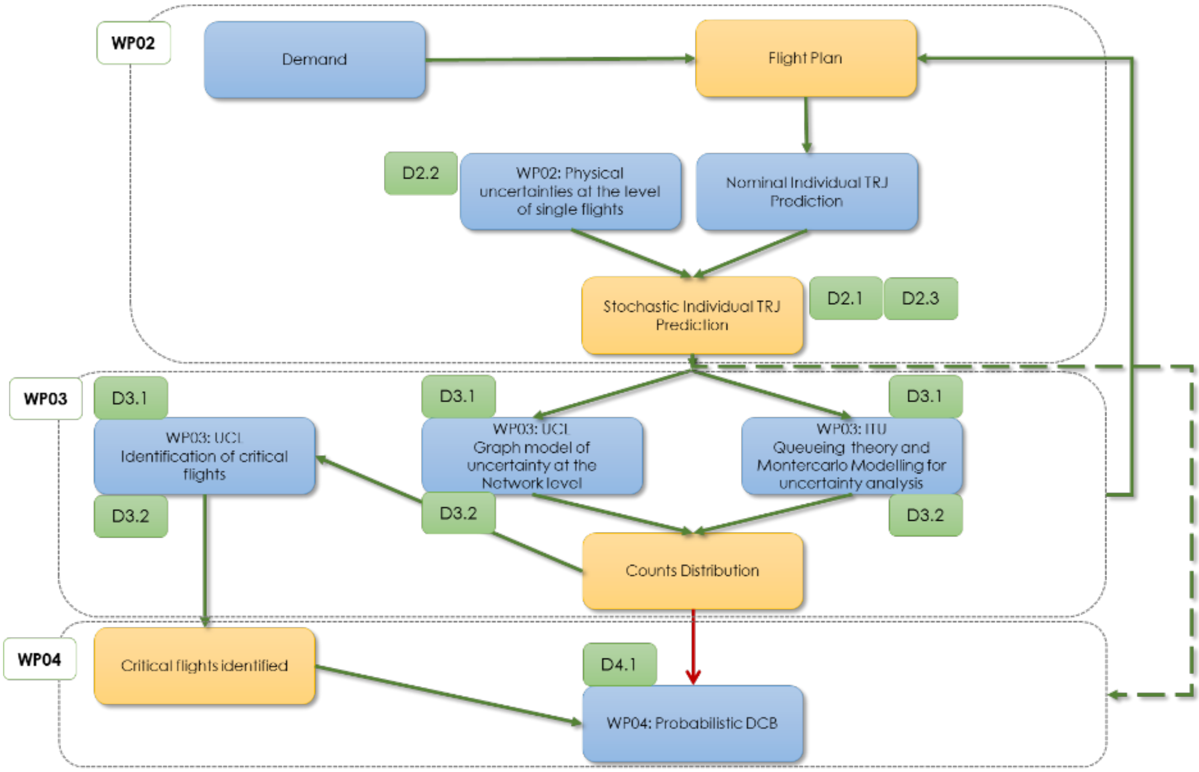

Figure 1. COPTRA block diagram

2.4 Key Project Results

2.4.1 Quantification of TP Uncertainties

2.4.1.1 Characterization of Sources of TP Uncertainties

This part of COPTRA focuses on the characterization of sources of trajectory prediction uncertainty. Specifically, the approach is to monitor deviations between predicted and actual trajectories and defining the uncertainties that cause these deviations in terms of probabilistic distributions [2]. In COPTRA, the main sources of trajectory prediction uncertainty that have been considered are: initial aircraft mass, initial time, cruise altitude, cruise speed and top-of-descent location (measured as the flown distance from the departure point). These parameters of interest are considered as the primary sources (details are given in D2.1 [2]) due to their significant impact on trajectory prediction.

In this WP, three different database types are utilized to obtain probabilistic distributions that characterize the sources of uncertainty: Quick Access Recorder (QAR), Automatic Dependent Surveillance Broadcast (ADS-B) and ALLFT+ of EUROCONTROL's Demand Data Repository (DDR). QAR refers to an airborne flight data recorder designed to provide quick and easy access to raw flight data. ADS-B is a surveillance methodology widely utilized by airborne vehicles and based on broadcasting their state information periodically. The other data source that is being utilized for analysing sources of trajectory uncertainty is ALLFT+ from DDR2 (Demand Data Repository version 2) published by EUROCONTROL. This dataset includes different data profiles for each flight such as FTFM and CTFM.

Even though sources of uncertainty to be characterized are reduced to a small number, the investigated flights are undoubtedly affected by all of them. Besides the selected parameters, Air Traffic Controller actions have the significant influence on deviations from planned trajectories. This uncertainty is considered as out of scope because it cannot be modelled as a stochastic input. In order to extract distributions regarding the considered sources of uncertainty and to be consistent in the results, specific origin-destination pairs are selected and applied to cluster the flights. Figure 2 shows an example of selecting proper subset of trajectories by clustering. In the clustering process, most frequent waypoints are observed in FTFM trajectories so that a nominal trajectory for the specified origin-destination pair is obtained. The rest of the section describes how the distributions are extracted from the available dataset.

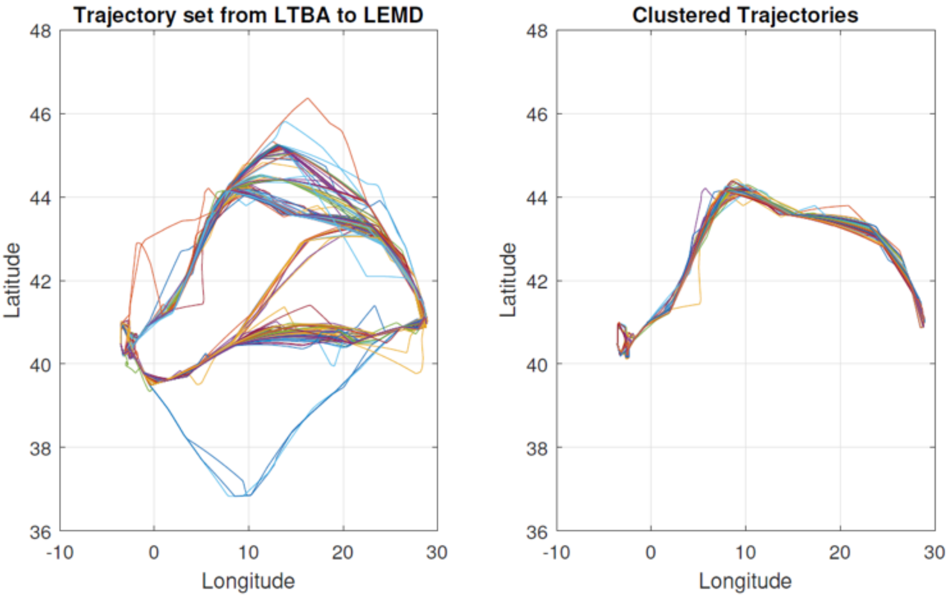

Figure 2. An example of trajectory clustering

In order to characterize the uncertainty sources, three different approaches have been applied. First, the required parameters are directly sampled from the dataset, without any process. Second, the concerned parameters are obtained by implementing a post-process to the available information. Third, planned and the actual states are compared based on waypoints in common. In this last technique, if the aircraft flies by one waypoint in the FTFM profile (within a specified distance tolerance), that waypoint is added into the common waypoint list. Then, the discrepancies between the planned and the actual trajectories at these waypoints are analysed. Figure 3 illustrates an example of a part of this process. In this picture, the waypoints in which the aircraft flown by are depicted. This is repeated for all the flights in the clustered trajectory subset. Then, the common waypoints for these flights are acquired. For instance, this set contains waypoints VADEN, DOLAP, TORPO, BAGNO, OIVKO and SELVA.

Utilizing the described techniques, the distributions related to the parameters of interest are acquired from the data as follows:

1. Initial Mass: Mass uncertainty is considered as the difference between the baseline take-off mass (evaluated through BADA) utilized by generic trajectory predictors and take-off mass recorded in QAR.

2. Initial Time: Initial time distributions are obtained by fitting probabilistic distribution functions at arrival times to these locations from their take-off moments, which are obtained through FTFM data.

3. Cruise Altitude: Cruise altitude identification is straightforward for the flights with single cruise phase. On the other hand, waypoint-based analysis is utilized for those flights with step-climbs or multiple cruise segments at different Flight Levels. In this case, discrepancies between planned and actual altitudes at common waypoints are considered to quantify the prediction uncertainty. Figure 4 reveals an example for the second case. In this example, it can be seen that there are multiple cruise segments hence evaluating a single value for cruise altitude is not a proper solution. Differences between cruise altitudes at the common waypoints of planned and actual trajectories are considered instead. Cruise altitude distributions are obtained through QAR and FTFM data comparison.

4. Cruise Speed: Cruise speed distributions are obtained through QAR and FTFM data comparison, which includes time stamp synchronization processing as their recording sources are entirely different. Mean values of aircraft speeds during flights at cruise altitudes are considered while generating the distributions.

5. Top of Descent (ToD): ToD locations and their deviations are obtained through planned (i.e. FTFM) and actual flight records (i.e. QAR) comparison. The process is straightforward for the flights performing a continuous/single descent. However, many flights include cascade descent, where there exist multiple level-off segments between the descent segments. Additionally, some flights contain drops between 2,000-5,000 ft in cruise altitude far in advance from their actual ToD point. To avoid these cases, heuristic decision methodologies have been developed, e. g., ToD locations are computed such that the aircraft lose a specified amount of altitude for a specified amount of time. These parameters, of course, depends on the type of the aircraft.

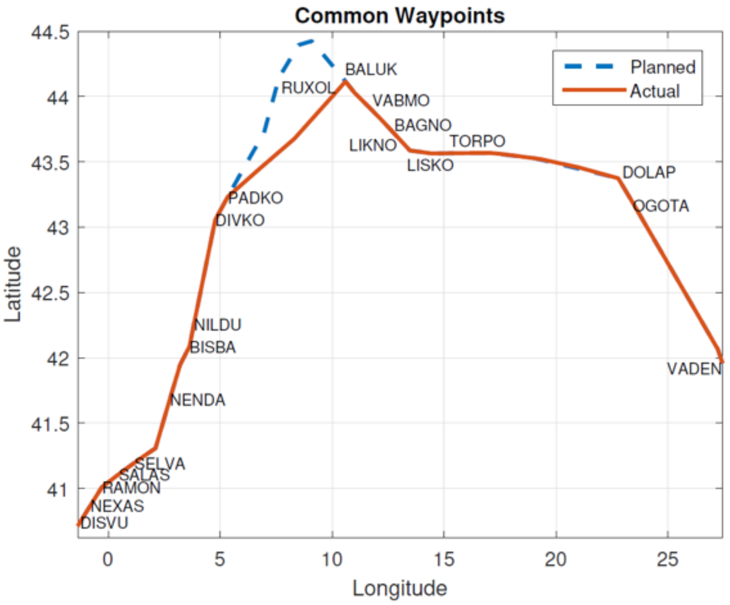

Figure 3. An example of waypoint-based analysis

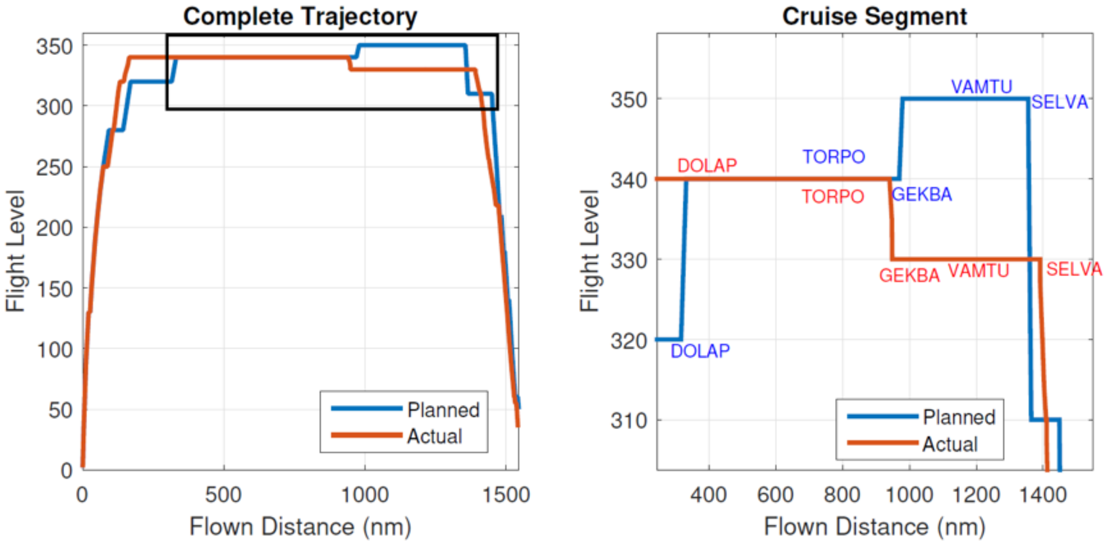

Figure 4. An example of waypoint-based analysis for cruise altitude uncertainty

2.4.1.2 Uncertainty Quantification Framework

The COPTRA approach to quantify the uncertainty associated with individual aircraft trajectory predictions is based on the application of the Polynomial Chaos (PC) theory. The proposed method relies on univariate polynomial descriptions of the sources of uncertainty affecting the trajectory prediction process that are used to determine the multivariate polynomial expansions that represent the variability of the predicted aircraft state variables.

Aircraft trajectory prediction uncertainty can be described as the estimated amount or percentage by which a predicted trajectory may potentially differ from the actual trajectory. Dissimilar to trajectory accuracy, trajectory uncertainty cannot be obtained by comparing predictions against actual trajectories because the uncertainty represents an a priori estimation of such probable deviations based on the knowledge and quantification of the input sources.

Leveraging a classical trajectory prediction framework [1] extensively used for ATM purposes, the uncertainty sources affecting the process of predicting an aircraft trajectory can be classified as:

- Initial Conditions (IC) uncertainties, which consider the deviations between the actual and assumed initial values of the aircraft state variables.
- Aircraft Motion Model (AMM) uncertainties, which represent the differences between the real aircraft behavior and the mathematical system of equations that models it. The assumptions and simplifications considered to formulate the AMM leads to inaccuracies and, therefore, introduce uncertainty to the process.
- Aircraft Performance Model (APM) uncertainties, which collect all inaccuracies of the mathematical models used to represent the actual aircraft performance.
- Earth and Weather Model (EWM) uncertainties, which include the errors introduced by the considered earth model respect to the actual earth surface and gravity, and also, the intrinsic stochasticity associated to any weather forecast.
- Aircraft Intent (AI) uncertainties, which identify the variations on how the aircraft is finally operated compared to the original plan. The AI can be described by a chronologically ordered sequence of operations. Each operation represents a set of command and control actions that determine a unique aircraft behavior during a certain time interval.

Because it is not possible to analytically characterize all uncertainty inputs, the arbitrary PC Expansions (aPCE) approach has been considered as most suitable to quantify the trajectory predictions uncertainty [2]. This approach requires the construction of the polynomial basis representing the stochastic behaviour of each input source by means of the statistical moments calculated from recorded data. Once the univariate expansions that characterize the inputs uncertainty are computed, the multivariate expansions representing the trajectory prediction uncertainties can be obtained by following the non-intrusive Probabilistic Collocation Method (PCM). This approach treats the Trajectory Prediction module as a black-box. The input uncertainty data are sampled to obtain the set of corresponding outputs from which the multivariate expansions can be identified by regression methods. Main advantages of this solution are: explicit representations of the uncertainty sources is not required; polynomial expansions are easily obtained; it does not imply any modification of the original definition of the Trajectory Predictor (TP) specification; and it can be applicable to different models by just using a different input sampling. The PCM establishes at which collocation points the TP needs to be evaluated to obtain the intentioned set of trajectory predictions that enable the identification of the outputs PCEs.

2.4.2 Propagation of Uncertainties on Network

2.4.2.1 Probabilistic Occupancy Count Model

Nowadays, air traffic controllers base their decisions on the nominal expected occupancy count, which is often computed by using the flight plans, added with a heuristic, experienced-based, confidence bound. Within COPTRA, we provided a novel solution to compute rigorous probabilistic occupancy counts from individual trajectories and associated uncertainties.

The idea is to leverage uncertainties on flight trajectories in two steps. First, obtain the probability that, at any given time, a flight is within a sector. Second, compute the distribution of the probabilistic occupancy counts by combining the individual probability distributions computed in the first step. In order to achieve this, we provided optimized algorithms for both tasks.

COPTRA solution to this issue [3] is demonstrated on the European network using data provided by EUROCONTROL (DDR2 database [5]). It is observed that the computation time of the developed algorithms was low, and that this model could be used for network-wide demand capacity balancing.

Numerical experiments have been presented to support the results. Figure 5 reports a probabilistic occupancy count for a sector over Belgium at 12h00 on May 12 2016. It can be easily observed there, for instance, that the probability of having 12 or more flights in the sector at that time is close to 0.

Figure 6 puts together all probabilistic occupancy charts for all sectors across Europe. There, the average occupancy of each sector normalized by its area is shown for May 12 2016, at 12h00. We see that such visualization allows us to quickly determine "hot spots" over Europe, where the traffic density is higher, and "cold spots", where the traffic density is lower.

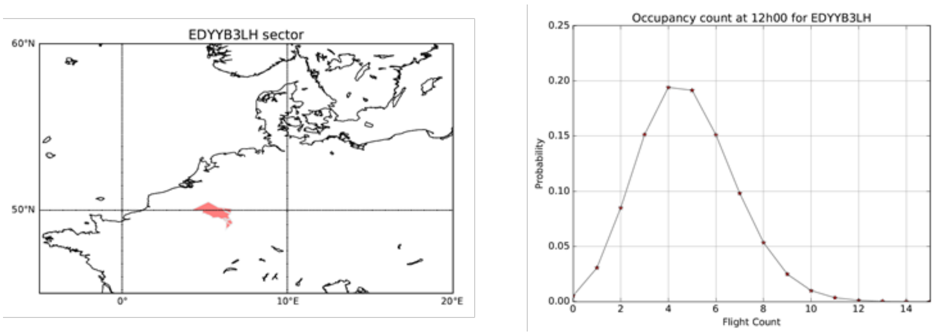

Figure 5. Sector EDYYB3LH and its probabilistic occupancy count at 12h00 on may 12 2016

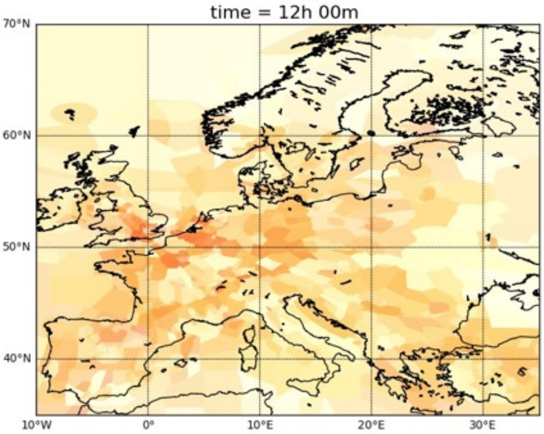

Figure 6. Expected occupancy counts across Europe at 12h00 on May 12 2016, normalized by sector area. Hotter colors represent higher normalized occupancy

2.4.2.2 Flight Criticality Measures

One of the main challenges in ATM is to manage congestion within sectors, that is, making sure that the sectors capacity is not overloaded. This is mainly achieved through a careful scheduling and routing of flights, as well as through the work of air controllers. With this work, our aim is to provide the tools to identify critical flights – those that contribute the most to the congestion of the air traffic network as a whole. These tools take the form of metrics. Their aim is to support the decision process followed to decide whether or not a flight should be subject to Air Traffic Flow and Capacity Management measures for the purposes of maintaining network [4].

In COPTRA, two families of metrics are established. Both computed using the tools developed in Section 3.3.1. The first family relies on the *congestion index*, defined as *the probability that, at a given time, the occupancy of a sector exceeds its capacity.* The second relies on the *buffer index*, defined *as the ratio, at a given time, of the expected occupancy of a sector plus standard deviation over its capacity.*

As a rule of thumb, *a buffer index smaller than one, for a sector at a given time, means that around 85% of the traffic there and then is below its capacity.*

For a given flight, then 6 indices are computed from these two metrics. The three first indices are related to the congestion index and are: (1) **Total Congestion Index (TCI)**, i.e. understood as the probability that a flight crosses an overloaded sector; (2) **Average Congestion Index (ACI)**, which is the TCI of the flight normalized by the number of sectors crossed by it; (3) the **Maximal Congestion Index (MCI)**, which corresponds to the maximum probability, over all sectors, that a flight crosses an overloaded sector.

The three other indices are related with the buffer index instead of the congestion index. Namely, (4) the **Total Buffer Index (TBI)**, that can be understood as the average, over all sectors and times, of the buffer index of sectors crossed by the flight; (5) the **Average Buffer Index (ABI)**, which is the TBI normalized by the number of sectors crossed by the flight; and finally (6) the **Maximal Buffer Index (MBI)**, which corresponds to the worst case contribution of the flight to a buffer index, accounting for probabilities to cross the different sectors.

These indices allow us to detect the flights that contribute the most to the network's congestion. We can compute them, for each flight, using the tools of Section 3.3.1 as well as probabilistic flight plans. Once defined, their relevance is shown through the analysis of the effect of either ground-holding or cancelling flights with high indices.

This has been achieved by using the EUROCONTROL DDR2 database [5] and considering the day of May 12 2016. The process begun by defining a quantity to serve as a baseline indicating how congested was the network on that day". More precisely, It has been defined the *total overload probability* Ω as the sum, among all sectors and all times, of the probabilities that a sector is overloaded at that time. On that date it was observed as Ω = 105,409.06.

The following results were observed about the ground holding policy:

- By applying a ground holding of 14.4 minutes to the top 1% flights in terms of *Total Congestion Index* as well as to the top 1% flights in terms of *Average Congestion Index*, we obtained *a decrease of* 0.03% of Ω. A similar decrease was observed when using the buffer index metric (TBI and ABI).

- In comparison, when the ground delay was applied to randomly chosen flights, Ω *increased* by 0.01%.

This does show that the metrics capture relevant information about air traffic congestion and that they should be considered when making decisions about ground-holding policies. Figure 7 shows the impact of ground holding flights identified by the metrics. The left figure corresponds to the Congestion Index Metric, and that on the right to the Buffer Index metric. On both figures, the horizontal axis corresponds to the total index, the vertical index to the average index, and the size of the bubble to the max index of a flight. Green/red bubbles are obtained before applying the ground delay, and the blue bubbles are obtained after. We observe an overall reduction in the congestion metrics, indicating an improvement in the network's congestion.

For the matter of cancelling flights, the following results were observed:

- By cancelling the top 1% flights in terms of *Total Congestion Index* as well as the top 1% flights in terms of *Average Congestion Index*, it was observed a decrease of 6.19% of Ω. . The decrease is of 6.51% when using the buffer index metrics (TBI and ABI).
- *When cancelling random flights, the decrease in Ω was of 2.85%, only half of the effect obtained when relying on the indices.*

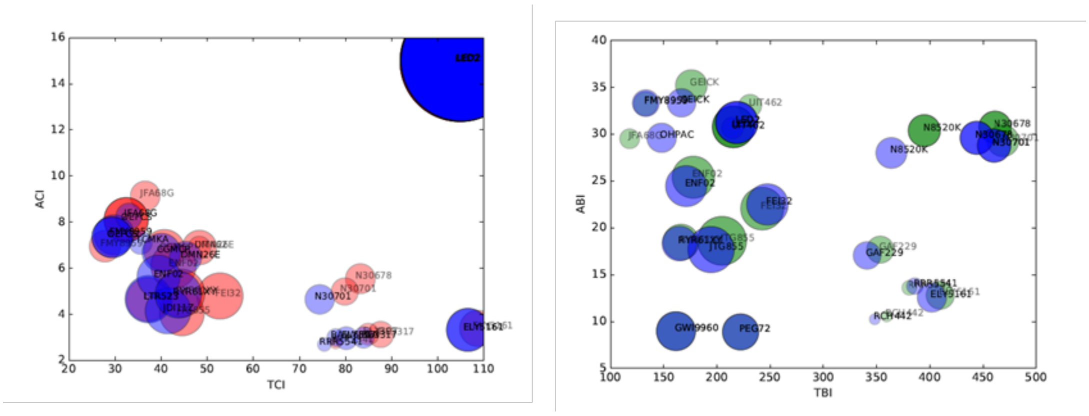

Figure 7. Visualization of criticality metrics, before and after applying ground delays on the flights with metrics in the top 0.5%.

In conclusion, we observe that the metrics are relevant and should be considered for deciding on Air Traffic Flow and Capacity Management measures to apply.

2.4.2.3 Stochastic Queuing Network Model

New procedures and concepts that are being developed in SESAR are leading to a global paradigm shift from air traffic "control" to efficient air traffic "management", which requires redesigning the identification of the interactions between the elements of the system. For example; deciding how much capacity reduction on the airport should be applied under severe weather conditions and how the remaining capacity will be allocated without interrupting the entire traffic network are not trivial issues. Queuing network models are mainly considered to model air transport network system to see how delay or uncertainty propagation affects over the air traffic network and to understand how the network responds collectively to local delays.

Queue model deals with modelling waiting lines with mathematical expressions and estimating queue lengths and waiting times. To analyze queues properly, mainly two parameters are needed which are service time durations at servers and customer arrivals that can be named as inter-arrival times. In queuing models, customers wait in the queue to receive service and terminate their relation with the system when the service is completed. However, customers might need different services at different servers with different sequences. Therefore, that kind of situation can be modelled with queuing network models by connecting various queues to understand the causes of delays in the air transportation system and to see the delay propagation effects over the network.

In COPTRA approach through queueing network model [3], scheduled flights for the selected date are analyzed according to their departures, flight durations, and arrivals. In order to obtain the required information for the scheduled flights, EUROCONTROL’s ALLFT+ data is used.

Considered queue network consists of three main parts: airports, airspaces and flights. For the modelling of airport and airspace queues, maximum demands (both arrivals and departures for airports, entries for airspaces) -which are evaluated from processing ALLFT+ data for each season (summer and winter of 2016)- are taken into consideration. According to airport and airspace demands, airports and airspaces that are far from their capacity limits and service times are determined. In queueing network model, each airport and airspace is constructed as a $G(t) / \Gamma(t) / 1$ type queue that corresponds to arrival times that are obtained with general distribution that can be any distribution, and airport/airspace service times that are obtained using gamma distribution where single server per resource is used with first-come-first-served (FCFS) policy.

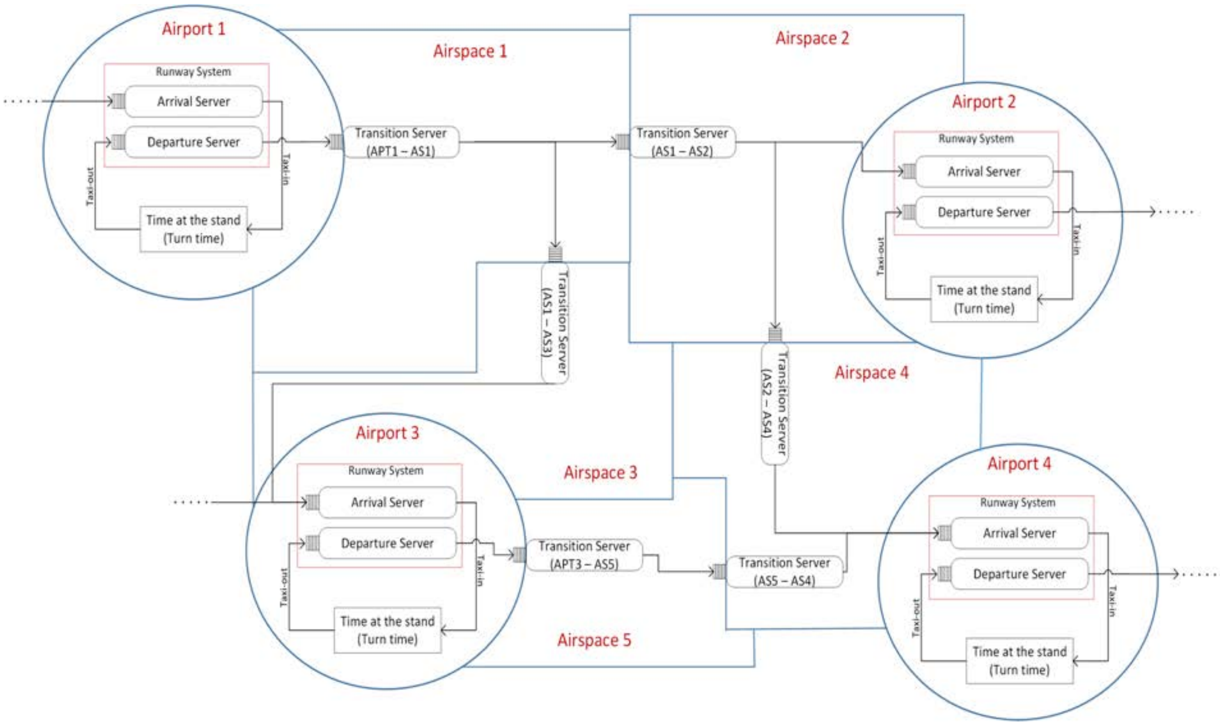

Figure 8. Air traffic queuing network model with airport/airspace queues

The model for the queueing network model consists of three subsequent processes; a) departure airport queues, b) airspace transition queues and c) arrival airport queues. Each aircraft is generated in a parallel manner, in other words, all the aircraft, which exist at that time (probabilistically), are run synchronously within the simulation. The simulation clock speed can be chosen arbitrarily, and the max speed depends on the available computational power.

Service time calculation for airports and airspaces are found by considering rush hours for airports/airspaces and using the current tactical flight model (CTFM) data of the flights. Afterwards, proper probabilistic distributions are fitted to obtained service time data.

For the service time calculations, shape (k) and scale (θ) parameters are found for the Gamma distribution by using obtained service time datasets for airports/airspaces. Service time distribution for France Upper Information Region (LFFFUIR) is as shown in Figure 9. Shape (k) and scale (θ) parameters are calculated as 0.8547 and 8.8038 respectively. If the mean value is calculated $(E[x] = k\,\theta)$, the mean service time for LFFFUIR can be obtained as 7.52 seconds per aircraft.

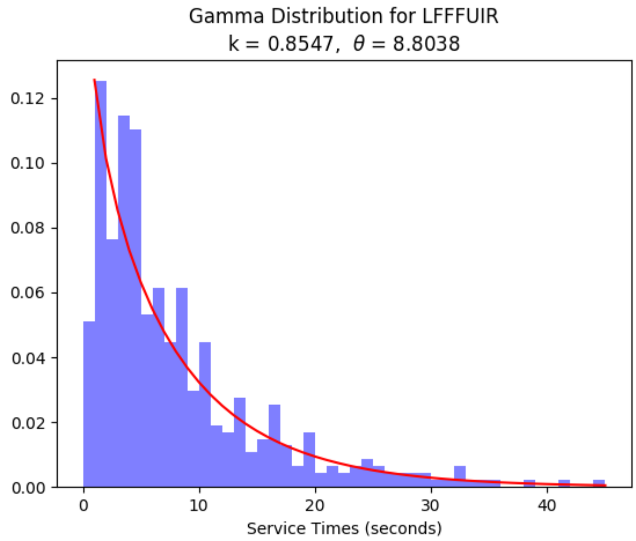

Figure 9. Service time histogram and gamma distribution for LFFFUIR

Simulations are conducted by considering both the service time uncertainty at airports/airspaces and inter-arrival time uncertainty. In Figure 10, results for both LFFFUIR maximum and average demand histogram and LFFFUIR demand histogram and fitted normal distribution for the 13:00 – 13:15 interval is given.

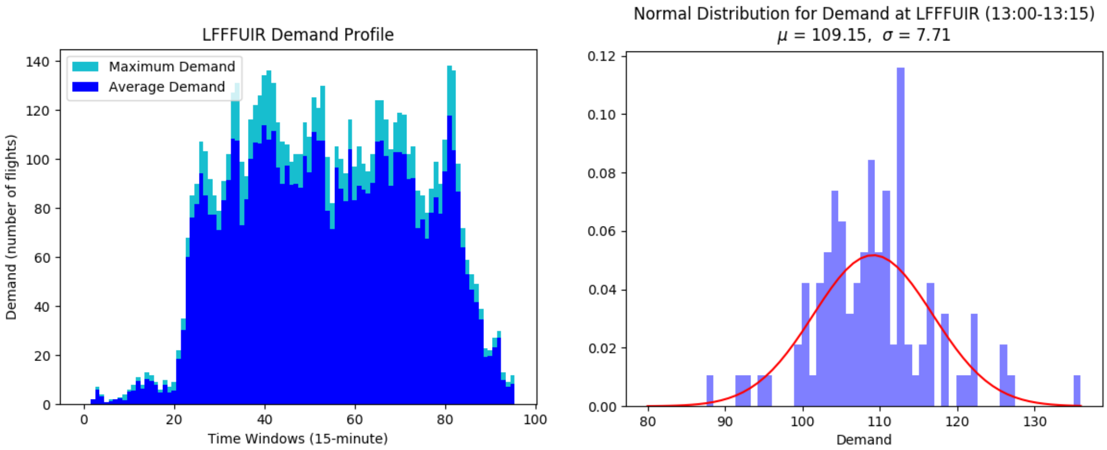

Figure 10. Histogram for max. and avg. demand at LFFFUIR with uncertainties (left), demand histogram and normal distribution for LFFFUIR at 13:00-13:15 (right)

2.4.3 Approaches for Application to ATC Planning

The application of the COPTRA approach to ATC Planning was researched by the fourth work package of the project. The objectives of this work package are to:

a. Inject probabilistic traffic predictions into DCB prototype tools. Existing prototypes (see below) were adapted to demonstrate the benefit of using and conveying probabilistic traffic predictions.

b. Measure the improvements in terms of traffic prediction accuracy. In particular compare occupancy predicted from probabilistic traffic situations with the predictions made with today's tools and with the real occupancies.

WP04 builds on the results of WP02 in term of probabilistic trajectory predictions and WP03 for the combination of probabilistic trajectory predictions into probabilistic traffic predictions (in the form of occupancy count distributions).

Results were generated through the performance of five validation exercises: Exercises 1 and 2 studied the viability of using probabilistic traffic prediction to improve occupancy count predictions (objective b.). Exercises 3 and 4 studied the potential impact of probabilistic traffic prediction on DCB and ATC planning processes by considering the detection of hotspot situations in a probabilistic setup (objective a. and b.). Exercise 5 researched how probabilistic traffic predictions can be (visually) conveyed to the local traffic manager. The exercises measured the improvement in prediction accuracy.

The approach taken by the exercises is quite similar and is depicted in the following Figure 11:

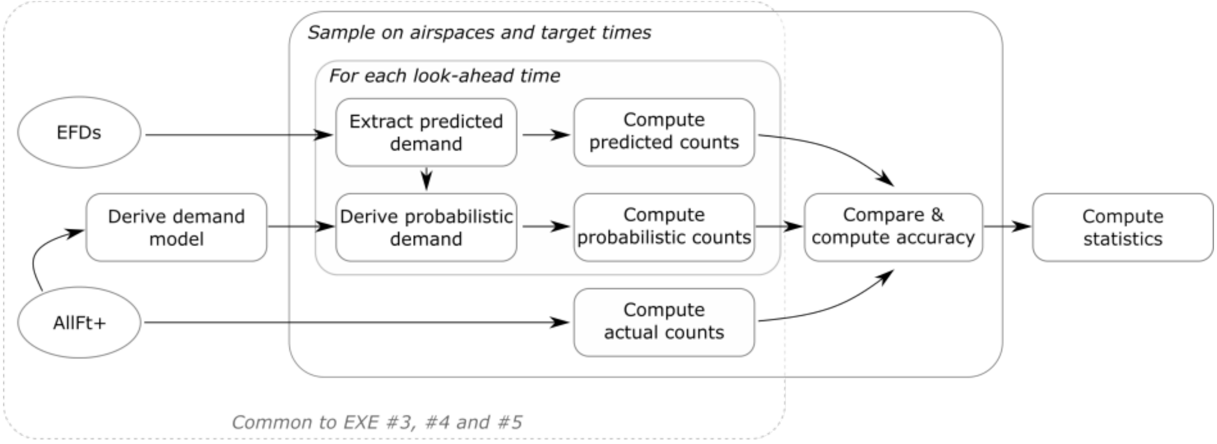

Figure 11. Methodology for application to ATC planning

The common part extracts and computes:

- The baseline counts (current method): the predicted demand for a given target time at for a selected look-ahead time is extracted from the ETFMS Oplog as a set of EFDs.
- The probabilistic counts (COPTRA approach): uncertainty is attached to each flight of the predicted demand (through the use of a “demand model”. The resulting probabilistic trajectories are used to compute the occupancy count distributions.
- The “actual” counts: The actual demand is extracted from the “after the fact” data contained in DDR2 ALLFT+ files. These are in fact the last profiles computed by ETFMS including all the information available at that time (CPRs).

The results of these exercises are detailed in the next section (Section 4).

2.4.4 Validation of DCB Algorithms via Exercises

2.4.4.1 Demand Prediction Accuracy with Improved Flight Plan

COPTRA Validation Exercise #01 compares occupancy counts obtained through flight plans (FPL) in different time horizons (-3h, -1h and 0h), with the occupancy counts obtained from the use of the improved flight plan, imFPL. The objective is to assess the quality of the predictions currently used to estimate the occupancy count of a sector and establish a baseline for further validation.

The applicability of the imFPL, understood as a ‘sort’ of probabilistic trajectory, is mainly to improve the accuracy of the predicted traffic demand, with respect of using the original flight plan, since it will allow a better calculation of the entry and occupancy counts in a sector.

The results of the exercise show that predictions become more accurate as the time of the operation approach. However, there is no match between real values and predicted values; instead, predicted values are always below the real ones, and the following conclusions are derived:

- The problem of uncertainty in the current occupancy count predictions is studied and confirmed.
- The variability is current occupancy count predictions with respect to real values is confirmed.
- The possible improvement on occupancy counts prediction with the use of the imFPL is confirmed as viable.
- The baseline for further validation in this project and forthcoming projects is stablished.

2.4.4.2 Uncertainty in Hotspot Prediction

COPTRA Validation Exercise #02 is focused on determining the occurrence (or not) of a hotspot, based on an improved prediction of the traffic demand. The improvements on traffic prediction are achieved by means of a confidence index associated to it. In this way, occupancy counts for each sector have a probability of occurrence of the occupancy counts predicted values indicating how reliable the numbers the Air Traffic Controller sees on his/her screen are. This allows a better awareness of the traffic situation, resulting in the application of the DCB measures which are strictly necessary.

Air Traffic Controllers are able to judge more accurately the probability of occurrence of a hotspot based on an improved knowledge of the situation, since the occupancy count probability associated to the traffic in their sector allows them to know the probability of flights to enter the sector at specific times. Thus, the number of false hotspots is expected to significantly reduce. This avoids the declaration of unnecessary hotspots with their consequent regulation.

The expected achievements of this scenario are the improvement of network efficiency, though the application of less regulations, the improvements in resource allocation through a better demand estimation, and the increase in flight efficiency.

This validation activity is conducted within the Barcelona ACC scenario. It is carried out by means of modelling and judgmental techniques.

The results from the solution scenario are commonly better than the prediction at -3h of the reference scenario and usually between 0h and 1h. In some cases, the value is even better than the prediction at 0h. Thus, two main conclusions can be stated with these results:

- The COPTRA approach can predict much better than the reference scenario with a prediction time horizon of 3h before departure.
- The COPTRA approach can predict more accurately the hotspots than in current reference scenario.

For the achievement of the success criteria, we can confirm that the baseline has been chosen with hotspot prediction from historical data (days with regulation), the hotspot probabilities are computed with COPTRA approach and compared with the baselines obtaining statistic tables and that COPTRA predicts correctly between 60% and 70 % of hotspot occurrence and reduces the number of 'false hotspots'.

2.4.4.3 Probabilistic Occupancy Counts

COPTRA aims to make a better traffic prediction. This exercise (Exercise #03) attempted to measure that.

Better-ness of prediction is here considered to be in two aspects:

a) That the COPTRA prediction at any moment is closer to the final measured value

b) When the COPTRA prediction is not equal to the final measured value, the uncertainty indicated in the COPTRA prediction is useful.

In the first case there needs to be a direct comparison of the COPTRA prediction with the current method. For the second case there needs to be a statistical analysis of many examples of COPTRA predictions to detect whether the predicted uncertainty is reflected in the counts.

To achieve this, the probabilistic predictions (*Probabilistic counts*) and current occupancy count predictions (*Baseline counts*) were compared to the occupancy counts computed from the final profiles available in the corresponding ALLFT+ archive (*Actuals counts*). The comparison was done for 37 target times falling every half an hour from 05:00 to 23:00 on the 5th of May, 2017. For each target time ***t***, the predictions were compared for 11 look-ahead times (***l***) ranging, every half an hour, from ***t* - 5h** to ***t***.

The comparisons were done using the *Ranked Probability Score* (RPS).

Statistical tests applied to both the means and standard deviations show, at 5% significance level, that:

- The baseline and probabilistic score standard deviations are significantly different for all the look-ahead times. The probabilistic prediction scores being less spread, there is a reduction in uncertainty on the count predictions that according to the *Capacity buffer theory* [14], would lead to a capacity increase.
- The baseline and probabilistic means are significantly different for all look-ahead times except for predictions made at time ***t*** (0-hour look-ahead time) and at ***t - 3h***: In the majority of the cases,

The stability over (look-ahead) time of the probabilistic prediction score has also to be noted as it would mean that probabilistic prediction provides more accurate and stable count predictions earlier in time.

2.4.4.4 Hotspot Probabilities

In ATC Planning and DCB, one of the operators' main questions (in addition to predicting occupancy count) is to detect when occupancy will exceed the available capacity: these events are called "hotspots". The presence of hotspots will trigger action in the form of regulations, STAMs or sectorisation change. Exercise #04 attempts to assess the possible improvements brought by the probabilistic approach in the detection of hotpots.

Hotspot prediction is difficult outside of an operational context. The main reasons include that:

- When capacity is indeed exceeded historical datasets already contain the "solution" to the hotspot situation.
- The applied capacity thresholds are not available in the historical datasets.

To work around these difficulties, exercise #04 takes the theoretical approach of comparing the ability of the baseline/current approach and COPTRA approach to predict over a given period of time if the occupancy counts are above a specified threshold (in an unregulated elementary sector).

This theoretical approach is close to what would be required in an operational setting.

For this exercise, one-hour intervals centered on the 37 targets times every half an hour from 05:00 to 23:00 were used. The baseline and probabilistic approaches were compared for 11 look-ahead times (t – 5h to t every 30 minutes). The capacity threshold was set to 80% of the actual maximum capacity during the period of interest.

The Brier Score is used to compare the baseline and probabilistic approaches to the actual counts. The scores of the probabilistic approach are consistently lower (better) than the baseline approach. The difference is statistically significant.

2.4.4.5 Visualizing Probabilistic Traffic Predictions

In this exercise, two different visualization types have been explored: The direct visualization of the occupancy count distributions, and the annotation of the current/baseline occupancy count graphs.

Direct visualizations of the occupancy count distributions included:

- Figures presenting occupancy count distribution in rather conventional (and "technical") way: the distributions are characterized by their mean and their quantiles.
- Attempts to convey more information about the distributions by giving a full account of the distributions' probability density functions (PDF).
- Presentation of the cumulative distribution functions (CDF) of the distributions instead. This is justified as the operator might be more interested in identifying the occupancy count values having a low probability of being exceeded instead of knowing what the most probable occupancy count values are.

These figures showing the full probability distributions (PDF or CDF) revealed to be difficult to interpret for the operator (in additions the continuous nature of the curves shows fractional occupancy counts that might be difficult to understand and use).

In an attempt to take the operator preferences (risk profiles) into account discrete color maps were used to clearly indicate probability thresholds.

Several ways to annotate the baseline instantaneous occupancy count graphs have been considered. Simple approaches included the annotation of the baseline occupancy count with its likelihood or the probability of it being exceeded.

Finally, in an attempt to indicate the likelihood of the baseline counts, graphs were produced showing the probabilities of the flights making the baseline flight lists. For each occupancy count, the probabilities were sorted with the highest probabilities at the bottom and lowest at the top. The probabilities were normalized on the figure time range.

Conveying probability/uncertainty information about the flights in baseline flight list has however some limitations: the baseline flight list is quite limited compared to the flights that have a not zero probability to be in the sector at that time. In this experiment, the number of flights in the baseline flight lists never represented more than 10% of the flights having a non-zero probability to be in the sector. Similarly, the sum of the probabilities of the flights in the baseline flight list never exceeded 50% of the sum of all flight probabilities. These questions the "representativeness" of the baseline flight list when conveying uncertainty about the baseline counts.

The different figures produced were presented to and discussed with EUROCONTROL ATC Planning experts. They made the following observations:

- "Traditional" ways to visualize uncertainty (mean + quantiles, boxplot…) do not work in practice as they need specific training and time to be correctly used and interpreted.
- Visualizations need to be linked to decision making: it is difficult if not impossible to design generic visualization. The amount of uncertainty information shown and the way it is represented depend on the task at hand.
- They would favor annotations of the current baseline graphs with uncertainty (even if more difficult) to direct display of the occupancy count distributions. This approach would ease the transition from the current tool: the introduction of new visualization types would be too disruptive.

- The uncertainty information should be conveyed through a (very) limited set of discrete levels (e.g. low, medium or high uncertainty) shown as a visual characteristic (e.g. darkness) of the current graphs.

2.4.4.6 Discussions about the Achievement of Goals

The application of the COPTRA approach to ATC planning aimed at:

a. Injecting probabilistic traffic predictions into DCB tools to demonstrate the benefit of using and conveying probabilistic traffic predictions.
b. Measuring the improvements in term of traffic prediction accuracy. In particular compare occupancy predicted from probabilistic traffic situations with the predictions made with today's tools and with the real occupancies.

To achieve its objectives, the five exercises described in the previous sub-sections were conducted.

The concept of COPTRA approach is oriented to the introduction of the uncertainty at individual trajectory level at first, and then extrapolated to traffic uncertainty for the improvement in hotspot prediction.

These exercises have shown that:

- The use of probabilistic traffic models derived from historical data to compute the occupancy count distributions shows at statistically significant reduction of the uncertainty and in most of the cases an improved accuracy in the prediction of occupancy counts.

- The use of occupancy count distributions allows better predicting when an occupancy count threshold will be exceeded. While this result is theoretical, it gives a strong confidence in the performance of the proposed approach at predicting hotspot in an operation environment.

- Different ways to visualize occupancy count distributions or annotate current occupancy count graphs have been explored and discussed with ATC planning experts. It was concluded that uncertainty visualization has to be tailored to decision-making process. At this stage the experts favor the annotation of the existing visualization tools with a limited number of uncertainty levels (e.g. low, medium, high) derived from the occupancy count distributions.

The introduction of the uncertainty associated to traffic demand prediction can increase the number of hotspots correctly predicted and reduce unnecessary DCB measures. The operational feasibility of this solution is proven and COPTRA approach has a great potential on today's DCB management systems.

The improvement in prediction accuracy is assessed and approved with the presented results. The final benefit of this approach is the efficient use of nowadays available human and platform resources, avoiding additional costs of DCB measures implementation.

2.5 Technical Deliverables

<table>
<tr><th>Reference</th><th>Title</th><th>Delivery Date[1]</th><th>Dissemination Level[2]</th></tr>
<tr><th colspan="4">Description</th></tr>
<tr><td>D1.1</td><td>Project Management Plan</td><td>27/07/16</td><td>CONFIDENTIAL</td></tr>
<tr><td colspan="4">Project Management Plan</td></tr>
<tr><td>D2.1 / D2.3</td><td>Techniques to determine trajectory uncertainty and modelling V1 & V2</td><td>07/06/17
15/02/18</td><td>PUBLIC</td></tr>
<tr><td colspan="4">Describe the techniques and calculation methods needed to describe a trajectory in terms of probability.</td></tr>
<tr><td>D2.2</td><td>Quantification of trajectory prediction uncertainty</td><td>07/02/17</td><td>PUBLIC</td></tr>
<tr><td colspan="4">Describe the framework for quantifying the trajectory prediction uncertainty, associating uncertainty boundaries around the nominal (deterministic) values and the future projections of the aircraft state variables</td></tr>
<tr><td>D3.1 / D3.2</td><td>Probabilistic traffic demand Models V1 & V2</td><td>29/08/17
08/01/18</td><td>PUBLIC</td></tr>
<tr><td colspan="4">Present the different models generated following the proposed approaches. The report will include both the textual description of the models as well as the models themselves.</td></tr>
<tr><td>D4.1</td><td>ATC Tools</td><td>30/01/18</td><td>PUBLIC</td></tr>
<tr><td colspan="4">Validation aspects of the use of probabilistic traffic demand applied to ATC planning. The report will describe the work done in the models and prototypes as well as the exercises performed to validate them. The report will include a cost feasibility analysis, a solution maturity analysis and an estimation of the benefit generation potential.</td></tr>
<tr><td>D5.1</td><td>COPTRA Report</td><td>15/02/18</td><td>PUBLIC</td></tr>
<tr><td colspan="4">Conclusions of the project based on quantitative and qualitative results, as well as recommendations for further research.</td></tr>
<tr><td>D6.1 / D6.3</td><td>Exploitation and Dissemination Plan V1 & V2</td><td>15/12/16
30/05/17</td><td>PUBLIC</td></tr>
<tr><td colspan="4">Establish the framework to ensure the correct dissemination of the project results defined in agreement with the consortium partners. Also, define an effective dissemination strategy to maximize the results and achievements of the project throughout both scientific and industrial channels.</td></tr>
<tr><td>D6.2 / D6.4</td><td>Exploitation and Dissemination Report V1 & V2</td><td>27/03/17
13/02/18</td><td>PUBLIC</td></tr>
<tr><td colspan="4">Report on the progress related to:</td></tr>
</table>

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[1] Delivery data of latest edition

[2] Public or Confidential

Reference	**Title**	**Delivery Date[1]**	**Dissemination Level[2]**
Description			
• How the exploitation plans have aligned with the market trends both as a whole and for each partner individually. • Creating scientific contributions to the research community • Establishing and managing dissemination and exploitation activities. • Participation / organization of events (workshops, seminaries) in order to disseminate project results			
D7.1	NEC-Requirement No. 4	23/03/17	CONFIDENTIAL
The applicant must confirm that the ethical standards and guidelines of Horizon2020 will be rigorously applied, regardless of the country in which the research is carried out			
D7.2	NEC - Requirement No. 3	21/04/17	CONFIDENTIAL
The applicant must provide details on the material which will be imported to/exported from EU and provide the adequate authorisations			
D7.3	POPD - Requirement No. 2	07/09/16	CONFIDENTIAL
Detailed information must be provided on the informed consent procedures that will be implemented			
D7.4	POPD - Requirement No. 2	23/03/17	CONFIDENTIAL
Detailed information must be provided on the procedures that will be implemented for data collection, storage, protection, retention and destruction and confirmation that they comply with national and EU legislation			

Table 1: Project Deliverables

3 Links to SESAR Programme

3.1 Contribution to the ATM Master Plan

Code	Name	Project contribution	Maturity at project start	Maturity at project end
CM-0103B	Automated Support for Traffic Complexity Assessment	Partial development of the technical enabler NIMS-30 (ATFCM scenario management equipped with tools for assessing the impact of DAC and capacity changes on trajectory efficiency). COPTRA Develop a model of the level of uncertainty associated to the traffic and airspace organization information obtained within the look ahead times related to the medium to short term planning phase (from 6 hours in advance), that permits to quantify the uncertainty in terms of reliability and airspace volume traffic density.	V0	V1-TRL-2

Table 2: Project Maturity

3.2 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	Yes. The problem identified (as related to the SESAR context) is the improvement on the accuracy of the demand prediction in the 3h to 0h prior to aircraft departure. This should result in improvements in planning, flight management and traffic control (traffic volume throughput). The main issue related to the improvement in the accuracy of the demand prediction is the uncertainty related to both the flight trajectory and to estimation of the sector occupancy.
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Partial - Non-Blocking	Yes, but not in terms of the SESAR KPI. The initial focus of the project was to quantify the uncertainty associated to the estimation process. This has resulted on a characterisation of the trajectory prediction uncertainties and their propagation. However, the impact of the demand prediction uncertainty on the SESAR KPIs has not been assessed.

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
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	There are no limitations to time, location, geographical location or environment (costs have been addressed through the elaboration of an initial CBA). The algorithms have been designed to be flexible. The main weakness of the COPTRA model lies in the uncertainty of the sector entry/leaving times. This issue has been addressed in D2.1 & D2.2 through the introduction of a trajectory model that is able to provide predictions that include uncertainty. Moreover, D3.1 & D3.2 have developed a queuing network model that models the departure time linked with the aircraft flight sequence. However, a more accurate description of the delay distribution could improve the estimation accuracy. Additionally, the validation of the algorithms and tools developed in COPTRA is limited in the sense that only a limited number of sectors and traffic samples has been considered. The use of the algorithms should be further validated in an operationally realistic environment to ensure their accuracy.

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Achieved	Yes. D2.2 & D3.2 provide an extensive state-of-the-art analysis that identifies past and on-going research.
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 use of probabilistic traffic models derived from historical data to compute the occupancy count distributions shows a statistically significant reduction of the uncertainty and in most of the cases an improved accuracy in the prediction of occupancy counts. Furthermore, the use of occupancy count distributions allows better predicting when an occupancy count threshold will be exceeded. While this result is theoretical, it gives a strong confidence in the performance of the proposed approach at predicting hotspot in an operational environment. Altogether, the results show a positive, significant impact on capacity (based on the capacity buffer theory as expressed in [D4.1 ref. 38] "R.Irvine, Enhanced DCB Step 1 R4 Validation Report (VALR) – Part II – EXE-13.02.03- VP723, SESAR Joint Undertaking, 2011")

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.6	Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities? - What are these new capabilities? - Can they be technically implemented?	Achieved	The results should be developed into an operational tool that uses historic demand, planned demand and actual tracks to predict the density of a region of airspace 3 hours in advance of the time of flight. This tool should be Integrated within the local toolset (INAP) and operated by the Local Traffic Manager (LTM). It would receive data from the Network Manager Operations Centre and the local ATM system and would support monitoring in the area of responsibility of the duty LTM, as well as supporting the identification of hotspots. The tool that is described would operate with the "Demand Forecast in Planning" use case and would be used to estimate the traffic density. This tool would be an enabler to CM-0103-B and would be dependent on the NIMS-30 enabler.
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Achieved	The work developed in D2.1 & D2.2 (used later on in D3.1 and D3.2) is based on the flight motion equations. This implies the use of the basic laws and assumption behind classic trajectory mechanics.
TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and drawbacks identified? - Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be	Achieved	The project has elaborated both a validation plan (included in D4.1) and an initial cost benefit analysis (included in D5.1). These two items are based on the identification and development of

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
	that quantitative information already exists, in which case it should be used if possible.		Benefit Impact Mechanisms that guide both the validation and the identification of costs and benefits. D4.1 provides quantitative data on the performance of 5 validation exercises. The analysis performed in this data can support the identification of future validation activities (as indicated in D5.1).
TRL-1.9	Have Initial scientific observations been reported in technical reports (or journals/conference papers)?	Achieved	Yes. Please refer to D6.1, D6.2, D6.3 and D6.4 for an exhaustive list of publication and participation in scientific conferences
TRL-1.10	Have the research hypothesis been formulated and documented?	Achieved	Yes. Please refer to D2.1 & D3.1
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	Even though the results are strongly promising, further research is needed to systematically evaluate the theoretical properties, the possibilities for improvement, and the practical implementability of the developed model. We believe that a research project at TRL 2-4 is the natural next step to take.
TRL-1.12	Are stakeholder's interested about the technology (customer, funding source, etc.)?	Achieved	The Cost Benefit Analysis performed in D5.1 indicates a positive economic model for the implementation of the COPTRA approach. Critical stakeholders (such as the NM and ANSP) have

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
			indicated interest in this type of approach.

Table 3: ER Fund / AO Research Maturity Assessment

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
OPS.ER.1	Has a potential new idea or concept been identified that employs a new scientific fact/principle?	Achieved	Yes. The problem identified (as related to the SESAR context) is the improvement on the accuracy of the demand prediction in the 3h to 0h prior to aircraft departure. This should result in improvements in planning, flight management and traffic control (traffic volume throughput). The main issue related to the improvement in the accuracy of the demand prediction is the uncertainty related to both the flight trajectory and to estimation of the sector occupancy.
OPS.ER.2	Have the basic scientific principles underpinning the idea/concept been identified?	Achieved	Yes. D2.1 and D3.1 describe in detail the theoretical background needed to implement and understand the work develop in COPTRA. Specifically, D2.1 introduces the trajectory prediction approach, the aircraft intent description language and the polynomial chaos expansion theory required to model trajectory

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
			uncertainty. D3.1 introduces the theory behind the computational methods used to model the probabilistic occupancy count, as well as the stochastic queuing theory models on which airport delay propagation is based.
OPS.ER.3	Does the analysis of the "state of the art" show that the new concept / idea / technology fills a need?	Achieved	The literature review and state-of-the-art analysis performed in D2.3 and D3.1 identify the different gaps which exist in today's body of research regarding uncertainty model in demand prediction. These gaps have been used to drive the research performed within COPTRA
OPS.ER.4	Has the new concept or technology been described with sufficient detail? Does it describe a potentially useful new capability for the ATM system?	Achieved	D5.1 describes the potential operational use of the COPTRA based approach. COPTRA proposes the development of a tool that is used as enabler for OI CM-0103-B ((Automated Support for Traffic Complexity Assessment). This would exploit the improved demand estimation to produce more accurate representations of the expected sector occupancy and resulting complexity
OPS.ER.5	Are the relevant stakeholders and their expectations identified?	Achieved	Both D4.1 and specially D5.1 describe in detail the stakeholders and their expectations.
OPS.ER.6	Are there potential (sub)operating environments identified where, if deployed, the concept would bring performance	Achieved	The CBA performed within D5.1 describes the potential operational environment. It also provides an estimation of expected costs and

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
	benefits?		benefits
SYS.ER.1	Has the potential impact of the concept/idea on the target architecture been identified and described?	Not Applicable	No consideration regarding the target architecture has been provided. At this stage, it is difficult to assess the specific technical architecture into which COPTRA should be fitted.
SYS.ER.2	Have automation needs e.g. tools required to support the concept/idea been identified and described?	Achieved	D5.1 describes the potential tool that could be developed to implement COPTRA
SYS.ER.3	Have initial functional requirements been documented?	Achieved	At the stage of maturity of COPTRA, functional requirements are not viable.
PER.ER.1	Has a feasibility study been performed to confirm the potential feasibility and usefulness of the new concept / idea / Technology being identified?	Achieved	Five validation exercises have been performed. These validation exercises focus on the use of the COPTRA approach to identify accurately sector occupancy and thus on the identification of potential hotspots. The exercises address different aspects of this usage such as Demand prediction accuracy, hotspot prediction uncertainty, probabilistic occupancy counts, hotspot occurrence probability and visualisation of uncertainty within an operational environment.
PER.ER.2	Is there a documented analysis and description of the benefit and costs mechanisms and associated Influence	Achieved	D5.1 includes a cost benefit assessment. This assessment should a positive net present value

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
	Factors?		(based on the existing information available).
PER.ER.3	Has an initial cost / benefit assessment been produced?	Achieved	Included in D5.1
PER.ER.4	Have the conceptual safety benefits and risks been identified?	Not Achieved	No safety analysis has been produced due to the lack of operational information related to the early maturity stage
PER.ER.5	Have the conceptual security risks and benefits been identified?	Not Achieved	No security analysis has been produced due to the lack of operational information related to the early maturity stage. Since it is expected that the COPTRA toolset would be connected to the NM, it is expected that an initial security assessment should identify the need to perform a full analysis
PER.ER.6	Have the conceptual environmental impacts been identified?	Not Achieved	No environmental impact analysis has been produced due to the lack of operational information related to the early maturity stage
PER.ER.7	Have the conceptual Human Performance aspects been identified?	Not Achieved	No human performance assessment has been produced due to the lack of operational information related to the early maturity stage
VAL.ER.1	Are the relevant R&D needs identified and documented? Note: R&D needs state major questions and open issues to	Achieved	Available in D5.1

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
	be addressed during the development, verification and validation of a SESAR Solution. They justify the need to continue research on a given SESAR Solution once Exploratory Research activities have been completed, and the definition of validation exercises and validation objectives in following maturity phases.		
TRA.ER.1	Are there recommendations proposed for completing V1 (TRL-2)?	Achieved	Available in D5.1

Table 4: ER Fund / AO Research Maturity Assessment

4 Conclusion and Lessons Learned

4.1 Conclusions

Further research is needed to systematically evaluate the theoretical properties, the possibilities for improvement, and the practical implementability of the developed model. We believe that a research project at TRL 2-4 is the natural next step to take.

The concept of Trajectory Based Operation (TBO) aims at computing, for each flight, an optimal 4D (time and space) flight trajectory to tackle the challenges of tomorrow's Air Traffic Management (ATM). To enable TBO, one must be able to deal with the numerous sources of uncertainties inherent to ATM (e.g. trajectories may be altered due to unpredicted delays or weather conditions) to make informed control decisions.

The COPTRA project sought to provide algorithms and models to that end. The broad goal was to build probabilistic models for the prediction of the occupancy and demands of the European airspace and airports, taking into account the uncertainty in planned flight trajectories. Several key challenges have been singled out: a) the characterization of uncertainties on the individual trajectories and possibly controlling them, b) *the development of accurate models for the uncertainty in air traffic network*, c) *the study of control strategies for providing optimal aircraft trajectories within a TBO environment*, and d) t*he integration of these tools into the current ATM system.*

These areas overlap as, e.g., the uncertainty in air traffic network can be linked to the choice of a control strategy, and the integration of a model providing pertinent information to a controller can serve to better control the status of the whole air traffic network. Table 3 summaries the potential future research needs in the scope of COPTRA will lead operational improvement, and following subsections explain their details.

Field	**R&D Needs**	**Potential Operational Improvement**
Trajectory Uncertainty Quantification/Reduction	Improved uncertainty estimation through model-driven state estimation based on machine learning and hybrid estimation theory	• Improved uncertainty quantification / Improved air sector entry/occupancy time calculation • Online trajectory synchronization between airborne and ground-based systems
Air Traffic Network Modeling with Uncertainty	Applying/Comparing/Connecting several mathematical models, which have applications to other modes of transportation and strong theoretical foundation	• Developing a model with *a clear quantitative understanding of delay propagation dynamics in space and time*

Field	R&D Needs	Potential Operational Improvement
Air Traffic Network Management/ Demand-and-Capacity Balancing	Elaboration of fast algorithms and heuristics, backed up with theoretical analysis, able to provide control strategies leading to near-optimal solutions	• Development of control strategies to manage the network leading to optimality in ATM
	Defining air traffic complexity metric and integrating into demand and capacity balancing	• Improved capacity management based on "Demand-and-Complexity Balancing"
	Applying network resiliency and integrating into air traffic network flow management through "network stability"	• Improved centralized air traffic flow network management based on system dynamics theory
Visualization and Operational Transfer	Developing advanced visualization techniques to present relevant information in an efficient way	• Smooth and effective transition to TBO relying on the training of air traffic controllers

Table 5. Potential Future Research Needs in the Scope of COPTRA

4.2 Technical Lessons Learned

4.2.1 Trajectory Uncertainty Reduction

COPTRA in WP02 aimed to accurately characterize the sources of uncertainties of trajectory prediction process and quantify them as deviations with respect to the nominal trajectories. A set of variables are considered to have the highest impact on flight trajectories.

Historical data are used to generate probability distributions of these variables. This statistical information is given as input to the stochastic trajectory prediction infrastructure. In summary, COPTRA has utilized preprocessed probabilistic definitions of uncertainty sources to calculate stochastic individual trajectory predictions depending on them. Moreover, the study in D2.1 has shown that in addition to quantifying an uncertainty through data analytics, it is possible to limit it through model-driven state estimation techniques. It enables not only to include flight intent or initial condition uncertainties but also to take into account model uncertainties.

This approach would allow us to focus on the contingencies over individual trajectories and potentially limit it, as such tools enable the updating/training its own model. Using machine learning techniques based on hybrid estimation theory, could lead to the development of several methodologies that result on a powerful trajectory generation methodology. This approach would facilitate the use of such tools in tactical operations, which obviously implies the prediction of inbound traffic, or occupancy times in the air sector, etc. in real time.

Moreover, this approach addresses another operational issue in controlling individual flights; airborne trajectories synchronization with the ground-based systems [16] via minimum information sharing. Specifically, monitoring different flight phases of airborne flight trajectories (e.g., climbing, en-route, descending, etc.) enables to recover the separate set of uncertainties embedded in the model. This would lead to answers to operational questions such as "could ATM systems benefit from such kind of trajectory uncertainty recovery tools?" and "how much can trajectory prediction process be improved?" The potential extension of COPTRA could integrate such capability to effectively improve its very first step in the original goals-list.

4.2.2 Models of Uncertainty for Air Traffic Network

The first challenge is providing models for understanding the effect of perturbations on the flight network. We use the term *perturbation* to denote any modification of the currently planned set of flights (including the *effect of control actions*, the addition of a flight in the planning, or deviation of flights from their planned 4D trajectories). In particular, such a model should provide us with *a clear quantitative understanding of delay propagation dynamics in space and time*, e.g. capturing the fact that delaying a flight now may be the cause of unexpected delays (or even cancellation) of a connecting flight downstream with high probability. Such a model aims *at enabling us to investigate optimal operations of ATM.*

A first approach to do so is from the perspective of mathematical models able to simulate (a part of) ATM. The scientific literature provides a range of tools to this end.

For example, tools based on the so-called *Max-Plus algebra have been used successfully to study delay propagation and support operations for railway systems* (see [22, 23]). These tools allow taking into consideration key elements of the transportation network such as the existence of *precedence constraints* between flights.

Additionally, researchers from the field of *operation research* have provided us with several *stochastic optimization tools for modelling and optimizing air transportation* ([17, 18, 24-27, 30]). The downfall of such models is that they are often monolithical, requiring a full description of the current situation and future uncertainties in order to compute solutions. Moreover, the nature of these models (*mixed-integer optimization program)* makes the computation of the corresponding control strategies difficult. On the positive side, these models naturally lead to a *top-down* view of ATM*,* as *they highlight the optimization opportunities and algorithmic challenges* to be tackled to create ideal ATM strategies*.*

Alternatives, such as the ones investigated in [20] and developed within the COPTRA project, follow a *bottom-up* approach. By *analyzing and modeling critical parts of the current system,* we may devise *novel algorithms and strategies* leading to *improvements of the current operations*. For example, the integration of the tools of [20] (focusing on the prediction of sector demand at any given time in a uncertain setting) would give a clearer picture of the air traffic situation to the controllers, aiding them to make informed decisions.

Machine learning techniques and big-data analytics appear as a *promising complement to* the above (see e.g. [21] for applications of machine learning techniques to predict delays in air traffic). In particular, this has been used in COPTRA [20] for selection of a set of indicators aimed at *highlighting flights that contribute the most at the congestion of the network.*

Now that several models exist in the literature, there is a need for comparing them, connecting them, and selecting the best model for each particular problem to be solved in practice. Note that the ability to model the actions of air-traffic controllers would be a valuable asset to any model of the currently deployed ATM system.

4.2.3 Air Traffic Network Management

The purpose of the models discussed above is of course to allow computing and recommending actions leading to optimality in ATM. The task is undeniably hard, and even the concept of "optimality" is ambiguous because the different entities involved in air traffic management (airlines, controllers, customers, etc...) do not necessarily share the same set of priorities. Nevertheless, TBO will rely on the computation of trajectories at the individual aircraft level leading to a *robust and highly performing* air traffic network. This task has attracted the attention of several research communities, including *from the field of control* and *from the field of operations research and optimization*.

On one hand, air traffic management can be seen as a *Cyber-Physical System,* i.e. a complex dynamical system where algorithms and physical devices are made to interact in order to reach a desired goal. This approach is followed in [28], [29], where optimal control strategies taking into account aircraft dynamics have been investigated. Extensions of these works are currently investigated for the design of efficient *"drone-highways"* [19], which can inspire TBO research efforts.

On the other hand, as mentioned above, several tools from the field of operation research have already had a deep impact on ATM. A striking example is the concept of ground-holding (delaying a flight on the ground in order to avoid airborne congestion at destination) has been introduced from researchers of this field in [17]. The papers [18] and [17] present historical perspective of the impact of the works in the field on ATM. Other important issues have been studied as well, such as the optimal scheduling of aircrafts [27] and airport capacity management [24], [25].

The main challenge inspired from this field is *the elaboration of fast algorithms and heuristics, backed up with theoretical analysis, able to provide control strategies leading to near-optimal solutions to the global optimization programs presented in e.g. [30]*.

For instance, the subproject of COPTRA in WP3 focused on to construct a network model to accurately analyse the delay/uncertainty propagation over the European air traffic network. Probabilistic computations for flight durations and service times were applied to the network model to include stochasticity due to uncertainties in the calculations of occupancy counts, and to apply them for the effective demand-capacity balancing at both airport and airspace levels. In the existing system, capacity, which affects the service time, is used to determine the limits of throughput in elements of the network. However, air traffic complexity [31] much more powerful indicator of performance, which is based on the cognitive complexity of an air traffic controller reflects the workload of him/her. The efficiency assessment to replacing the capacity with complexity in order to utilize the airspace's "buffers" and "manage" the airspace is one of the potential further research issues. In that case, occupancy and service time distributions will be the probabilistic function of the complexity. Novel models including the exploration of air traffic complexity metrics and focus on the balancing demand-complexity instead of demand-capacity in the network level, which can be seen as an extension of COPTRA, would be potentially powerful tools to analyze the network uncertainty propagation.

Network resiliency assessment could be another potential extension of COPTRA's demand-and capacity balancing methodology. Resiliency [32] is the ability of a system to recover quickly from disrupted conditions. From the standpoint of an outbreak in the network such as generating delay/uncertainty, the resiliency is inversely proportional to the die out time of the outbreak, on the other words, it is a performance model of the time-based behavior of the network. Furthermore, the stability, which defines oscillatory response to the disruptive events, stemming from control theory has a direct projection to the air traffic flow management. This linkage with network resiliency and stability translates the problem into nonlinear or stochastic system dynamics problem, which has numerous well-defined rigorous solutions in control theory. Modelling the network through resiliency metrics and determination of buffers for airspaces according to the complexity and stability, for instance, would potentially be the scope of further research needs.

4.2.4 Visualization and Operational Transfer

It is important to keep in mind that the research effort should aim at facilitating the transition from our current ATM system to a TBO based system. Our current ATM system relies on highly trained air control operators for making control decisions. We believe that a part of the research effort should be dedicated to evaluating and preparing the tools for this operational transfer. Indeed, it appears natural that any smooth and effective transition to TBO has to rely on the training of air traffic controllers to operate new tools and techniques. Additionally, these tools should be presented in a convenient way, motivating us to devise visualization techniques to present relevant information in an efficient way.

In conclusion, we believe that future research efforts should consider following areas: First, the understanding of the behavior of the uncertainty dynamics on trajectories and the air-traffic network through the unification of the diverse mathematical models and big-data analysis. Second, the design of control strategies to manage this network in an optimal manner by using state-of-the art optimization and control techniques. Last, the implementation and deployment of novel techniques within the current ATM architecture. Altogether, these efforts will foster the transition to TBO, leading to an optimal management of air transportation resources.

4.3 Recommendations for future R&D activities (Next steps)

The present report describes the purpose of the COPTRA, methodology constructed and used during the project and explains the validation process and possible implementation into operational usage. This document contains summary of all the research work packages that take place under the project and general evaluation of COPTRA.

In this document, first demand and capacity problem in ATM is explained by considering its definition, place in current operational concept and drawbacks. Afterwards, the methodology for the project is elaborated. After the input and output structure is given, how trajectory prediction uncertainties are quantified is revealed under two steps. Trajectory uncertainty is deviations between planned and actual trajectories which also leads to trajectory prediction uncertainties. Therefore, as a first step characterization of uncertainty sources is made. After that, in the second step, uncertainty quantification framework is introduced for the quantification of uncertainty sources. Moreover, uncertainty propagation on air traffic network is analyzed by proposed methods which are probabilistic occupancy count model, flight criticality measures and stochastic queuing network model. In probabilistic occupancy count model, decomposition of the uncertainty into a distribution of delays and a set of possible 3D trajectories are examined. The model developed for the computation of probabilistic occupancy counts achieved its goals. Not only provided efficient tools for computing these important congestion indicators, but also allowed us to identify further metrics, highlighting which flights contribute the most to the flight network's congestion. Secondly, in flight criticality measures, analysis of the contribution of individual flights to the network congestion is made and flights that have the biggest impact on network are identified by using output of the occupancy count distributions as an input. Then, airport and airspace-based queuing network model is constructed to compute the network uncertainty that depends on airport/airspace queues and to simulate the air traffic network with both uncertainties based on trajectories and airport/airspace queues to understand the behaviour of the system. Finally, the validation process of demand capacity balancing algorithms is described with proper examples and potential usage of the project results in air traffic operations is considered.

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Appendix A

A.1 Acronyms

Term	Definition
ACC	Area Control Centers
ADS-B	Automatic Dependent Surveillance – Broadcast
AI	Aircraft Intent
AMM	Aircraft Motion Model
ANSP	Air Navigation Service Provider
aPCE	Arbitrary Probability Chaos Expansion
APM	Aircraft Performance Model
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
AU	Airspace User
BADA	Base of Aircraft Data
BR&T-E	Boeing Research & Technology – Europe
CDM	Collaborative Decision Making
COPTRA	Combining Probable Trajectories
CRIDA	Centro de Referencia de Investigación, Desarrollo e Innovación
CTFM	Current Tactical Flight Model
DCB	Demand & Capacity Balance
DDR	Demand Data Repository
EFD	ETFMS Flight Data
EMOSIA	European Model for Strategic ATM Investment Analysis
EPP	Extended Projected Profile
ETFMS	Enhanced Tactical Flow Management System
EUROCONTROL	European Organization for the Safety of Air Navigation
EWM	Earth and Weather Model
FAA	Federal Aviation Administration

FCFS	First Come First Served
FIR	Flight Information Region
FPL	Flight Plan
FTFM	Filed Tactical Flight Model
HC	High Complexity (airport)
IC	Initial Condition
ICAO	International Civil Aviation Organization
ITU	Istanbul Technical University
LC	Low complexity (airport)
LFFFUIR	France Upper Information Region
LTM	Local Traffic Manager
PAR	Performance Assessment Report
PC	Polynomial Chaos
PCM	Probabilistic Collocation Method
PDF	Probability Density Function
QAR	Quick Access Recorder
RBT	Reference Business Trajectory
SBT	Shared Business Trajectory
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking (Agency of the European Commission)
TBO	Trajectory Based Operations
TP	Trajectory Predictor
TPP	Trajectory Prediction Process
UCL	Université Catholique de Louvain
UQ	Uncertainty Quantification
WP	Work Package

Table 6: Acronyms and terminology