Strategic Planning in Air Traffic Control as a Multi-Objective Stochastic Optimization Problem

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- Motivation
- Rationale behind the probabilistic model
- Model
- Optimization
- Further research questions
- Conclusion
What is Strategic planning in Air Traffic Control?

“The relatively long-term (or upstream) process is often called ‘strategic’ ATC and the short-term (or downstream) process ‘tactical’ ATC. The present paper is concerned with the problem of distributing the control effort between upstream and downstream activity.”

In the abstract of “Strategic or Tactical Air Traffic Control” by S. Ratcliffe 1978

- Our definition: regulation given by an AC to a flight with the goal of minimizing the complexity of one or multiple sectors of the network
  - Require the AC to have a network view, or at least a feedback from his neighbors
  - Require the AC to have an accurate prediction of the complexity over time
  - Require the AC to be aware of the actions of the other ACs
  - Consequence: Workload increase => Capacity decrease!
  - Does not respect the Collaborative-Decision Making philosophy
  - Solution: split the responsibility between a Network Manager and the ATC
Air Traffic Flow and Capacity Management Perspective

- Central Flow Management Unit (Europe)
  - Enhanced Tactical Flow Management System

- SESAR WP 07.06.05 Dynamic Demand Capacity Balancing

"Currently, the systematic application of ground regulations limits the traffic entering a sector because of the allocation of departure slots to all flights, regardless of how they contribute to the expected overload"

Eurocontrol, 2011

- Short-term ATFCM measures (STAMs)
  - Minor ground delays
  - Flight level capping
  - Minor re-routings applied to flights contributing largely to complexity

- Implemented in the control centers via the Flow Management Positions
Our idea

- Objectives on the time of arrival on each point of the flight plans
- A controller owns a subset of the objectives
  - Give a partial information of the global plan
  - They are not responsible to implement it, because safety is the priority
  - Workload sharing
- Respect more the CDM
- Can be achieved with:
  - Decision support tool for manual handling by the controller
  - The implementation of Required Time of Arrival (RTA)
We are interested in the automation of ATFCM

So, we need a central algorithm capable of

1. Monitoring the evolution of the airspace
2. Detecting perturbations and hazardous situations
3. Changing dynamically the objectives in order to bring the system back to an efficient state
Many models exist in the literature divided in two main classes:

- Eulerian Models: based on sectors with inflow and outflow rates
- Lagrangian Models: based on the trajectories themselves

For our application, we choose a Lagrangian model

- Reason: objectives concern specific flights
- Consequence: need a simple trajectory model for the simulations to be tractable
- Fact: we are interested in time-based operations
- Is this deterministic model sufficient?

\[ T_{i+1}^f = T_i^f + T_{i\rightarrow i+1}^f \]
What is the prediction error?

All-Causes Departure punctuality

Based on CODA sample of 67.4% of commercial flights in the ECAC region in 2012. EUROCONTROL 2013 www.eurocontrol.int/CODA
Prediction error on the top of climb

BADA Error in the climbing phase

Work undertaken by Noé Gaumont at Thales Air Systems
Rationale behind the model

- Prediction error in en-route phase
Before and after takeoff

Based on the work of:


Parameter estimation of a Gaussian on prediction errors

1 Sigma (68.2%)

- Active: 4 Minutes
- Proposed: 15 minutes
Rationale behind the model

The magnitude of prediction error means:

- false alarms on the detection of congestion
- Inefficient implementation of regulations
- Unnecessary delays

The main idea of my thesis:

- model the uncertainty via probability theory and work with confidence intervals
- include it directly in the optimization loop
How to define the Probabilistic Flight Model:

\[ T_{i+1}^f = T_i^f + T_i^{f ightarrow i+1} \]

These are now random variables

1. Transform into a more convenient expression
2. Generalize to N points

\[
p_{1:N}(t_1:N) = p_{N|1:N-1}(t_N|t_1:N-1) \cdot p_{1:N-1}(t_1:N-1)
\]
\[
= p_{N|N-1}(t_N|t_{N-1}) \cdot p_{1:N-1}(t_1:N-1)
\]
\[
= \ldots
\]
\[
= \prod_{i=2}^{N} p_{i|i-1}(t_i|t_{i-1}) p_1(t_1)
\]

(3)

Intents Arrival in airspace
How to capture uncertainty from the data?

- **Parametric Model**
  - e.g. PERT Distribution

- **Non-parametric Model**
  - e.g. Histogram
Probability of delay

- Marginalize on the last point

\[ p_N(t_N) = \int \ldots \int p_{1:N}(t_1:t_N) dt_1 \ldots dt_{N-1} \]

\[ = \int \ldots \int \prod_{i=2}^{N} p_{i|i-1}(t_i|t_{i-1}) p_1(t_1) dt_1 \ldots dt_{N-1} \]

\[ = \int \ldots \left[ \int p_{3|2}(t_3|t_2) \left[ \int p_{2|1}(t_2|t_1) p_1(t_1) dt_1 \right] dt_2 \right] \ldots dt_{N-1} \]

\[ p_1(t_1) \quad p_2(t_2) \quad p_3(t_3) \]

- Can be computed with
  - Numerical Integration tools (Clenshaw-Curtis Quadrature)
  - Monte-Carlo Simulation (Forward sampling directly on the model)
Other possible queries:

- Probability to be in a sector along time

\[ \Pr(S_{s,f}(t)) = F_i^f(t) - F_j^f(t) \]

\[ = \int_{-\infty}^{t} p_i^f(t_i) dt_i - \int_{-\infty}^{t} p_j^f(t_j) dt_j \]

\[ = \int_{-\infty}^{t} p_i^f(t) - p_j^f(t) dt \]

- Probability for two flights to be at the same point at the same time

  - Independence between flights => product of the previous functions
Probabilistic Sector Model

\[ \Pr(K_s(t) = n) = \sum_{|a|=n} \prod_{f \in \mathcal{F}} \Pr(S_{s,f}(t))^{a_f} \cdot \Pr(S_{s,f}(t))^{1-a_f} \]

**WARNING:** Direct methods for computing it at only one timestamp are intractable

\[ \Pr(K^t_s = 1) = \Pr(S^t_{s,f_1}) \Pr(S^t_{s,f_2}) \Pr(S^t_{s,f_3}) + \Pr(S^t_{s,f_1}) \Pr(S^t_{s,f_2}) \Pr(S^t_{s,f_3}) + \Pr(S^t_{s,f_1}) \Pr(S^t_{s,f_2}) \Pr(S^t_{s,f_3}) \]

Other possible methods are:

- Characteristic function of a Binomial-Poisson distribution
- Monte-Carlo simulation with sweep line algorithm
Possible other queries:

- What are the time intervals when there is a probability over a threshold to have N flights in a given sector?
  - Used to monitor when the sector becomes congested with a degree of confidence

- Which flights contribute to the probability of congestion at time $t$ of a given sector?
  - Useful to know which flights to regulate from a local perspective

- Which flight contributes the most in the probability of congestion of a set of sectors?
  - Useful from a global perspective
First sketch of the methodology

1. Real Dataset
2. Real Occupancy Count
3. Comparative Probability of Occurrence
4. Probabilistic Occupancy Count
5. Adjust
6. Flight Model
7. Inference Mechanism
8. Parameters
Numerical Method

- **Methods used:**
  - Clenshaw-Curtis Quadrature
  - Monte-Carlo Simulations

- **Testbench**
  - 121 sectors with 192 flights
  - Accuracy requirement: 1% of error
  - Non-parallelized
  - Order of magnitude of the computational time: seconds
  - Tractable
Bayesian Network View:

- Square: Decision node
- Circle: Random variable
- Diamond: Random process
The two main goals of the system are:

- Reduce the congestion
- Reduce the delays

Definition of the cost functions

- Use multi-objective algorithm in order to avoid aggregation
- Define simple cost functions:

\[
C_1(\gamma) = \sum_{f \in \mathcal{F}} \mathbb{E}_{\phi_f}(T_{n_f}^f; \gamma|f) = \sum_{f \in \mathcal{F}} \left[ \int_{\Omega} (t - A_f)_+^2 \cdot p_{n_f}(t; \gamma|f) dt \right]
\]

\[
C_2(\gamma) = \int_{\Omega} \sum_{s \in \mathcal{S}} \mathbb{E}_{\psi_s}(\cdot,t)(K_s^t; \gamma) dt = \int_{\Omega} \sum_{s \in \mathcal{S}} \sum_{n = C_s + 1}^{N_s} (n - C_s)_+^2 \cdot \Pr(K_s^t = n; \gamma) dt
\]
**Toy Benchmark**

- 10 flights
- 5 sectors
- 60 decision variables
- Central sector is congested
- Each flight takeoff at the same time
- Triangular uncertainty
- Support of uncertainty equals 180 seconds
- Optimization algorithm: NSGA-II
Pareto Front Approximation

Hypervolume indicator
Further work on optimization

- How to model more precisely the “health” of the airspace?
- How to choose between ground delay, speed regulation, rerouting and flight level capping?
  - Which cost to choose associated to the regulations? (airline, controller workload, …)
- Comparison of network strategies for decongestion
  - Local first come, first served for every sector
  - Most impacting flights
  - …
Current and further research

- Statistical methods for learning the flight model
  - From the data (with FMS information)
  - From other models (Aircraft kinematics with noise)
- Cost function definition
  - Define more accurately the “health” of the airspace
- Optimization Algorithm
  - Integrate more knowledge from the probabilistic model
- Generalize to the spatial dimensions
  - 4D probabilistic model (required kinematics information)?
  - Integration of tactical operations from air traffic control
    - Conflict detection & Conflict resolution


- **Link between strategic planning of air traffic control and tactical air traffic flow management**
  - Temporal objectives given to the controllers

- **Time-based probabilistic model**
  - Definition of the flight model
  - Inference mechanism for probabilistic occupancy count
  - First sketch of a validation scheme

- **Optimization**
  - Antagonist criteria: delay and congestion
    - Multi-objective optimization
  - Possibility to create easily new operators

- **Next: validation, validation and validation**
Thank you for your attention

Questions or comments?