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Automated Traffic Scheduling in TMA with Point Merge to Enable Greener Descents

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Presentation Content

- Background and Introduction
- Methodology
- Experimental Evaluation
- Conclusions
- Future Work

Background and Introduction

Introduction

- In previous work, we uncovered significant inefficiencies in Dublin TMA, where point merge is in use
- Can the point merge procedures be used more efficiently to improve the flight efficiency, using optimization (Mixed Integer Programming)?
- Idea is to apply an optimization framework to a real scenario and evaluate the results

Point Merge - General

- Sequencing legs at level flight used to delay the aircraft
- Merge point, equidistant from each sequencing leg
- ”Direct to” merge point when the desired separation is achieved

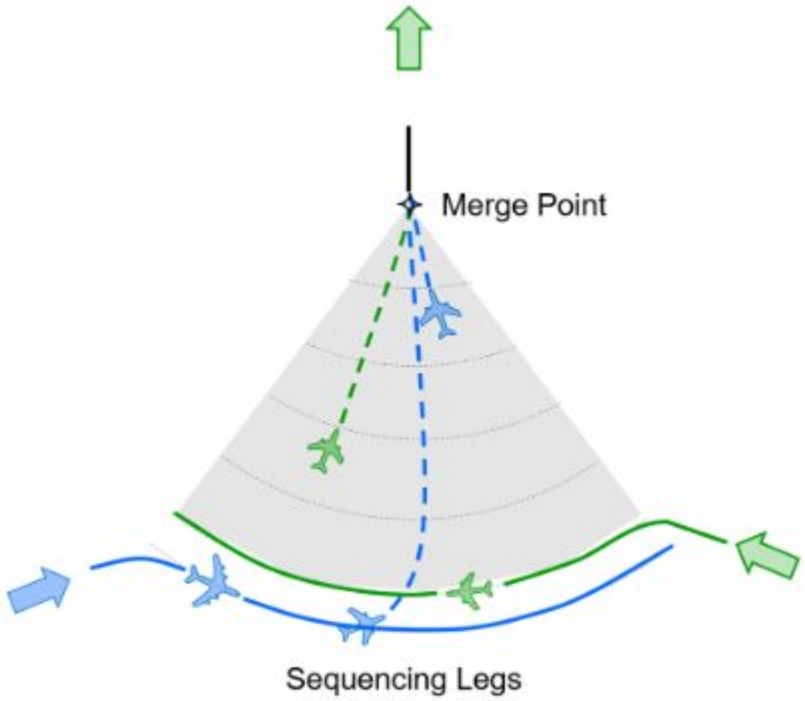


Figure: EUROCONTROL

Point Merge in Dublin

- 10 entry points to the TMA
- RWY 28
- Sequencing legs at FL70/80, max IAS 230 kt
- Merge point at >3000 ft, max IAS 180 kt

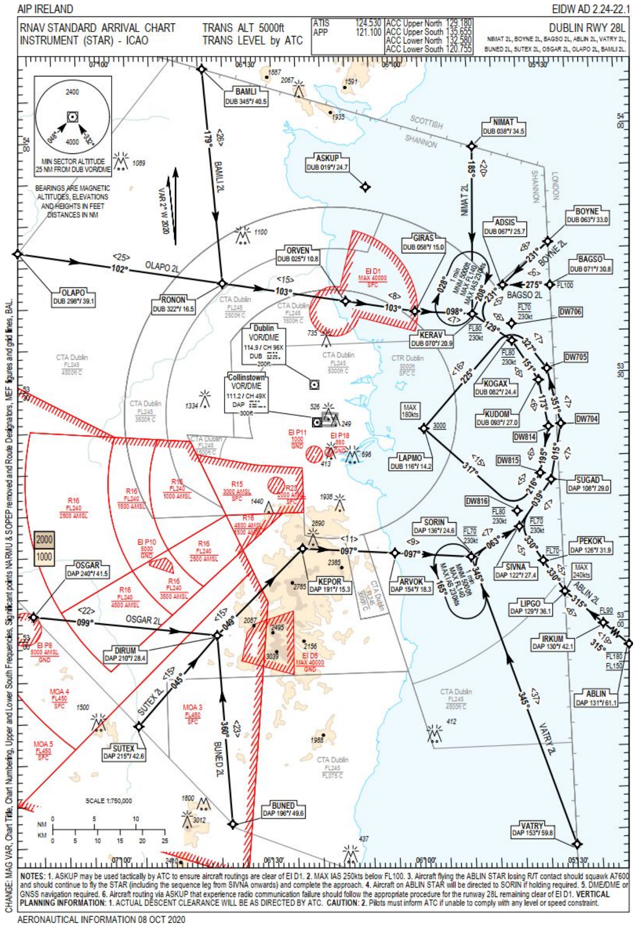
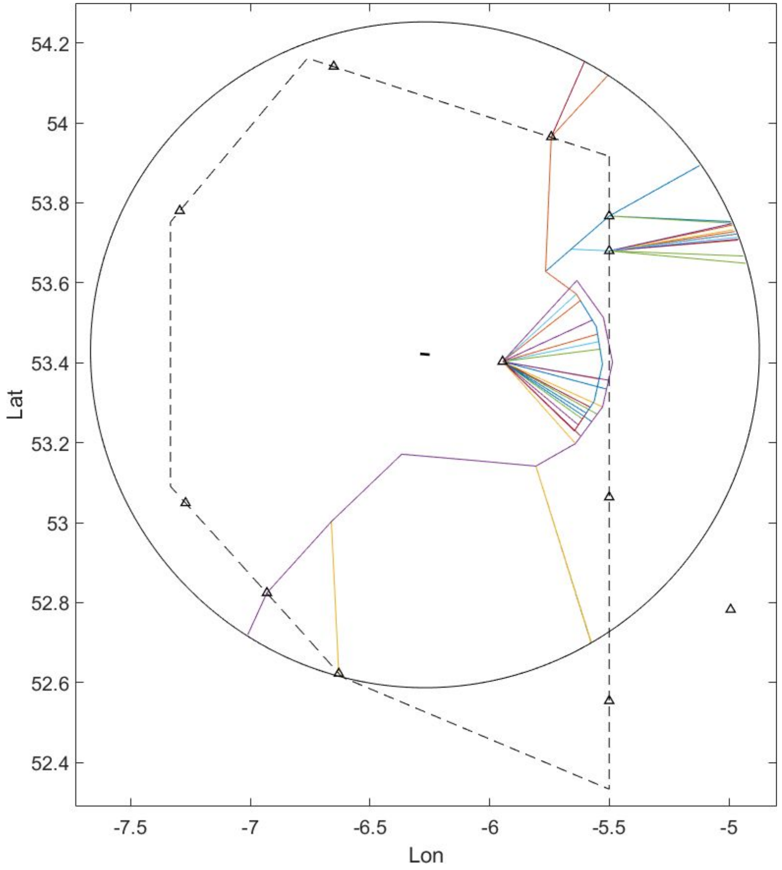


Chart: Irish AIP

Methodology

Arrival Routes

- Area of interest is a 50 NM circle centered at the airport
- Set of feasible routes connecting the TMA entry points to the final merge point (LAPMO)
- First waypoint corresponds to where the actual flight enters the 50 NM circle

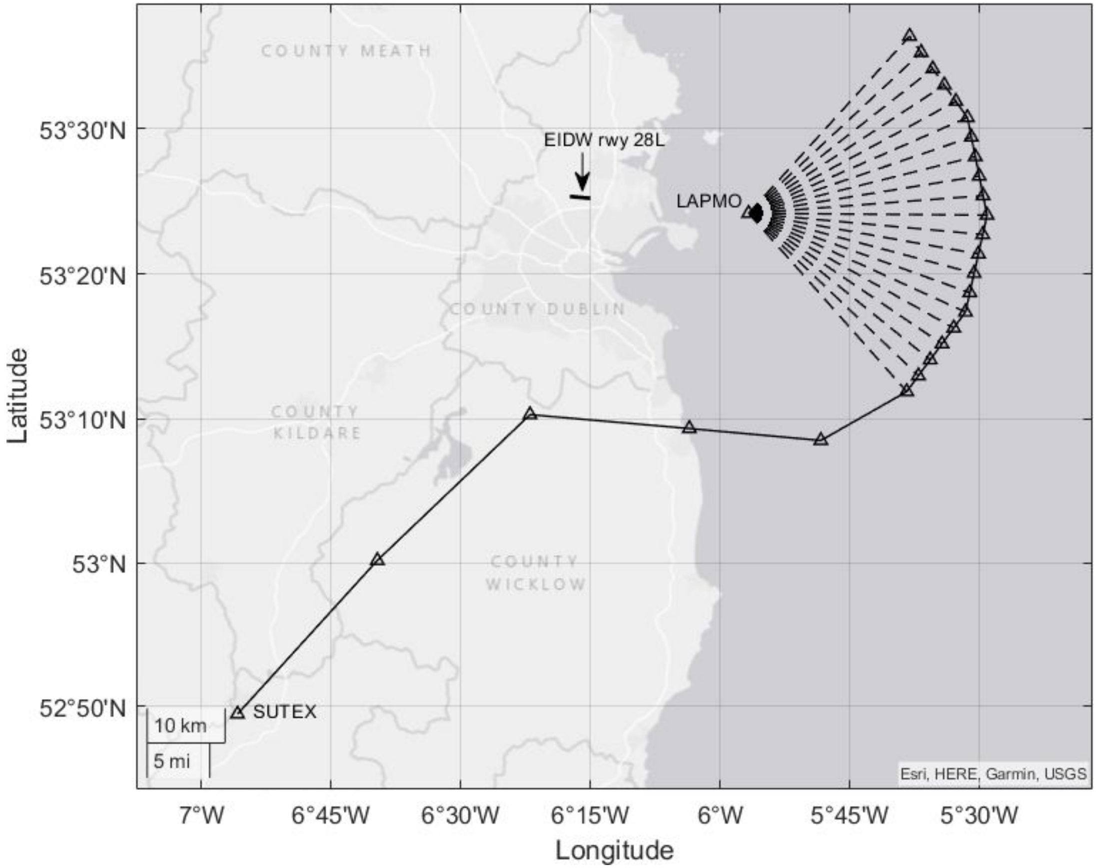


Arrival Routes

- Four new, equally spaced, waypoints between every pair of published waypoints along the sequencing legs

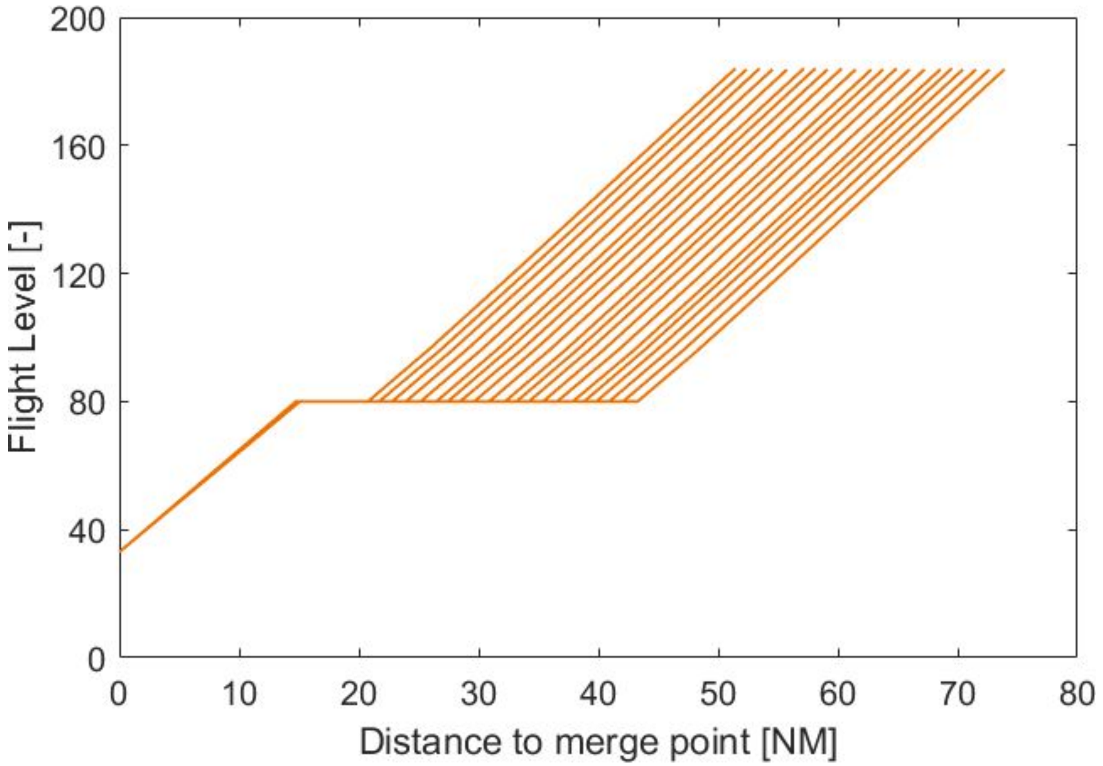
- 21 different routes for each aircraft

- Interested in finding the optimal point where the aircraft should leave the sequencing legs and initiate a turn towards the merge point



Vertical Profiles

- Realistic vertical profiles created using Total Energy Model (TEM) and EUROCONTROL BADA v4
- Aircraft type-specific speed profiles
- Idle-thrust descent (except at sequencing legs)
- Published altitude and speed restrictions adhered to
- Max IAS 250 kt below FL100



Flexible Arrival Time Window

- Flexible, short arrival time window to TMA
- Managed in the en-route phase by speed adjustments
- Small speed adjustments possible without a significant increase in fuel consumption

Weather Data

- ECMWF ERA5 reanalysis dataset, provided via the C3S Data Store
- Data on temperature and wind at different pressure levels, times and positions
- Data is linearly interpolated in pressure level, time and position to obtain desired value
- Used in the calculation for the vertical profiles (e.g. for conversion between GS and TAS) and for calculating the fuel consumption

Problem Description

- Aircraft scheduling problem modelled as MIP
- 21 possible arrival routes per arriving aircraft (called profiles) and $2 \cdot 21$ additional profiles for each minute of flexibility
- Goal: optimal aircraft-to-profile assignment for fully-automatic deconfliction

Deconfliction Pre-processing

- The algorithm compares all profiles and checks for common waypoints
- If common waypoint(s) found, mark the profile pair as incompatible if the time separation requirement is violated
- Results in an incompatibility matrix used in the optimization

Algorithm 1 Deconfliction pre-processing step

for each pair of a/c **do**
  for $i = 1$ to #profiles of a/c 1 **do**
    for $j = 1$ to #profiles of a/c 2 **do**
      for $k = 1$ to #waypoints in profile i **do**
        for $l = 1$ to #waypoints in profile j **do**
          if i and j share a waypoint w **then**
            if difference in time at $w < t_{sep0}$ **then**
              mark the profile pair as conflicting
            end if
          end if
        end for
      end for
    end for
  end for
end for=0

Objective Function

$$\min \quad J := \sum_{a \in \mathcal{A}} \sum_{p \in \mathcal{P}_a} x_{a,p} \cdot |\mathrm{RTA}_{a,p} - \mathrm{ETA}_a|$$

Set of all arriving a/c

Set of all profiles for aircraft *a*

- Objective is to minimize the difference between $RTA_{a,p}$ and ETA_a
- ETA_a is the estimated time of arrival if aircraft a would fly a direct route from TMA to the merge point (vertical profile and speed profile modelled with BADA)
- $RTA_{a,p}$ is the required time of arrival for aircraft a flying profile p
- $x_{a,p}$ is a binary variable which indicates if aircraft a flies profile p

Constraints – Arrivals

- Both profiles in a conflicting pair may not be used simultaneously:

$$x_{a_i,p_k} + x_{a_j,p_r} \leq 1,\ \forall a_i, a_j \in \mathcal{A},\ \forall p_k \in \mathcal{P}_{a_i},\ \forall p_r \in \mathcal{P}_{a_j} \\ \mid ((a_i, p_k), (a_j, p_r)) \in \mathcal{I}$$

- Each aircraft flies exactly one profile:

$$\sum_{p \in \mathcal{P}_a} x_{a,p} = 1, \quad \forall a \in \mathcal{A}$$

Departures

- Single runway operation – one runway used by both departures and arrivals
- We want to schedule the departing aircraft to use the runway without conflicting the arrivals
- Flexible departure time: Departing later than the actual time of departure is possible

Constraints – Departures

- Flexible departure time:

$$t_{depos_i} \leq t_{dep_i} \leq t_{depos_i} + X;\ i \in \mathcal{D}$$

- t_{depos_i} is the actual time of takeoff for a/c i
- t_{dep_i} is the optimized takeoff time for a/c i
- X is the amount of time for the flexible departure time window
- D is the set of all departing a/c

Constraints – Arrivals/Departures

- Maintain separation between arriving and departing aircraft:

$$t_{land} + t_{sep1} + x_{a,p} \cdot RTA_{a,p} - t_{dep_i} \leq M \cdot y_{i,a,p};$$
$$i \in \mathcal{D}, a \in \mathcal{A}, p \in \mathcal{P}_a$$
$$t_{dep_i} - x_{a,p} \cdot RTA_{a,p} + t_{land} - t_{sep1} \leq M \cdot (1 - y_{i,a,p});$$
$$i \in \mathcal{D}, a \in \mathcal{A}, p \in \mathcal{P}_a$$

- t_{land} is the flight time from LAPMO to the runway threshold
- t_{sep_1} is the required time separation between a departing and an arriving aircraft
- M is a very large number
- $y_{i_{a,p}}$ is a binary variable that activates one of the constraints

Constraints – Departures

- Maintain separation between two consecutive departures:

$$t_{dep_i} - t_{dep_j} + t_{sep2} \leq M \cdot y_i;\ i \in \mathcal{D}, j \in \mathcal{D} \setminus \{i\}$$
$$t_{dep_j} - t_{dep_i} + t_{sep2} \leq M \cdot (1 - y_i);\ i \in \mathcal{D}, j \in \mathcal{D} \setminus \{i\}$$

- t_{sep_2} is the required time separation between two consecutive departing aircraft
- t_{dep_i} and t_{dep_j} are the optimized time of departures for aircraft i and j, respectively

Performance Metrics

- Used to evaluate the optimized solutions by comparing with the actual scenario

- The chosen KPIs to calculate are:
  - Entry conditions (min. time to final, sequence pressure, throughput and metering effort)
  - Horizontal flight efficiency
  - Time in TMA
  - Vertical flight efficiency
  - Fuel efficiency

Performance Metrics

- **Minimum time to final**
  - Plot all trajectories
  - Overlay a rectangular grid with the cell side ≈ 1 NM over the TMA
  - Calculate the minimum time needed from any point within the cell of the grid to the merge point, along any of the aircraft trajectories passing through the cell

- **Sequence pressure**
  - The number of aircraft with the same time to final within a given time window ω
  - Reflects the aircraft density at different time t
  - Calculated for each aircraft at any time of its presence within the TMA with the discrete time steps (here, ω= 120s.)

Performance Metrics

- **Throughput**
  - Calculated by, at a given time horizon, counting the number of aircraft with the minimum time to final within a given time window
  - Throughput crossing iso-minimum time lines calculated from 900 to 30s to final, sampled at a 30s rate over 5-minute periods

- **Metering effort**
  - Defined as the difference between the throughput at the given time horizon and the one close to the final (30s in this work)
  - Quantifies the controllers effort for metering
  - May be used as a proxy to controllers workload

Performance Metrics

- **Horizontal flight efficiency**
  - Assessed by calculating the horizontal distance
- **Time in TMA**
  - Assessed by calculating the flight time
- **Vertical flight efficiency**
  - Assessed by calculating the duration of >30 sec segments where the vertical speed is lower than 300 ft/minute (EUROCONTROL definition)

Performance Metrics

- **Fuel efficiency**
  - Calculated according to BADA formulas and coefficients provided by BADA v4
  - Idle thrust fuel coefficient used for CDO parts
  - Where additional thrust is required, the fuel coefficient is calculated from the thrust (TEM)
  - Weather data from ECMWF ERA5 reanalysis dataset

Experimental Evaluation

Dataset

- Data obtained from the OpenSky Network
- The busiest hour during the busiest month: October 4, 2019, 16:00-17:00 UTC
- 32 (4 t/p and 28 jet) arriving and 5 departing (jet) aircraft for Dublin detected by the Opensky Network connected sensors
- All Medium WTC

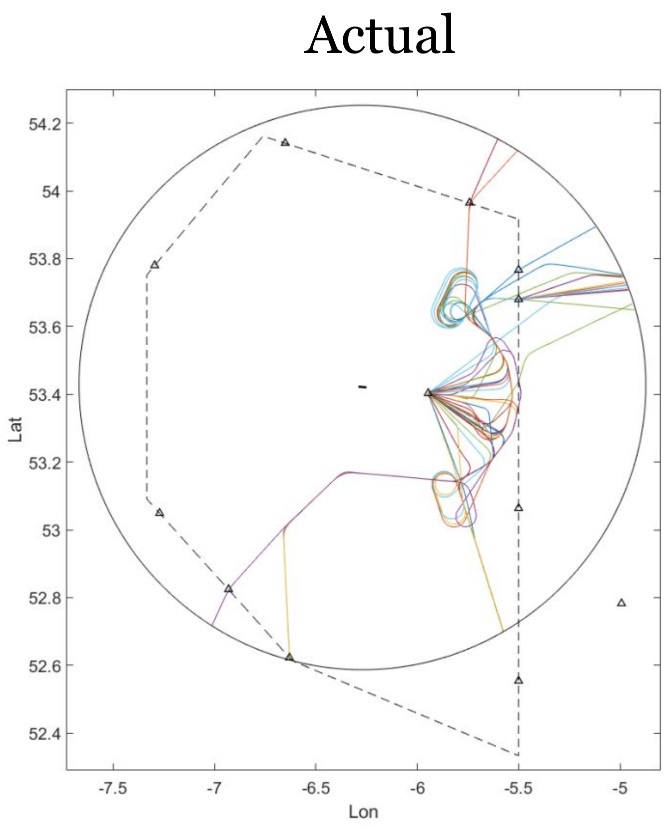
Case-specific Requirements

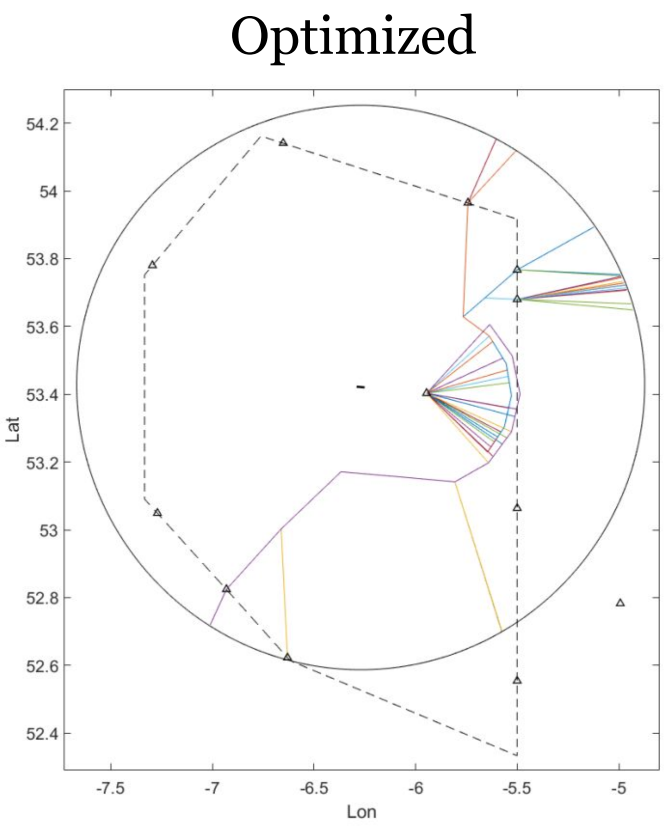
- ≥2 minutes between two arriving aircraft at any waypoint
- ≥1.5 minutes between an arriving and a departing aircraft, at the runway threshold
- ≥1.5 minutes between two consecuitive departing aircraft
- Flexible arrival time window: ±2 minutes → 4704 profiles
- Flexible departure time window: +1 minute
- Assumed flight time from LAPMO (merge point) to runway threshold: 4 minutes

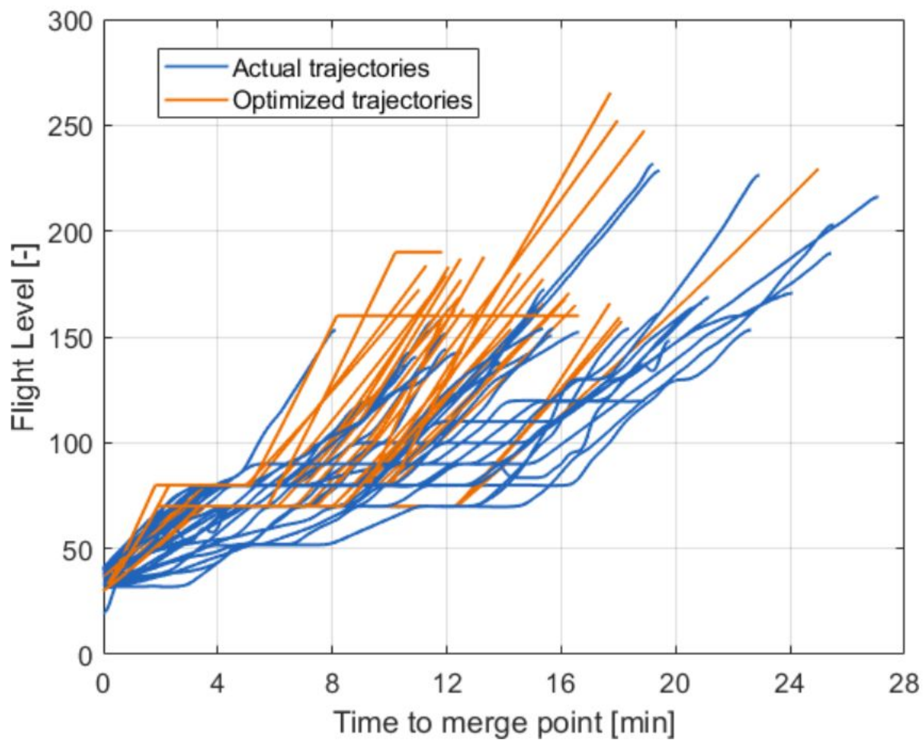
Computation

- CDO profiles generation, pre-processing and PI calculations performed in Matlab
- Optimization solved using MIP Gurobi Solver
- Pre-processing and optimization solved on a powerful Tetralith server
- Pre-processing time: 51 hours (subject to improvement)
- MIP solved in <15 seconds

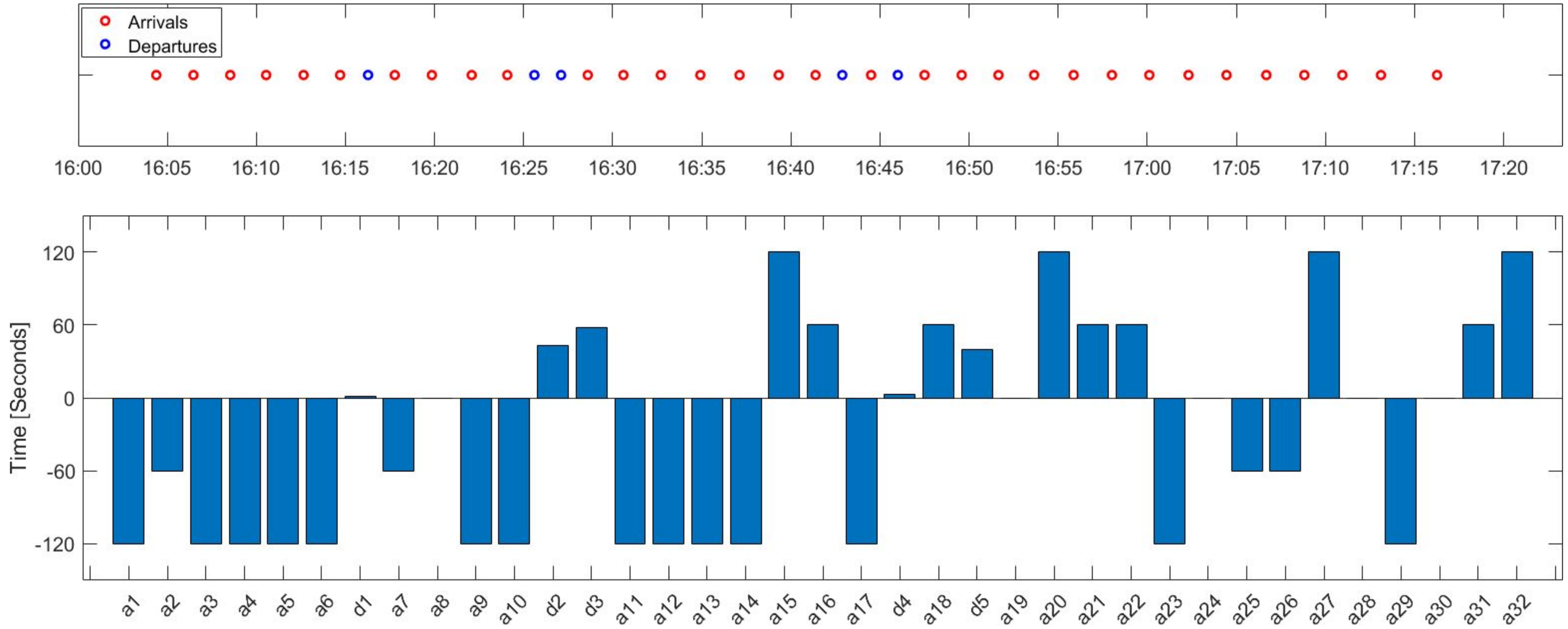
Arrival Routes - Comparison







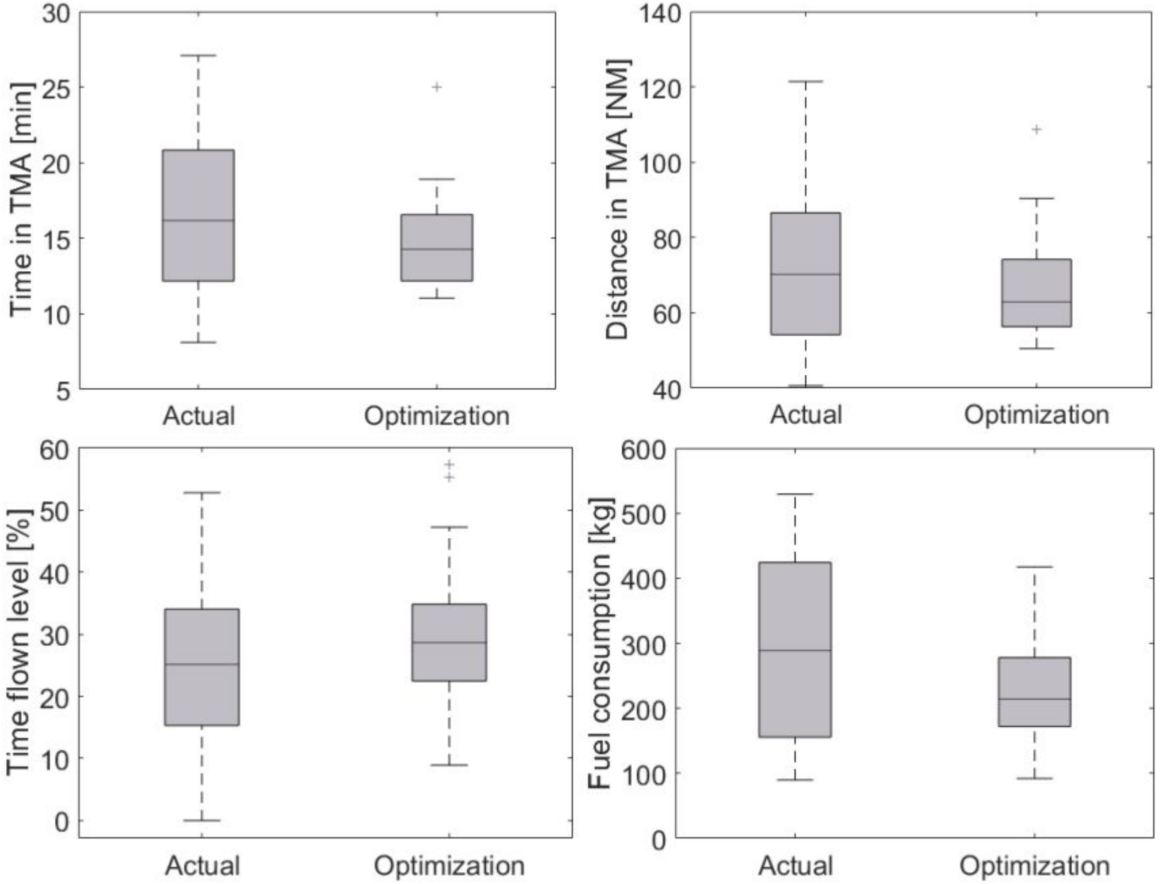
Arrival/Departure Times & Time Shift



Performance Indicators - Results

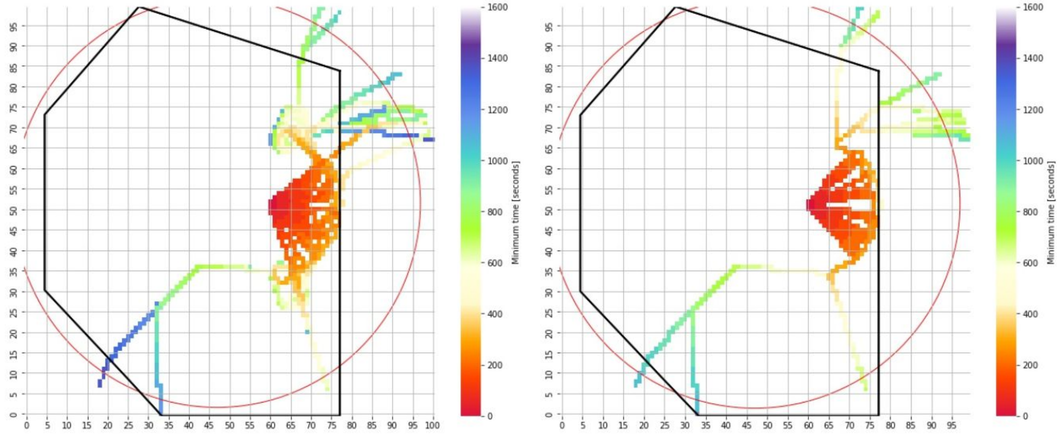
- Time in TMA decreased
- Distance in TMA decreased
- Time flown level increased (greater portion of time in TMA spent on sequencing legs)
- Fuel consumption decreased

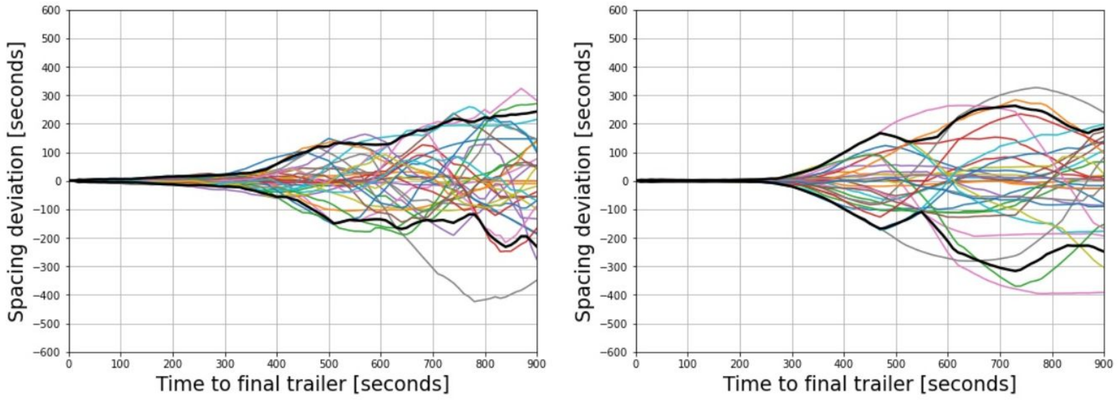
	Average time [min]	Average distance [NM]	Average time flown level [%]	Average fuel burn [kg]
Actual	17.0	73.0	23.7	294.5
Optimization	14.7	66.9	29.8	229.3



Performance Indicators - Results

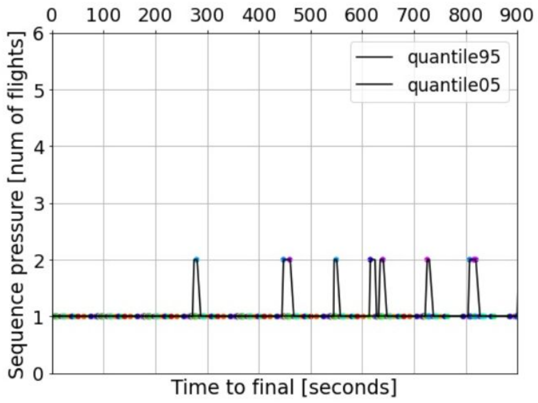
- Minimum time to final heatmap
    - Results are in line with time in TMA
- Spacing deviation
    - Less outliers outside of the 95-5th quantile

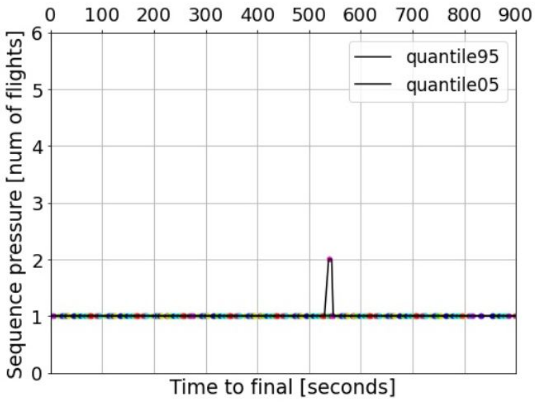




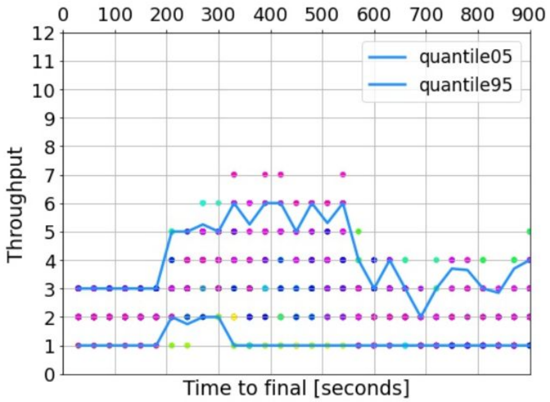
Performance Indicators - Results

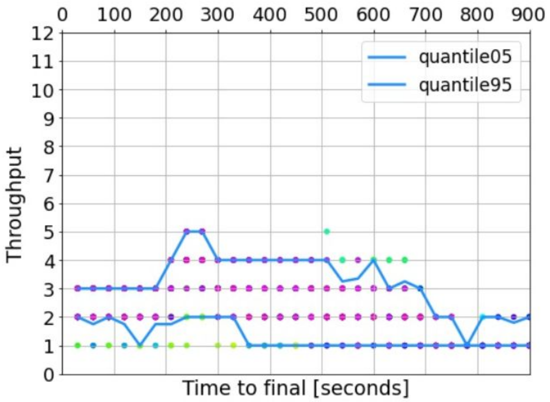
- Sequence pressure
  - Less occurrences with two aircraft sharing the window of 120 seconds at any point within TMA
  - Indicates that the traffic is more uniformly distributed





- Throughput
  - Both maximum (7 vs 5) and average (2.54 vs 2.34) are lower





Conclusions and Future Work

Conclusions

- Highly flexible framework that can be used as a tool for ATCOs to calculate the best combination of flight profiles, and can be applied to any airport implementing point merge
- Synchronization of arrivals and departures, in a single-runway or mixed-mode operation
- Point merge system can be used in a more efficient way with better utilization of its sequencing legs and less holdings, providing better organized arrival flows, significantly reducing time and distance in TMA, and requiring less control effort as a result
- Fuel saving of 22%, corresponding to an average of 65 kg per flight

Future Work

- Evaluate noise impact and non-CO2 emissions, associated with the improved efficiency provided by our approach
- Apply our optimization framework at a dual-runway airport, where aircraft may arrive and depart from either runway
- Perform additional case studies with different aircraft fleet mix and weather conditions
- Explore the trade-offs between the robustness against uncertainties and arrival efficiency
- Improve pre-processing computational time

Thank you for your attention

Questions?

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