A novel ATFM model to optimise network delay

- Towards innovative enhancements for CASA -

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Outline

1. Introduction & motivation: the interacting regulations problem
2. The novel ATFM model
   • Fundamental analysis of interactions between regulations
   • The heuristic optimisation model (ECASA)
3. Simulations and results
4. Conclusions and next steps
Outline

1. Introduction & motivation: the interacting regulations problem
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Basics of today’s ATFM operations

1. NM makes predictions of 4DTs from flight plans (hours in advance)

2. Entry Counts (expected) per TV

3. Demand-Capacity problem

4. Regulation for a period

Traffic delayed to solve the imbalance
Impact of delay on Airspace Users (AUs)

Cost of delay of 1 flight

Flight on time (delay = 0)

Non-linear cost structure:
- PAX flow: transit, high yield passengers, rotations, …
- Resource Mgt. (cascade): curfew, crew constraints, pilots constraints, maintenance, …

Impact:
- 0
- acceptable
- large

Delay

In July 2018 delay > 15 min doubled (x2) compared to July 2017.
Total cost of delay in 2018: ~16 billion €

Delays ≤ 15 min typically have ‘acceptable impact’ for the AUs

Delays > 15 min can cause disruptions to AUs operations (high costs)
Computer-Assisted Slot Allocation (CASA) sequences

In a regulation, ‘ATFM slots’ are allocated with the CASA tool to time-separate the traffic following the FPFS policy.

The sequence of FPFS is considered *fair* because it preserves the original order.

FPFS uses *capacity* efficiently and minimises the *delay* in a single regulation.

Too many flights expected at the same time (safety risk)
The MPR rule for combined flights

Often flights cross multiple regulations at different sectors (combined flights)

The Most Penalising Regulation (MPR) determines the delay of combined flights in all the regulations

A slot is forced in the non-MPR regulations (FPFS is not followed)
Interactions between flights (basic idea)

Negative Interaction (NI):

Positive Interaction (PI):

Important: positive or negative interactions propagates through domino effect / chain reaction that must be taken into account
Motivation and contribution of this research

Problem of *interacting regulations*: it was identified that the NIs were more frequent than PIs, thus increasing the total delay in the network.

WHY this happens and HOW to avoid it was not well-understood ➔ it is addressed in this research

- Classical optimisation approaches have two major difficulties:
  - Computational *intractability*
  - *Acceptability* of the solutions by AUs (equity)

- Contributions of this research:
  1. **Formal analysis** of the interacting regulations dynamics
  2. New ATFM model: **Enhanced CASA** (ECASA)
     - **Features**: for real time operations, **FPFS** as a baseline, min change in the system (**fast-implementation orientation**)
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Definition of tension zones (a.k.a. compressible zones)

• **Tension Zones (a.k.a. Compressible Zones):** periods/positions in the sequence in which flights can take earlier positions (i.e., can be compressed). Typically in TZs there is delay.
Analysis of interactions & chain reactions (in a nutshell)

1. Positive Interactions only propagate if there are compressible flights that can take the released positions (i.e., in tension zones). Empty slots appear if there are no compressible flights (i.e., out of tension zones).

2. Negative Interactions will propagate (increasing tension) until the end of the sequence or until an empty slot is found.

3. Blocked positions may change the impact of PI/NI for adjacent flights (i.e., impact > 1 position). Extra impact generated by blocked flights (EX or MPR) is referred as collateral impact.
Properties of the interactions on flights: accumulative and commutative

- **Accumulative**: the total net impact on a flight is direct addition of all the impacts received
  \[ TI_i = \sum NI_i - \sum PI_i + \Delta EmptySlots \]

- **Commutative**: the order of the impacts does not alter the final sequence.
  - Note: Intermediate states and impacts may evolve differently with the change of order (but does not affect to the final sequence)
1. We now have a **good understanding of chain reactions**, i.e., how the interactions propagate along the sequences.

2. PIs and NIs produce asymmetrical impacts: NIs tend to affect more flights than PIs ➔ **extra delay** due to interactions.

3. The major “delay generator” interactions are: flights **pushed at the beginning of large sequences of flights** ➔ increasing the delay for a lot of flights.
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Optimisation strategy proposed to mitigate the problem (ECASA)

Before optimisation (default CASA sequences)

After optimisation (enhanced sequences)

ECASA makes a better use of the available capacity to reduce the total delay.
A simple example to assess the potential

Before activation of R1 in TV1

Flights F, G, H cross TV1 and TV2 in non-regulated periods (i.e., they are not regulated)

Delay in R1 = 90 min
Delay in R2 = 50 min
Total Delay = 140 min

Flights F, G, H become combined flights crossing R1 and R2

28% delay can be saved

After activation of R1 in TV1

Flights F, G, H become combined flights crossing R1 and R2

Delay in R1 = 90 min
Delay in R2 = 104 min
Total Delay = 194 min

Regulations without interactions

TV1 - Pre-R1: A, B, C, D, E, F, G, H, J, ...
TV2 - R2: K, L, M, N, O, P, Q, R, S, T, U
Delay: 0 2 4 6 8 10 8 6 4 2 0

Delay in R2 = 50 min

Non-optimised

ECASA

Slot amendments in R1 to optimise network delay

Delay in R1 = 90 min
Delay in R2 = 50 min
Total Delay = 140 min

28% delay can be saved

Delay in R1 = 90 min
Delay in R2 = 104 min
Total Delay = 194 min
ECASA principle: apply *small amendments* to the default *CASA sequences* to mitigate the *Interacting Regulations problem* (thus optimising network delay)

**ECASA algorithm:**

At each CASA *True Revision Process* (every 1 minute):

1) Run *CASA* as usual (*CASA* is the core)
2) Identify the flights to be amended (for network optimisation)
3) Change the priority for those selected flights

Note: Slot amendments are managed by *CASA* (in step 1)

**ECASA follows an innovative approach (min change & max benefit)**
ECASA vs CASA benchmarking

SIMULATIONS AND RESULTS
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EUROCONTROL’s R-NEST tool includes a dynamic ATFM simulator to perform slot allocation tasks with an accurate CASA engine (same as used by the Network Operations in real operations)
Research methodology (with R-NEST)

ECASA performance has been analysed with these KPIs:
1. Delay in the network
2. Impact to AUs (delay >15)
3. Impact to stability in the network (network effects)
ECASA: optimisation of network delay

In the period **July-August 2018** (AIRAC 1808):

- An **average of 27%** of delay could be reduced in the period
- **Up to 35%** of reduction in some days (min. case: **18%**)
- **In general:** the higher the delay, the higher the optimisation potential
Impact of ATFM delay to AUs

**Flights with delay > 0 (average per day)**

- CASA: 10616 flights delayed (-13.7%)
- ECASA: 9161 flights delayed

**Delay distributions and variation (AIRAC 1808)**

- 01-15 min
- 16-30 min
- 31-45 min
- 45-60 min
- 61-75 min
- 75-90 min
- >90 min

-1455 flights delayed (-13.7%)

-42% flights delayed >15 min
Impact of ECASA to the stability of the network

**TVs penalised with additional flights**
(ECASA sequences with respect CASA sequences)

<table>
<thead>
<tr>
<th>Throughput variation (in 10 min slices)</th>
<th>Number of TVs</th>
<th>% of TVs (total #TVs: 9857)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 1 flights</td>
<td>817</td>
<td>8.29%</td>
</tr>
<tr>
<td>≥ 2 flights</td>
<td>315</td>
<td>3.20%</td>
</tr>
<tr>
<td>≥ 3 flights</td>
<td>140</td>
<td>1.42%</td>
</tr>
<tr>
<td>≥ 4 flights</td>
<td>66</td>
<td>0.67%</td>
</tr>
<tr>
<td>≥ 5 flights</td>
<td>32</td>
<td>0.33%</td>
</tr>
</tbody>
</table>

- These are not necessarily overloads (no safety issue)
- The regulation schemes will adapt dynamically (no safety issue)
- Especial treatment to some specific flights could be applied (e.g., STAM)

**Numbers are promising**: it seems quite unlikely to have large impact on the stability of the network. Further validation is on the way.
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Conclusions and future work

- The interacting regulations problem has been presented, showing that the FPFS policy cannot minimise the overall delay in the network.

- ECASA (Enhanced CASA) has been proposed to minimise the extra delay generated by the interacting regulations problem.

- ECASA vs CASA benchmarking has shown very promising results (27% less delay and 42% less flights impacted, on average).

- ECASA requires minimum change in the system (fast-implementation approach).

- Currently we are exploring the potential implementation of the ECASA in the Network Manager for real operations.

- Future research will include new optimisation strategies for ECASA to further reduce delays.
Thanks for your attention.

Questions and comments are welcome.
ATFM SLOTS & Computer-Assisted Slot Allocation (CASA) sequences

In a regulation, the NM assigns ‘ATFM slots’ to separate flights by time, in order to reduce traffic complexity at overloaded sectors. The baseline delay of FPFS sequence is considered fair. ATFM slots are allocated with the CASA tool following FPFS policy. FPFS minimises the delay in regulations (but not at network level). The baseline delay of FPFS sequence is considered fair.
Interacting regulations and their effect in the total network delay

**Regulations without interactions**

**R1:**

| A | B | C | D | E | F | G | H | I | J | ...
|---|---|---|---|---|---|---|---|---|---|---
| 0 | 2 | 4 | 6 | 8 | 10| 8 | 6 | 4 | 2 |   

**Delay:**

| A | B | C | D | E | F | G | H | I | J | ...
|---|---|---|---|---|---|---|---|---|---|---
| 0 | 2 | 4 | 6 | 8 | 10| 8 | 6 | 4 | 2 |   

**R2:**

| K | L | M | N | O | P | Q | R | S | T | U | ...
|---|---|---|---|---|---|---|---|---|---|---|---
| 0 | 2 | 4 | 6 | 8 | 10| 8 | 6 | 4 | 2 | 0 |   

**Delay:**

| K | L | M | N | O | P | Q | R | S | T | U | ...
|---|---|---|---|---|---|---|---|---|---|---|---
| 0 | 2 | 4 | 6 | 8 | 18| 16| 14| 12| 10| 0 |  

**Total delay in R1:** 50 min  
**Total delay in R2:** 50 min  
**Total delay:** 100 min

**Regulation R1 receiving interactions from R2**

**R1:**

| A | B | C | D | E | N | O | P | Q | F | G | H | I | J | ...
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---
| 0 | 2 | 4 | 6 | 8 | 18| 16| 14| 12| 10| 10|  

**Delay:**

| A | B | C | D | E | N | O | P | Q | F | G | H | I | J | ...
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---
| 0 | 2 | 4 | 6 | 8 | 18| 16| 14| 12| 10| 10|  

**R2:**

| K | L | M | N | O | P | Q | R | S | T | U | ...
|---|---|---|---|---|---|---|---|---|---|---|---
| 0 | 2 | 4 | 6 | 8 | 10| 8 | 6 | 4 | 2 | 0 |   

**Delay:**

| K | L | M | N | O | P | Q | R | S | T | U | ...
|---|---|---|---|---|---|---|---|---|---|---|---
| 0 | 2 | 4 | 6 | 8 | 10| 8 | 6 | 4 | 2 | 0 |  

**Total delay in R1:** 90 min  
**Total delay in R2:** 50 min  
**Total delay:** 140 min

Delay increases with the interactions between regulations

The problem becomes bigger when congestion grows (⇒ more regulations = more probability of interactions)
Another example, found in the simulations

In this case the flight in the left can optimise the delay in 2 different regulations (175 flights in one + 45 in the other = 218 flights)

Reducing the delay of the left flight by 24 minutes (from 36 min to 12 min) could reduce 5.5 h of total delay in the network.
Ontology of sequence positions (uses and statuses)

• **Note:** this is a simplified abstract model that may use terminology slightly different from the one used in real operations.
Micro-analysis of direct impacts and domino effect / chain reaction

<table>
<thead>
<tr>
<th>Id</th>
<th>Case</th>
<th>Direct impact and chain reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>{P^1, P^n}</td>
<td>A position is released in front of a flight that is compressible</td>
</tr>
<tr>
<td></td>
<td>{L_x, L_y &gt; 0}</td>
<td>The position of flight (i) is taken by flight (x)</td>
</tr>
<tr>
<td></td>
<td>Chain Reaction Example: (assumed (L_x, L_y &gt; 0))</td>
<td>A combination of different “direct impacts” could be found during the chain reaction.</td>
</tr>
<tr>
<td></td>
<td>Direct Impact:</td>
<td>Taking (P^1) Pushing (P^n)</td>
</tr>
<tr>
<td></td>
<td>Release</td>
<td>(P^1) (P^n) (P^1) (P^n)</td>
</tr>
<tr>
<td>C2</td>
<td>{P^1, P^n, P^m}</td>
<td>A position is released in front of a flight that is blocked and a compressible flight is next</td>
</tr>
<tr>
<td></td>
<td>{L_x, L_y &gt; 0}</td>
<td>The position of flight (i) is taken by flight (x) while there is at least one blocked position adjacent and after the position of flight (i).</td>
</tr>
<tr>
<td></td>
<td>Chain Reaction Example: (assumed (L_x, L_y &gt; 0))</td>
<td>Taking (P^1) Pushing (P^n)</td>
</tr>
<tr>
<td></td>
<td>Direct Impact:</td>
<td>Release (P^1) (P^n) (P^1) (P^n)</td>
</tr>
<tr>
<td></td>
<td>Chain Reaction Example: ((L_x, L_y, L_z &gt; 0))</td>
<td>No compressible (no chain reaction)</td>
</tr>
<tr>
<td>C3</td>
<td>{P^1, P^n}</td>
<td>An empty position located in front of flight (i) is taken by flight (x)</td>
</tr>
<tr>
<td></td>
<td>(K^x_i = R^x_i = 0)</td>
<td>No impact</td>
</tr>
<tr>
<td></td>
<td>Chain Reaction Example: (assumed (L_x, L_y &gt; 0))</td>
<td>Taking (P^1) Pushing (P^n)</td>
</tr>
<tr>
<td></td>
<td>Direct Impact:</td>
<td>Release (P^1) (P^n) (P^1) (P^n)</td>
</tr>
<tr>
<td>C4</td>
<td>{P^1, P^n}</td>
<td>A position is released in front of a flight that is not compressible (Flight is blocked in tension)</td>
</tr>
<tr>
<td></td>
<td>(K^x_i = R^x_i = 0)</td>
<td>No compressible (no chain reaction)</td>
</tr>
<tr>
<td></td>
<td>Chain Reaction Example: (assumed (L_x, L_y &gt; 0))</td>
<td>Taking (P^1) Pushing (P^n)</td>
</tr>
<tr>
<td></td>
<td>Direct Impact:</td>
<td>Release (P^1) (P^n) (P^1) (P^n)</td>
</tr>
</tbody>
</table>

Note: what is important is the direct impact. The chain reaction is showed just as an example.
1. Compression is applied if and only if there is a hole in a tension zone (where flights are in tension, i.e. compressible).

2. There cannot be any holes (empty slots) in tension zones. If a release occurs within a TZ, then the hole will be occupied and ‘displaced’ by chain reaction until the hole appears in the final position in the original TZ.

3. A taking of a slot will always fill a hole (empty slot) in a sequence. If the hole does not exist (it is occupied by another flight), the allocated flight will be forced ('pushed') to take the next non-blocked position. Other later flights may also be pushed by a chain reaction.

4. The chain reaction of a taking will only be stopped when a hole is found (sometimes at the end of a sequence).

5. Chain reactions do not alter the position of blocked flights in a sequence and do not change the order of non-blocked flights in a sequence (FPFS policy is preserved).
Methodology to assess interactions

- A PI occurs when a flight (or a blocked empty slot) is present in the baseline sequence but is not present in the linked sequence.
- A NI occurs when a flight (or a blocked empty slot) is not present in the baseline but it is present in the linked sequence.
- The variation of Empty slots is also considered:

\[ \Delta K_i = \sum_{i} N_i - \sum_{i} P_i = NFNO_{iS} - NFNO_{iS}^{\prime} + \Delta FES_i \]
The average delay increases with the number of regulations.

The average number of empty slots also increases (capacity inefficiencies) → it is perhaps the cause of the delay increase.
Network delay (in the ECAC airspace)

The period **July-August 2018 (AIRAC 1808)** has been analysed. On average:

- **337 regulations** per day (**max peak: 450**)  
- Around **3368 h** of delay per day (**19 min on average per flight delayed**)  
- The average delay is **highly correlated** with the number of regulations
How ECASA optimises: manual example

Flights can be sorted by optimisation potential
This flight for instance could potentially reduce the delay of 218 flights
In this case two regulations are penalised by the selected flight.

In this case the flight can optimise the delay in 2 different regulations (175 flights in one + 45 in the other = 218 flights).
Penalisation of MGY3428M to MGY1228A

If the delay of the flight in 1 is reduced by 24 min in MGY3428M then it will take a free slot in 4-5 instead of the slot in 2-3, thus saving $45 \times 2 = 1.5$ h delay in MGY1228A
Penalisation of MGY3428M to EHYR28

If the delay of the flight in 1 is reduced by 24 min in MGY3428M then it will take a free slot in 6-7 instead of the slot in 2-3, thus saving 175 * 1:20 = 4 h delay in MGY1228A.
Optimisation strategy implemented in ECASA

F in its ETO position

Delay of F (in positions)

R1: ...
    A  B  C  D  E  EX  F  G

R2: ...
    H  I  J  EX  EX  F  K  L  EX  M  N  ...

R3:  O  P  E  Q  R  S  EX  T  U  ...

Flight trajectory

R1: ...
    A  F  B  C  D  EX  E  G

R2: ...
    H  I  F  EX  J  EX  K  L  M  EX  N  ...

R3:  O  P  Q  R  S  T  EX  U  ...

Same delay in R1 (little bit of more delay for D and E)
Typically much less delay in R2 and in R3
Optimisation strategy proposed by ECASA

Before optimisation (default CASA sequences)

<table>
<thead>
<tr>
<th>R1:</th>
<th>...</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>EX</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
</table>
| R2: | ... | H | I | J | EX|   | EX| K | L | EX| M | N | ...

Delay of F (in positions)

Empty slots

After optimisation (enhanced sequences)

<table>
<thead>
<tr>
<th>R1:</th>
<th>...</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>F</th>
<th>D</th>
<th>EX</th>
<th>E</th>
<th>G</th>
</tr>
</thead>
</table>
| R2: | ... | H | I | J | EX| F | EX| K | L | M | EX| N | ...

Delay of F (in positions)

Same delay in R1 (a bit more delay for D and E)
Normally, much less delay in R2 and in R3

Flight using a former empty slot

Flight not entering into R3

ECASA makes a better use of the available capacity to reduce the total delay.
Strategy 1: Avoid flights entering into Tension Zones (of other regulations)

Removing flights from the beginning of large tension zones can save **hours** of delay in a single regulation.
Strategy 2: overloading slots nearby the existing empty slots

Case 1:

- Better usage of spare capacity (slots) with no negative impact on ATC workload and important reduction of delay

Case 2:

- Idem, but using the empty slots in the middle of the sequences
Strategy 3: systematic overloading of slots

Sometimes the ATCOs may have **less workload if the traffic is smoothed** by a regulation (less probability of bunching ⇒ less complexity and less workload): **TBC by ATC experts**

This situation could perhaps be improved by adding a **second rate parameter** under control of the FMP: **the overloading rate** (e.g.: rate 60/3 ⇒ 1 overload every 20 minutes)

**Important delay reductions are expected**, while the **ATCO’s actual capacity could be better used** during periods of congestion
Today’s ATFM operations

1. NM makes predictions of 4DTs from flight plans (hours in advance)

2. Entry Counts (expected) per TV

3. Demand-Capacity problem

4. Regulation period

Traffic delayed to solve the imbalance
Impact on network stability: Penalisations and Protections to TVs due to Regulations

**Common demand** is the set of flights that get through at least traffic volumes A and B.

**Penalising flights:** the delay produced by A pushes flight f1 inside the observed period.

**Protecting flights:** the delay produced by A pushes flight f2 outside the observed period.

Optimised solutions should not de-stabilise the network ➔ TVs should not receive too many additional flights.