A linear programming approach to maximum flow estimation on the European air traffic network

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Presentation Plan

- Introduction
- Background
- Methodology
- Results and discussion
- Findings
- Limitation and future work
- Conclusion
Introduction

• In Europe, the number of flights doubled between 1999 and 2008 and is forecast to grow with a compound annual growth rate of 0.6% between 2013 and 2019.
• Although traffic growth has flattened and the performance of the European air traffic network has improved, the congestion at busy airports and in Area Control Centres (ACCs) still remains severe.
• In order to cope with the need to satisfy the increasing demand for air travel, the Single European Sky (SES) Air Traffic Management (ATM) Research programme (SESAR) in Europe have been launched.
Introduction - Current ATM

Gate   Taxiing   Take-off   Climb   Cruise   Decent   Landing   Taxiing   Gate
Ground   ATCO   Runway   ATCO   Terminal   ATCO   Planning   ATCO   Tactical   ATCO

TWR (Supervisor)   ACC (Supervisor)   TWR (Supervisor)

Ground Handler   Airport Operator   Slot Coordinator   Aircraft Operator

Slot Management   Flight Plan   Demand Management

Flight Plan   ATFM   CFMU   Flight Plan   Demand Management

Airport Capacity   Airspace Capacity   Airport Capacity

Runway Throughput   Air Traffic Controller Workload   Runway Throughput

Introduction - Current ATM
Introduction - Future ATM

An Air Transport Network

Network Capacity Estimation

SWIM

CDM

Aircraft Operator

Airport Operator

ATFCM (Network manager)

AOM

ATC
The research problem is:

**How to measure the network capacity of an air transport system?**

The aim of this research is:

**To develop a method to estimate the network capacity that is flexible and accommodates the new ConOps.**
Background

- European air traffic network
- Network capacity
- Maximum flow
- Capacity factors
The European air traffic network can be displayed as a graph, where the nodes represent airports and ACCs. A critical notion is connectivity, which can be defined as a binary state that exists between any two nodes in the network, and takes value 1 if the two nodes are connected by a link and 0 otherwise.

850 nodes + 4,431 links
EUROCONTROL: Network capacity is the network throughput taking traffic demand patterns and the network effect of airports and airspace into account.

This definition does not capture the influences of all factors that affect capacity i.e. capacity factors.

Traditionally, the maximum network flow is the theoretical maximum amount of traffic.

We argue that the gap between theoretical and empirical maximum network flow is caused by the inefficiencies in the capacity factors.

\[ C_{net} = f(F_{\text{max}}, D_i) \]
Conventional approach

In graph theory, network capacity is the maximum flow in a transport network.
Max-flow and min-cut theory
The renowned max-flow min-cut theory is commonly used to calculate the maximum flow and identify the bottlenecks within a transport network.
Background-Capacity Factors

Airspace capacity factors

- Spatial-Geometrical
  - Airspace configuration
    - restricted airspace
    - navigational capacities
    - capacity management
    - capacity planning
- Controllability
  - Controller
    - team cooperation
    - training
      - experience
    - fatigue
    - airspace factors
    - traffic complexity
    - airspace configuration
  - H-M Interaction
    - individual difference
    - training
      - experience
    - routine
    - cognitive
    - physical
- Workload
  - workload
    - traffic demand
    - traffic patterns
    - network effects
    - global airspace awareness
  - flow management
    - solution performance
    - coordination
    - traffic performance
  - airspace management
    - solution performance
    - control area awareness
    - controllability
- Capacity resilience
  - Pilot
  - Automation
Background-Capacity Factors

- Wake turbulence
- Aircraft mix
- Runway occupancy
- Separations
- Space consumption
- Speed
- Trajectory
- Lin-up constraints
- Length of the approaching path
- Terminal area
- Quantity
- Runway
- Taxiway
- Configuration
- Gate/ramp mix
- Ceiling and visibility
- Weather

- Spatial-Geometrical

- Airport capacity drivers
  - Controllability
  - ATCO
  - Separation violation
  - Approaching procedure
  - Technical support
  - Information
  - Communication
  - Pilot
  - Skill
  - Radar
  - Coverage
  - availability
  - Arrival/departure ratio
  - Touch/go ratio
  - Aircraft mix
  - Demand
  - Traffic characteristics
  - Slot management
  - Usage
  - Runway
  - Maintenance
  - Surface condition
  - Gate/ramp
  - turnaround
  - Environmental constraints
  - Noise
  - Winds

- Resilience
### CORRELATION BETWEEN IATA DELAY CODES AND THE CFMU REASONS FOR REGULATION

<table>
<thead>
<tr>
<th>Reason for Regulation</th>
<th>Code</th>
<th>Regulation Location</th>
<th>Example</th>
<th>CFMU</th>
<th>IATA Code</th>
<th>Delay Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATC capacity</td>
<td>C</td>
<td>D</td>
<td>Demand exceeds the capacity</td>
<td>D</td>
<td>89</td>
<td>RESTRICTIONS AT AIRPORT OF DEPARTURE</td>
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<tr>
<td></td>
<td>C</td>
<td>E</td>
<td></td>
<td>E</td>
<td>81</td>
<td>ATFM due to ATC ENROUTE DEMAND/CAPACITY</td>
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<tr>
<td></td>
<td>C</td>
<td>A</td>
<td></td>
<td>A</td>
<td>83</td>
<td>ATFM due to RESTRICTION AT DESTINATION AIRPORT</td>
</tr>
<tr>
<td>ATC Ind action</td>
<td>I</td>
<td>D</td>
<td>Controller’s strike</td>
<td>D</td>
<td>89</td>
<td>RESTRICTIONS AT AIRPORT OF DEPARTURE</td>
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<td>I</td>
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<tr>
<td>ATC Routings</td>
<td>R</td>
<td>E</td>
<td>Phasing in of new procedures</td>
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<td>RESTRICTIONS AT AIRPORT OF DEPARTURE</td>
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<tr>
<td></td>
<td>S</td>
<td>E</td>
<td>Illness, traffic delays on the highway</td>
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<td>ATC Staffing</td>
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<tr>
<td>ATC equipment</td>
<td>T</td>
<td>D</td>
<td>Radar failure, RTF failure</td>
<td>D</td>
<td>89</td>
<td>RESTRICTIONS AT AIRPORT OF DEPARTURE</td>
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<td></td>
<td>T</td>
<td>A</td>
<td></td>
<td>A</td>
<td>83</td>
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<tr>
<td>Accident / Incident</td>
<td>A</td>
<td>D</td>
<td>Rwy23 closed due to accident</td>
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<td>RESTRICTIONS AT AIRPORT OF DEPARTURE</td>
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<tr>
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<td>A</td>
<td>A</td>
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<tr>
<td>Aerodrome capacity</td>
<td>G</td>
<td>D</td>
<td>Lack of parking; taxiway closure; areas closed for maintenance; demand exceeds the declared airport capacity</td>
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<td>87</td>
<td>AIRPORT FACILITIES</td>
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<tr>
<td></td>
<td>G</td>
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<td>A</td>
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<td>AIRPORT FACILITIES</td>
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<tr>
<td>De-Icing</td>
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<td>De-icing</td>
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<td>RESTRICTIONS AT AIRPORT OF DEPARTURE</td>
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<tr>
<td>Equipment non-ATC</td>
<td>E</td>
<td>D</td>
<td>Runway or taxiway lighting failure</td>
<td>D</td>
<td>87</td>
<td>AIRPORT FACILITIES</td>
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<tr>
<td></td>
<td>E</td>
<td>A</td>
<td></td>
<td>A</td>
<td>87</td>
<td>AIRPORT FACILITIES</td>
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<tr>
<td>Ind Action non-ATC</td>
<td>N</td>
<td>D</td>
<td>Firemen’s strike</td>
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<td>INDUSTRIAL ACTION OUTSIDE OWN AIRLINE</td>
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<tr>
<td>Military activity</td>
<td>M</td>
<td>D</td>
<td>Brilliant Invader; ODAX</td>
<td>D</td>
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<td>INDUSTRIAL ACTION OUTSIDE OWN AIRLINE</td>
</tr>
<tr>
<td>Special Event</td>
<td>P</td>
<td>D</td>
<td>European football cup; Heads of Government meetings</td>
<td>D</td>
<td>98</td>
<td>INDUSTRIAL ACTION OUTSIDE OWN AIRLINE</td>
</tr>
<tr>
<td>Weather</td>
<td>W</td>
<td>E</td>
<td>Thunderstorm; low visibility; X winds</td>
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<td>73</td>
<td>WEATHER EN ROUTE OR ALTERNATE</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>A</td>
<td></td>
<td>A</td>
<td>84</td>
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<tr>
<td>Environmental issues</td>
<td>O</td>
<td>D</td>
<td>Noise</td>
<td>D</td>
<td>89</td>
<td>RESTRICTIONS AT AIRPORT OF DEPARTURE</td>
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<td></td>
<td>V</td>
<td>E</td>
<td></td>
<td>E</td>
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<tr>
<td></td>
<td>O</td>
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<td>Security alert</td>
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</tr>
</tbody>
</table>
Methodology

- Linear Programming
Methodology

Objective function:

$$\max_{i \in BA} \sum f_i$$

Subject to

$$[\delta_{pv}]_{197 \times 28776} \times \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_{28776} \end{bmatrix} \leq \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_{197} \end{bmatrix}$$
Results and Discussion

EMF and TMF in the network.
Left: Correlation between TMF and EMF = 0.96;
Right: EMF = 0.6xTMF - 142.
EMF and TMF at 67 busy airports.

Left: Correlation between TMF and EMF = 0.79;
Right: EMF = 0.65 * TMF - 65.
EMF and TMF at 64 aggregated airports. Left: Correlation between TMF and EMF = 0.74; Right: \( EMF = 0.25 \times TMF + 38 \).
EMF and TMF in 64 ACCs.

- **Left**: Correlation between TMF and EMF = 0.98; between capacity baselines and EMF = 0.94.
- **Right**: $EMF = 0.63 \times TMF - 191$. 
Little’s Law

\[ L_s = W_q \times \mu = \frac{\rho}{1 - \rho} \]

Where
- \( L_s \): system queue length
- \( W_q \): waiting time
- \( \mu \): service rate
- \( \rho \): utilization rate
  - \( \rho = \frac{\text{arrival rate}}{\text{service rate}} \)

In the case of an air traffic network:
- Waiting time = ATFM delays
- Service rate = Capacity
- Arrival rate = Traffic

Comparison between the empirical queue lengths and the theoretical predictions.
Findings

- Validation of the LP model
- Influences of capacity factors
- Quantification of capacity factors
Limitation and Future Work

- Inherent limitations
  - Capacities
  - Static nature
  - Traffic demand pattern
- Future work
  - Overcome the limitations
  - Quantify the capacity factors.
  - Assess the contribution of SESAR by mapping new operational improvements to capacity factors.
• We have developed, for the first time, a linear programming to estimate maximum flows in the European air traffic network. The results suggest that this LP approach is relatively capable to model the air traffic in Europe.

• In addition, the influence of the capacity factors can be assessed by using regression analysis to quantify these parameters.

• Finally, ATFM delays and queuing theory can potentially be used to quantify capacity factors.
Questions