Combining Flight Level Allocation with Ground Holding to Optimize 4D-Deconfliction

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Outline

Introduction

Congested European Sky

- Regulation delays mainly due to en-route sector capacities
- Structural limits of the sector-based ATC system reached
- Optimization of airspace structure and ATFM regulations: SESAR

Two-Stage ATM Optimization

1. Flight Level Allocation
   - Vertical separation of 2D + time-intersecting flights
   - Graph Coloring, but minimization of discrepancy to requested FL
2. Ground Holding
   - Deconfliction by departure time adjustment
   - Graph Coloring as special case, minimization of delays

Solved by Constraint Programming (CP)

- Versatile modelling tool for combinatorial optimization problem
- Optimality proof for feasibility stage

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Ground Holding in Europe

Pre-tactical Flow Regulation

- **Safer** than handling the traffic while airborne
- **Costly** for airspace users, network effect

Sector Capacity and Regulation

- Air Traffic Control Centres **opening schedules**: designed by experts, based on previous traffic and demand
- Open sectors **capacities**: hourly entry rate
- **Regulation** on flows crossing overloaded sectors: Computer Assisted **Slot Allocation** (CASA/ETFMS) at CFMU

Accuracy and Effectiveness of the Model?

- **Relevance** of sector capacity to model **controller workload**?
- **Discrepancies** between planned schedule and actual openings
- CASA: **greedy** algorithm (optimality, soundness?)

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4D-Trajectory Deconfliction

4D-Trajectory Planning

- "Strategic" deconfliction (EC project Episode 3)
- Several opportunities: flight level, rerouting, delay, speed...
- Large scale combinatorial optimization problems

Conflict Model

- **Finest** grain (conflicts) vs aggregated model (sector capacity)
- **Sliding time windows** to handle **uncertainty**

Two-Stage Trajectory Deconfliction

1. **Flight Level Allocation**
   - Detection in the horizontal plane
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Conflict Model

Data

- **Flight plans** and airspace data for one day of traffic
- **Simulation** with CATS [Alliot,Durand 97]
- **Trajectories sampled** every 15 s (catch shortest conflicts)
- Notation: flight i at point p_i^k at time t_i^k if not delayed

Variables and Constraints

- **Decision variables**: flight level $FL_i \in [RFL_i - \text{dev}_{\text{max}}, RFL_i + \text{dev}_{\text{max}}]$ and delay $\delta_i \in [0, \delta_{\text{max}}]$ for each flight i
- Auxilliary variables: $\theta_i^k = t_i^k + \delta_i$ $\quad d_{ij} = \delta_j - \delta_i$
- **Constraints**: two flights cannot be at two conflicting points of their trajectories at the same time

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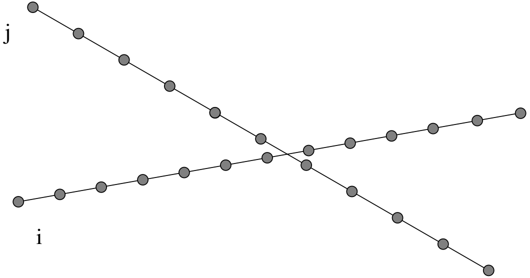
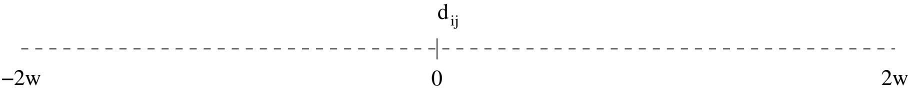


$$t_i^k \in [1000, 1180], t_j^l \in [600, 750]$$



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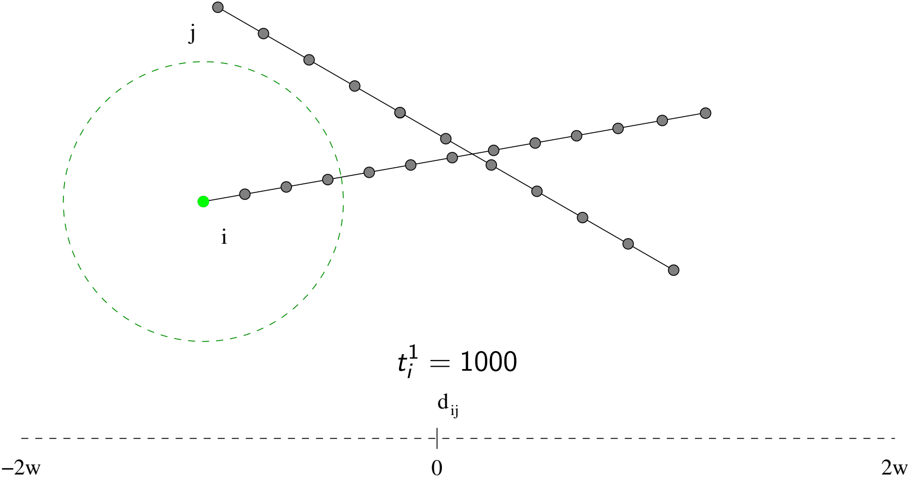

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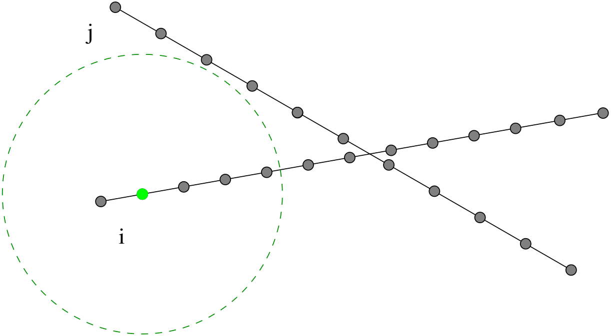
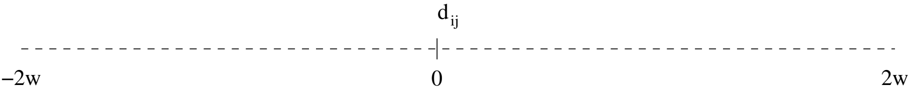


$$t_i^2 = 1015$$



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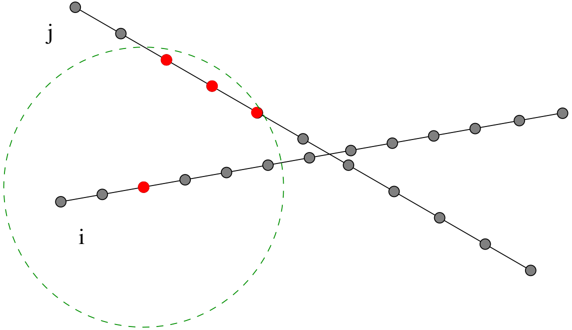
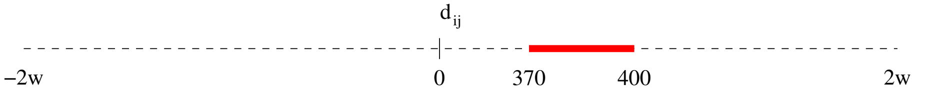


$$t_i^3 = 1030, [t_j^3 = 630, t_j^5 = 660], d_{ij} \notin [370, 400]$$



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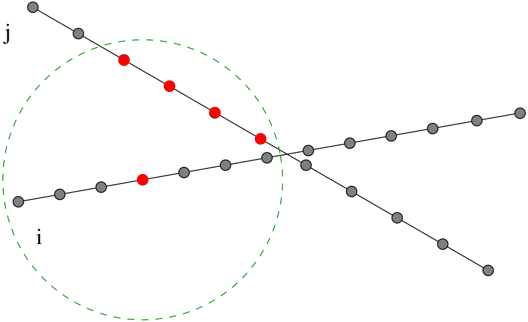
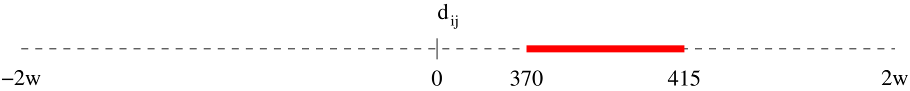


$$t_i^4 = 1045, [t_j^3 = 630 - t_j^6 = 675], d_{ij} \notin [370, 415] \subseteq [370, 415]$$



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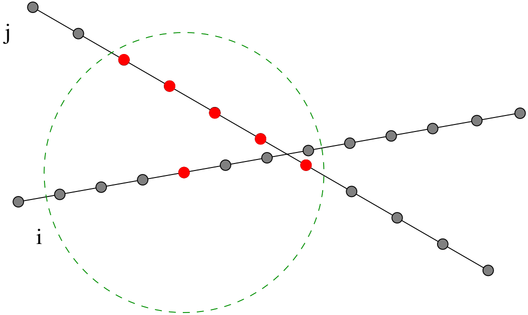
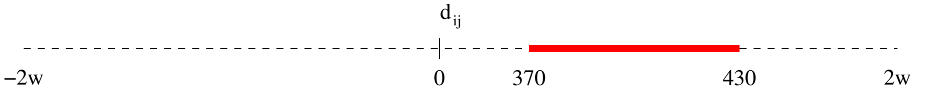


$$t_i^5 = 1060, [t_j^3 = 630 - t_j^7 = 690], d_{ij} \notin [370, 430] \subseteq [370, 430]$$



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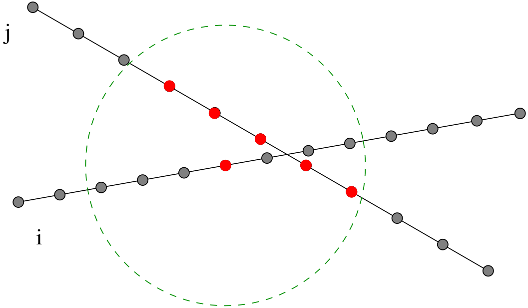
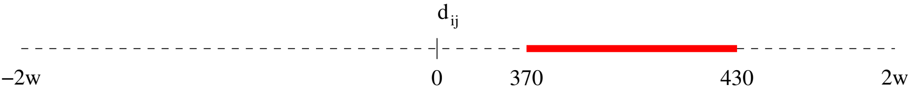


$$t_i^6 = 1075, [t_j^4 = 645 - t_j^8 = 705], d_{ij} \notin [370, 430] \subseteq [370, 430]$$



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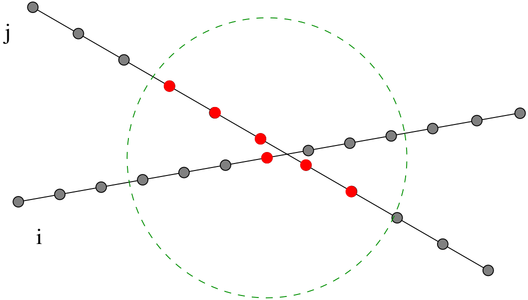
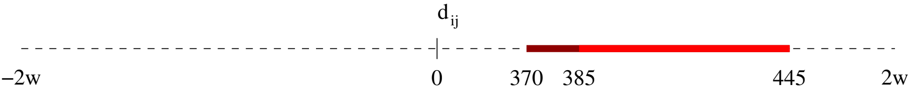


$$t_i^7 = 1090, [t_j^4 = 645 - t_j^8 = 705], d_{ij} \notin [385, 445] \subseteq [370, 445]$$



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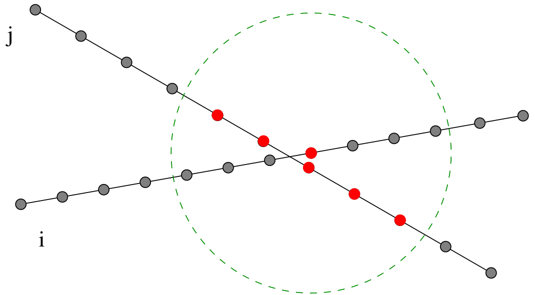
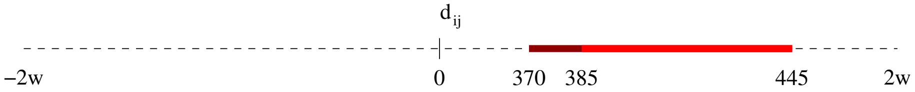


$$t_i^8 = 1105, [t_j^5 = 660 - t_j^9 = 720], d_{ij} \notin [385, 445] \subseteq [370, 445]$$



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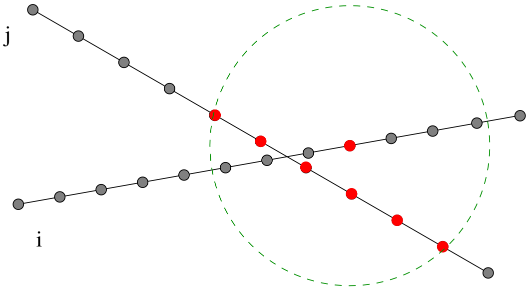
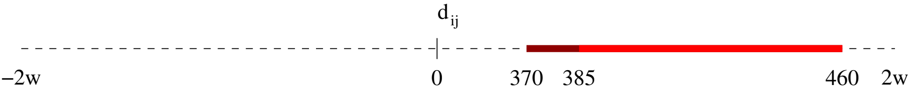


$$t_i^9 = 1120, [t_j^5 = 660 - t_j^{10} = 735], d_{ij} \notin [385, 460] \subseteq [370, 460]$$



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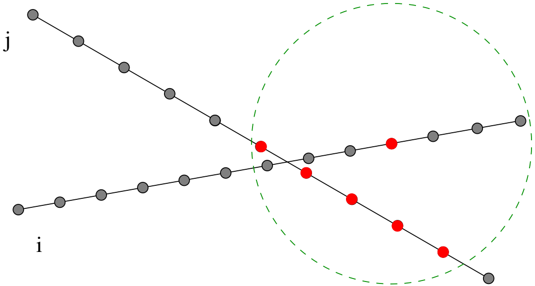
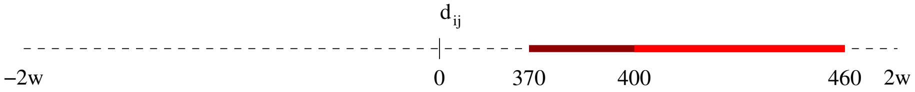


$$t_i^{10} = 1135, [t_j^{6} = 675 - t_j^{10} = 735], d_{ij} \notin [400, 460] \subseteq [370, 460]$$



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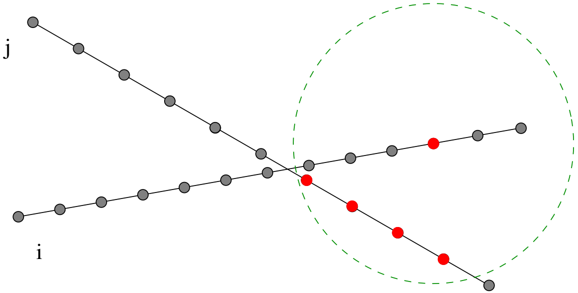
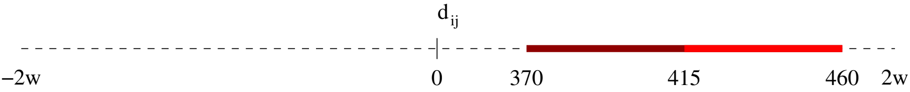


$$t^i_{11} = 1150, [t^7_j = 690 - t^{10}_j = 735], d_{ij} \notin [415, 460] \subseteq [370, 460]$$



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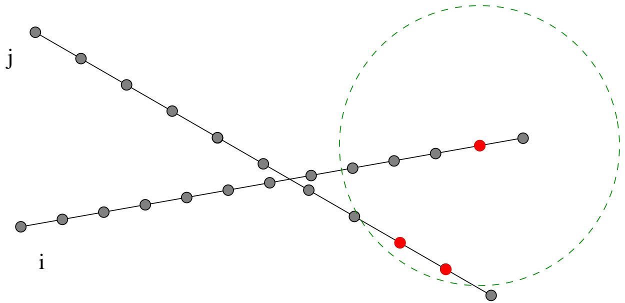
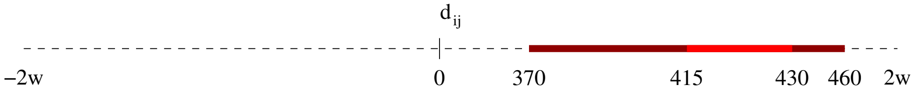


$$t^i_{12} = 1165, [t^9_j = 720 - t^{10}_j = 735], d_{ij} \notin [415, 430] \subseteq [370, 460]$$



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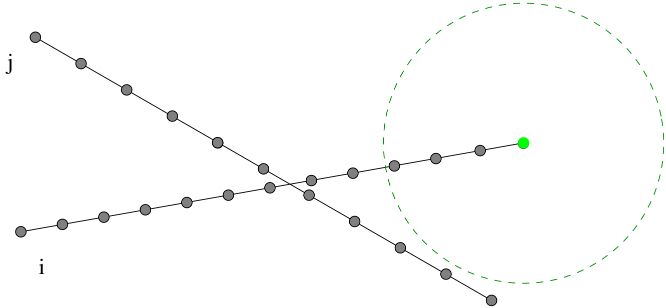
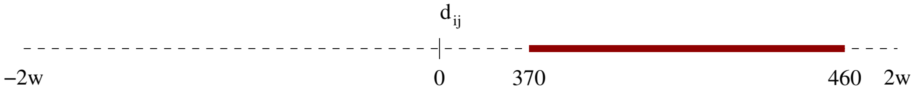
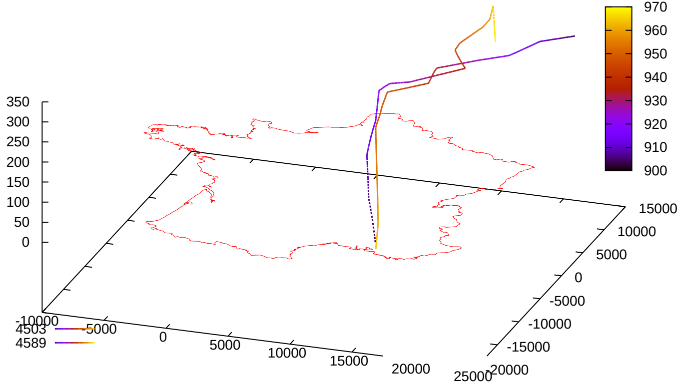


$$d_{ij} = \delta_j - \delta_i \notin [370, 460]$$



Multiply-Conflicting Flight Pair

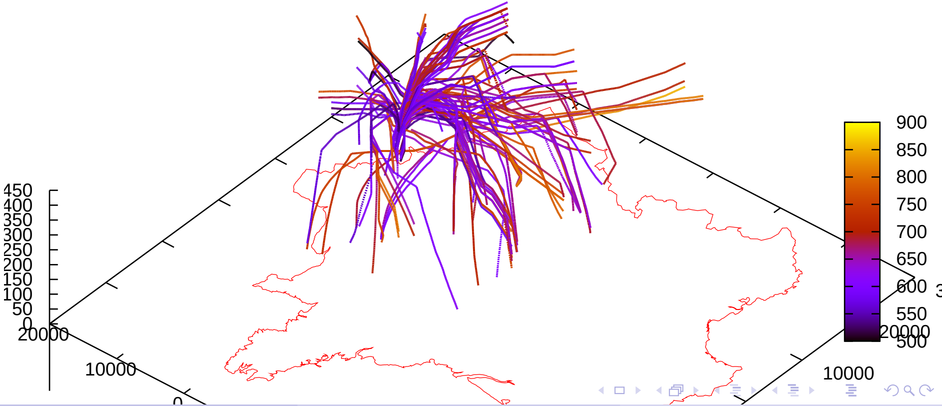


$$d_{ij} = \delta_j - \delta_i \notin \mathcal{C}_{ij} = [lb_{ij}^1..ub_{ij}^1] \cup \cdots \cup [lb_{ij}^k..ub_{ij}^k]$$

Flight Conflicting with Many Other

Constraint Graph of High Degree

- Highest degree > 650
- Large cliques > 150
- One single large connected component



2D+Time Conflicts

For each pair of flights $i \neq j$

$\forall k, l$, such that $d_h(p_i^k, p_i^l) < 5\,\text{NM}$ (horizontal plane only):

$$\begin{aligned}
\theta_i^k &\neq \theta_j^l \\
t_i^k + \delta_i &\neq t_j^l + \delta_j \\
d_{ij} &\neq t_i^k - t_j^l
\end{aligned}$$

Therefore: $$d_{ij} \notin \mathcal{C}_{ij}^H = [lb_{ij}^1..ub_{ij}^1] \cup \cdots \cup [lb_{ij}^m..ub_{ij}^m]$$

We note: $$conflict^H(i,j) \Leftrightarrow [-\delta_{\text{max}}, \delta_{\text{max}}] \cap \mathcal{C}_{ij}^H \neq \emptyset$$

Trajectories truncated to their largest possible level part (below $RFL - \text{dev}_{\text{max}}$)

FL Allocation: Flows Model

Model

- Flights sharing the same route and (almost) same RFL aggregated into flows $\mathcal{F}_k$
- Extension of conflicts to flows:

$$conflict(\mathcal{F}_k, \mathcal{F}_l) \Leftrightarrow \exists (i,j) \in \mathcal{F}_k \times \mathcal{F}_l \text{ s.t. } conflict^H(i,j)$$

Constraints: $conflict(\mathcal{F}_k, \mathcal{F}_l) \Rightarrow FL_k \neq FL_l$

Cost: $\text{cost}_{FL} = \sum_i |RFL_i - FL_i|$

Limits

- Few variables, but very dense constraint graph
- Does not solve catch-up conflicts

It was abandoned for the single flight model.

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Temporal Relaxation

- Very dense graph with costly solutions for feasible values of $\delta_{\max}$
- Most flights won't be delayed (or by a very small amount)
- Detection with $d_{ij} = 0 \in \mathcal{C}_{ij}^H$: solutions with low $\text{dev}_{\max}$ and cost_{FL}

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Ground Holding Conflict Constraints

For each pair of flights $i \neq j$ after FL allocation

$\forall k, l$, such that $d_h(p_i^k, p_i^l) < 5\,\text{NM} \wedge d_v(p_i^k, p_i^l) < 1000\,\text{ft}$:

$$\theta_i^k \neq \theta_j^l$$

Therefore:

$$d_{ij} \notin \mathcal{C}_{ij} = [lb_{ij}^1..ub_{ij}^1] \cup \cdots \cup [lb_{ij}^m..ub_{ij}^m]$$

Cost:

$$\text{cost}_{GH}^{\text{max}} = \max_i \delta_i$$

$$\text{cost}_{GH}^{\text{sum}} = \sum_i \delta_i$$

NP-hard problem

Non European Flights

- Flights originating outside the ECAC zone cannot be delayed by Eurocontrol instances ($\approx 10\%$): $\delta_i = 0$
- Conflicts between two such flights discarded (a few dozens)

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Instance Figures

- Traffic within French airspace in 2008 (time step: 1 min)
- Demand up to 8 700 flights
- Up to 37 000 intersecting flights during FL allocation
- Up to 315 000 during ground holding

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- All instances solved down to FL0 (except TMA)
- **Max optimality proof** for most of them
- A few seconds for FL allocation and about 1 min for ground holding
- No optimization of the mean/sum but minimizing search heuristic

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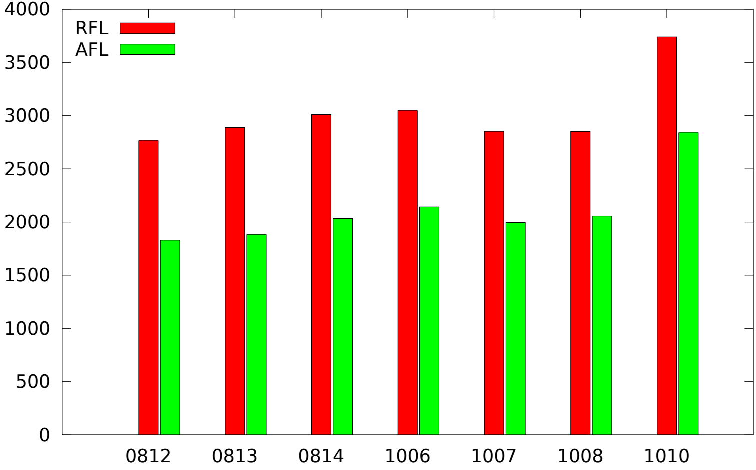
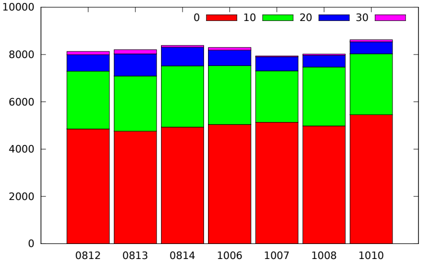
Reduction of the Number of Conflicts After FL Allocation

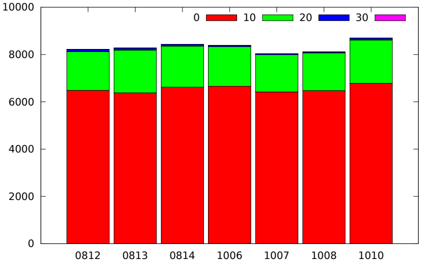


- Cannot take climb/descent phase into account ($\approx$ 75% of all conflicts)
- All cruising phase conflicts solved for $\text{dev}_{\text{max}} = FL30$

Distribution of Discrepancies from RFL After Allocation



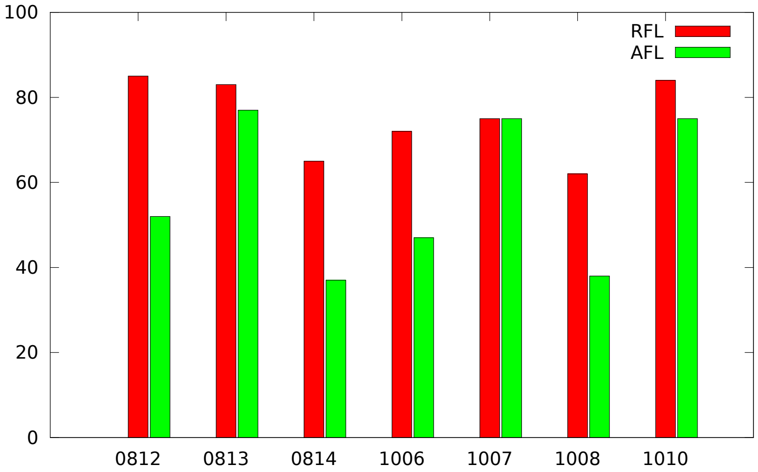
Flows Model



Single Flight Model

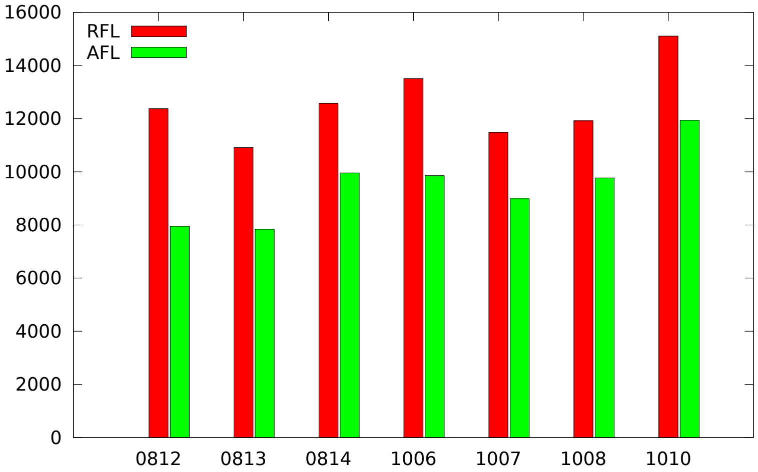
- Cost with Single Flight Model 55% better than with Flows Model
- All instances solved with $\text{dev}_{\text{max}} = FL30$, $\text{cost}_{FL} = 16\,000 - 20\,000$
- 80% at their RFL, 20% at FL10, 1% at FL20 and a couple at FL30

Optimal Max Cost Before and After FL Allocation



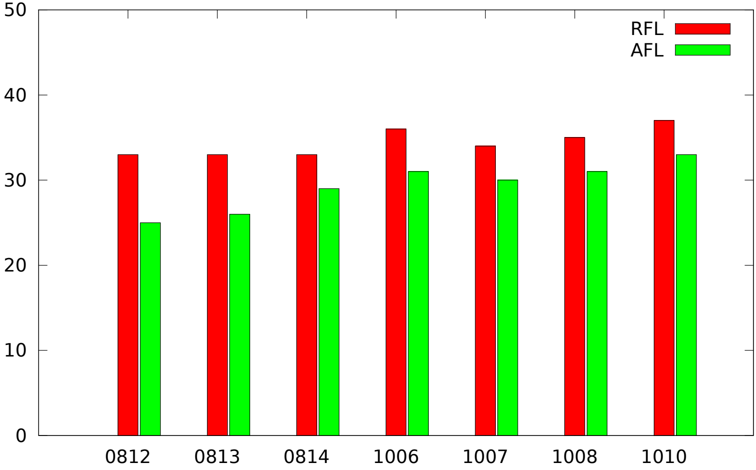
- Reduction up to 40% (average 25%)
- But max criterion does not reflect the overall amount of delay

Sum of delays before and after FL allocation



- Reduced by 25% on average (up to 36%)
- More consistent than max delay

Percentage of delayed flights before and after FL allocation



- Reduced by 5% on average (up to 8%)

Further Works

More Realistic Modelling

- **Temporal uncertainties** taken into account in real time with iterative resolution over a **sliding time window**
- Side constraints: aircraft rotation (easy to implement but lack of data)...
- Handling remaining conflicts with CATS resolution modules [Granger, Durand, Alliot 2001] (horizontal manœuvres, speed adjustment)

European Instances

- Up to 30 000 flights a day
- More RAM or other search paradigms (LS, meta-heuristics, combination with CP)

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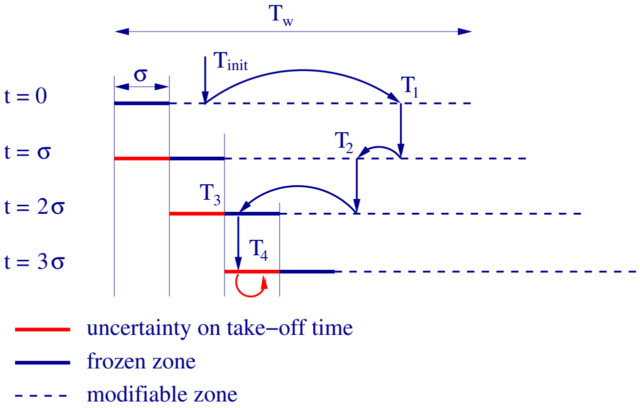
Handling Uncertainties with Sliding Time Window



- Flights with departure time between $t - \sigma$ and t are “noised”
- If the uncertainty brings them back to the “modifiable zone”, they are taken into account again for allocation

Conclusion

ATM

- **Flight level allocation** and **ground holding** combined
- **Deconfliction** vs aggregated regulation
- FL allocation with very low discrepancies to RFL
- Amount of allocated **delay compatible with typical CFMU figures**
- Large problem but **optimality proof** (w.r.t. max) obtained with CP
- Has to be **combined with other strategies** (e.g. sliding windows) when managing uncertainties

CP

- **Versatile** technology: quick prototyping, various search strategies, incremental refinement of the model, side constraints...
- CP technology **scalable** to such LSCOP, even with ECAC instances?
- May be **combined** with other search paradigms: LS to solve CSP, CP to speed up LS...

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