Sector Demand Analysis under Meteorological Uncertainty

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Motivation
In 2005, the European Commission stated the political vision and high level goals for the Single European Sky and its technological pillar SESAR. Accomplishing the goals of increasing capacity and improving safety requires a paradigm shift in operations through state-of-the-art, innovative technology and research. A promising approach that can improve current prediction and optimisation mechanisms towards meeting these goals is to model, analyse, and manage the uncertainty present in Air Traffic Management (ATM). The sources of uncertainty that affect the ATM system are very disparate, such as known data but in an inexact way (e.g. aircraft take-off weight) or the prediction of the decisions taken by individuals (pilots, controllers,...). Weather uncertainty is one of the main sources of uncertainty that affect the ATM system.

Demand-Capacity Balancing (DCB) is a key objective of Air Traffic Flow Management (ATFM), which seeks to regulate the flow of traffic such that demand matches available capacity. DCB is most useful when imbalances are predicted early enough to avoid tactical Air Traffic Control (ATC) intervention. Challenges to the effectiveness of ATFM measures in the enroute context arise from uncertainties in trajectory prediction and weather forecasts.

In this paper, an analysis of the effects of the wind uncertainty on the prediction of sector demand is presented. The goal is to understand how this uncertainty is propagated from the trajectory scale to the traffic scale. The wind uncertainty is provided by Ensemble Prediction Systems (EPS), an approach to weather forecasting that characterizes and quantifies the uncertainty inherent to the prediction. Typically, an EPS is a collection of 10 to 50 forecasts (referred to as members). They consist on running many times a deterministic model from very slightly different initial conditions [1]. Often, the model physics is also slightly perturbed, and some ensembles use more than one model within the ensemble or the same model but with different combinations of physical parameterization schemes. This technique generates a representative sample of the possible realizations of the potential weather outcome, and the hope is that the spread of the predictions in the ensemble brackets the true weather outcome [2]. The sector demand can be described in terms of occupancy count and of entry count. The occupancy count is the number of aircraft present in a sector at a given time \( t \). The entry count is the number of aircraft that enter into a sector between given times \( t_1 \) and \( t_2 \), \( t_1 < t_2 \).

Methodology
We will consider that there exist \( n \) different aircraft and that the EPS is formed by \( m \) different members. The trajectory of aircraft \( i \) (\( i = 1, ..., n \)) for the ensemble member \( j \) (\( j = 1, ..., m \)) at time \( t \), is denoted as \( x_{ij}(t) \). In case that this trajectory crosses the ATC sector, then there exist an entry time \( t_{ij,1} \) and an exit time \( t_{ij,2} \) \( (t_{ij,1} \leq t_{ij,2}) \).

The occupancy of the ATC sector by aircraft \( i \), for ensemble member \( j \), and at time \( t \), denoted as \( O_{ij}(t) \), takes the value 1 when the aircraft is inside the sector \( (t_{ij,1} \leq t \leq t_{ij,2}) \) and the value 0 otherwise. The occupancy count for ensemble member \( j \) at time \( t \), denoted as \( O_j(t) \), can be obtained as the sum of the occupancies of the different aircraft, \( O_j(t) = \sum_{i=1}^{n} O_{ij}(t) \). From these \( m \) values of occupancy count, the mean, maximum, and minimum values can be obtained at any time \( t \). It is also possible to obtain the probability of the occupancy count of being greater than a given value \( \alpha \) at time \( t \) as the number of occupancy counts \( O_j(t) \) that are greater than this value, divided by the total number of members \( m \).

The entry of aircraft \( i \) into the ATC sector, for ensemble member \( j \), between times \( t_1 \) and \( t_2 \), denoted as \( E_{ij}(t_1, t_2) \), takes the value 1 when the aircraft enters the sector between times \( t_1 \) and \( t_2 \) \( (t_1 \leq t_{ij,1} \leq t_2) \) and the value 0 otherwise. The entry count for ensemble member \( j \) between times
t_1 \text{ and } t_2, \text{ denoted as } E_j(t_1, t_2), \text{ can be obtained as the sum of the entries of the different aircraft, } E_j(t_1, t_2) = \sum_{i=1}^{n} E_{ij}(t_1, t_2). \text{ Again, from these } m \text{ values of the entry count, mean, maximum, and minimum values can be determined, and the probability of the entry count of being greater than a given value } \alpha \text{ between times } t_1 \text{ and } t_2 \text{ is obtained as the number of entry counts } E_j(t_1, t_2) \text{ that are greater than this value, divided by the total number of members } m.\text{ }

\text{Results}

Results will be presented for an enroute ATC sector, with a realistic number of aircraft. The EPS chosen is ECMWF-EPS, from the European Centre for Medium-Range Weather Forecasts, composed of 51 members, and winds will correspond to a given day, release time, and pressure level. An example of the expected results is shown in the following figure for the occupancy count. The value of the occupancy count is represented on the left (along with the value of the planned sector capacity, which is represented by a horizontal red line), and the probability of the occupancy count exceeding the airspace capacity is represented on the right.

The mean value of the occupancy count will evolve along time, increasing or decreasing, depending on the expected number of aircraft. The spread of the count (the difference between the maximum and the minimum values) is expected to increase over time, as the forecast horizon increases, since one has a larger spread in the wind forecast.

The probability of exceeding the airspace capacity is also expected to change over time, depending on the distribution of the occupancy count. This probability can be useful in the Demand-Capacity Balancing process. The higher the value of the probability, the higher the capacity shortfall, and the more severe the ATFM measure to be considered.

\text{References}
