4D-Trajectory Deconfliction Through Departure Time Adjustment

Nicolas Barnier and Cyril Allignol
barnier@recherche.enac.fr,allignol@tls.cena.fr

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Outline

Introduction

Congested European Sky

- Regulation delays mainly due to en-route sector capacities
- Structural limits of the ATM system reached
- Optimization of airspace structure and ATFM regulations
- EC Single European Sky (SESAR) / Episode 3 - WP4

Ground Holding with Constraint Programming

- Deconfliction by ground holding: departure time adjustment
- Highly disjunctive combinatorial large scale problem
- Constraint Programming (CP) technology:
  - versatile modelling tool
  - side constraints incrementally added
  - experiment with various search strategies
- Feasibility stage: CP able to achieve optimality proof

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Ground Holding in Europe

Pre-tactical Flow Regulation

- **Safest** than handling the traffic while airborne
- **Costly** for airspace users, snowball/network effect

Sector Capacity and Regulation

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

Accuracy 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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Conflict-Free 4D-Tubes

4D-Trajectory Planning

- European Commission Episode 3 project (WP4)
- 4D-trajectory planning to reduce the number of conflicts
- Many opportunities: flight level, speed, rerouting...
- Large scale disjunctive combinatorial optimization problem

Deconfliction by Ground Holding

- **Finest** grain vs aggregated model (sector capacity)
- Same degree of freedom than slot allocation (departure time)
- **Solve all conflicts** above a given FL **by delaying** flights only
- **Standard** (flight plan) and **direct** routes considered
- Assumption: aircraft able to follow their 4D-trajectories accurately...

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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) over French controlled airspace
- Notation: flight i at point p_i^k at time t_i^k if not delayed

Variables and Constraints

- **Decision variables**: delay δ_i for each flight i
- Auxilliary variables: $\theta_i^k = t_i^k + \delta_i \qquad d_{ij} = \delta_j - \delta_i$
- **Constraints**: two flights cannot be at two conflicting points of their trajectories at the same time

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Constraints

Conflict Constraints

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

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

Note: bandwidth coloring as a particular case (NP-hard)

Non European Flights

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

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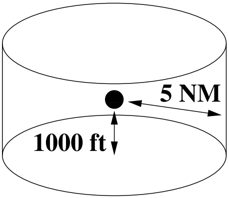
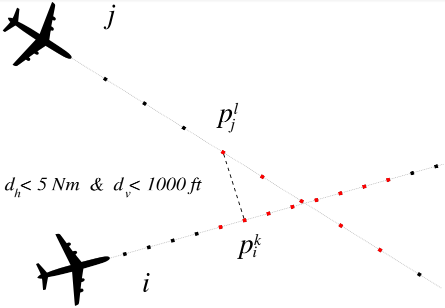
Conflict Detection

Conflicting Points Detection





Naïve 3D-Conflicting Segments

- 3D-transitive closure of segments of conflicting points
- Forbidden time intervals correspond to extremities of segments
- Same route: whole trajectory conflicting!

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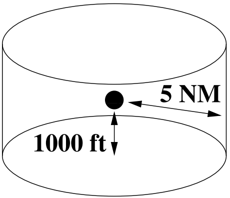

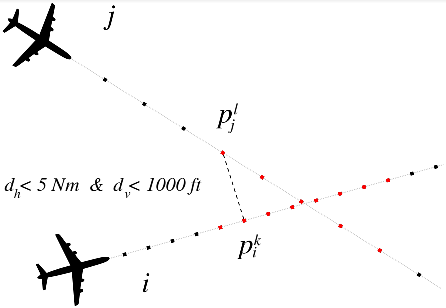

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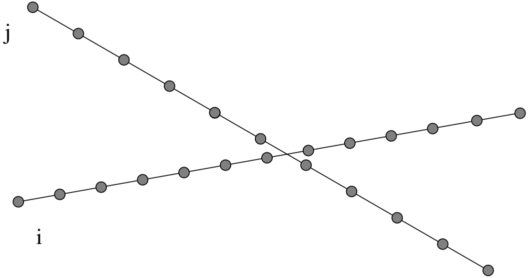
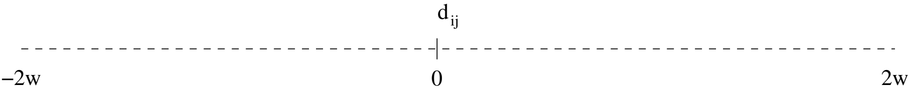
4D-Conflict Constraints



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



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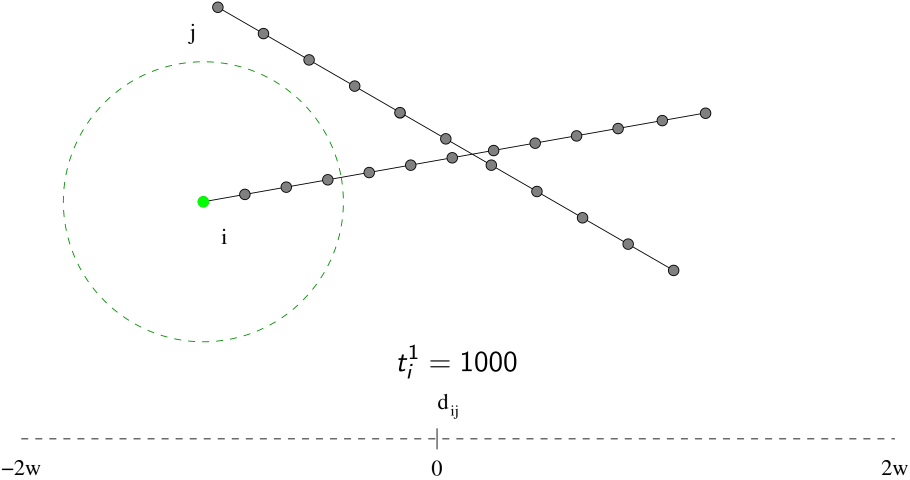

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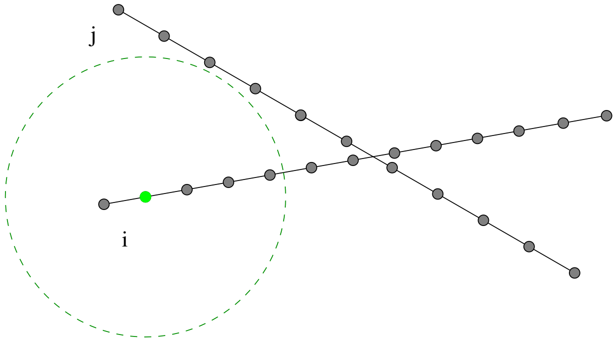
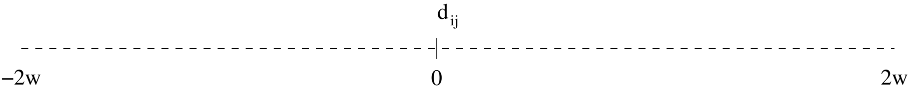


$$t_i^2 = 1015$$



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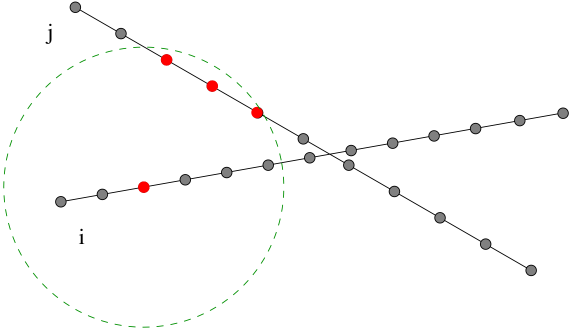
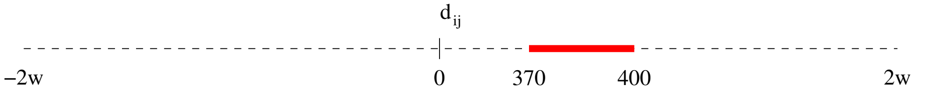


$$t_i^3 = 1030, [t_j^3 = 630, t_j^5 = 660], d_{ij} \notin [370, 400]$$



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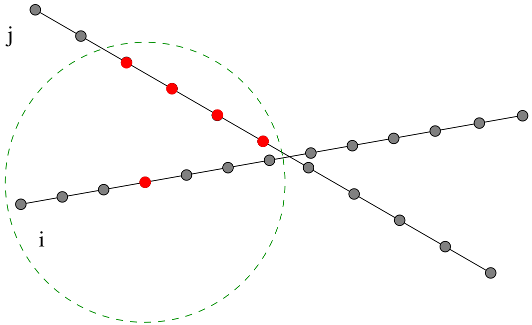
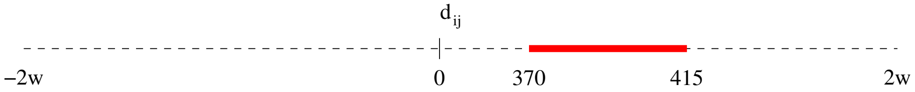


$$t_i^4 = 1045, [t_j^3 = 630 - t_j^6 = 675], d_{ij} \notin [370, 415] \subseteq [370, 415]$$



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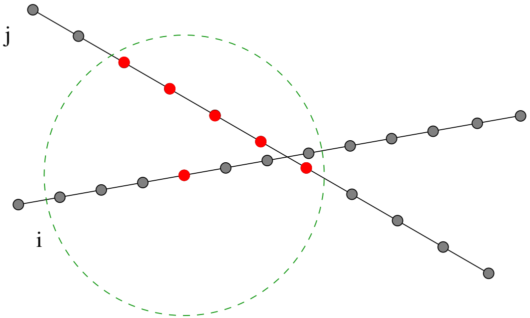
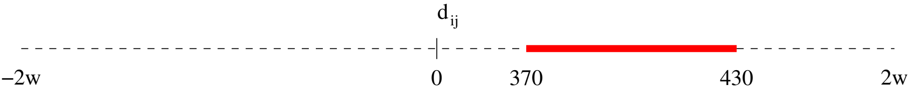


$$t_i^5 = 1060, [t_j^3 = 630 - t_j^7 = 690], d_{ij} \notin [370, 430] \subseteq [370, 430]$$



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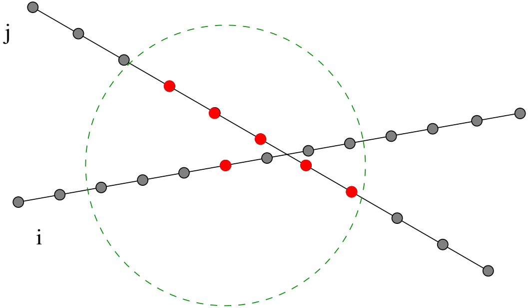
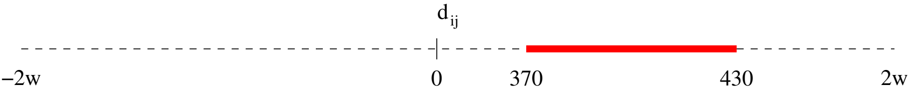


$$t_i^6 = 1075, [t_j^4 = 645 - t_j^8 = 705], d_{ij} \notin [370, 430] \subseteq [370, 430]$$



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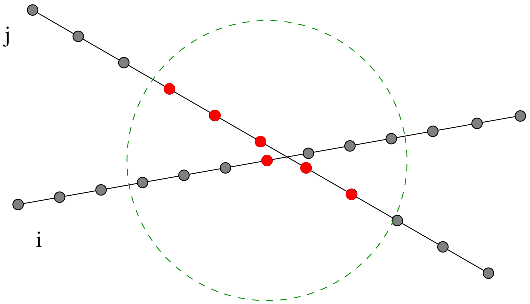
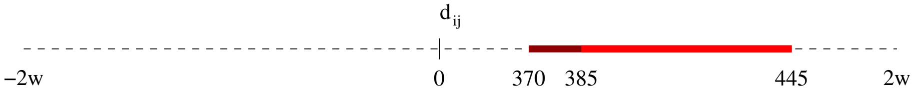


$$t_i^7 = 1090, [t_j^4 = 645 - t_j^8 = 705], d_{ij} \notin [385, 445] \subseteq [370, 445]$$



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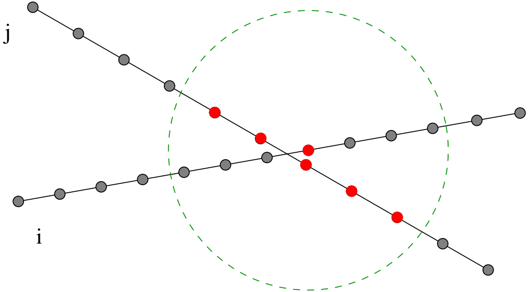
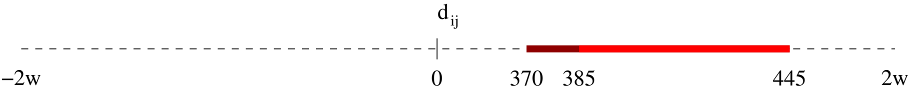


$$t_i^8 = 1105, [t_j^5 = 660 - t_j^9 = 720], d_{ij} \notin [385, 445] \subseteq [370, 445]$$



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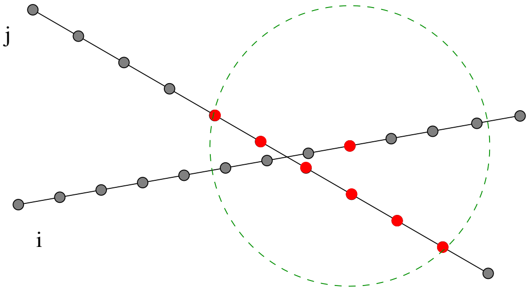
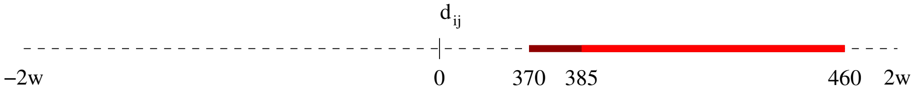


$$t_i^9 = 1120, [t_j^5 = 660 - t_j^{10} = 735], d_{ij} \notin [385, 460] \subseteq [370, {\color{red}460}]$$



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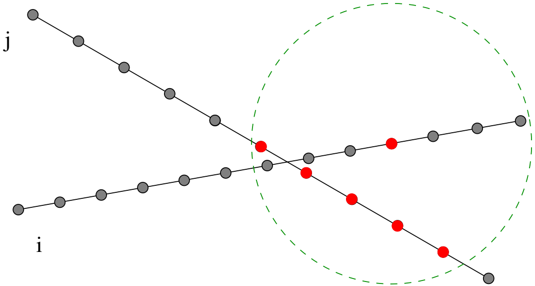
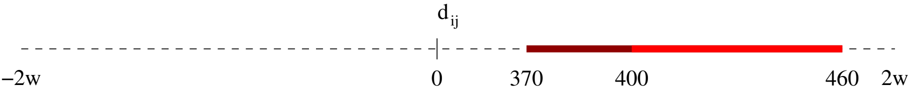


$$t_i^{10} = 1135, [t_j^6 = 675 - t_j^{10} = 735], d_{ij} \notin [400, 460] \subseteq [370, 460]$$



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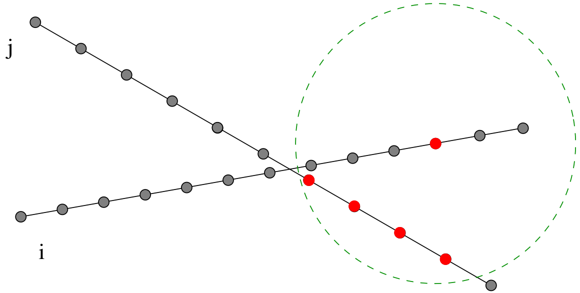
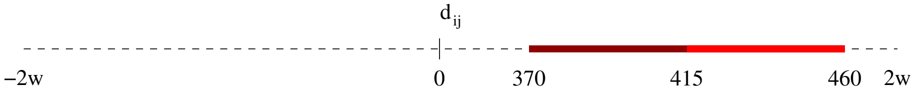


$$t^i_{11} = 1150, [t^7_j = 690 - t^{10}_j = 735], d_{ij} \notin [415, 460] \subseteq [370, 460]$$



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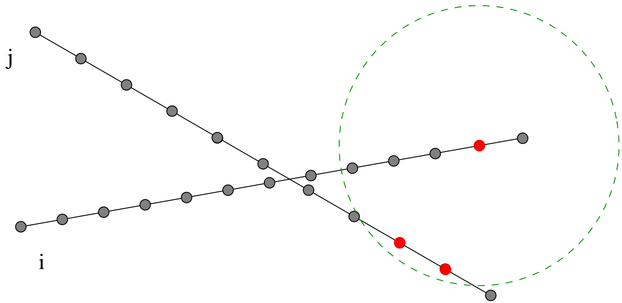
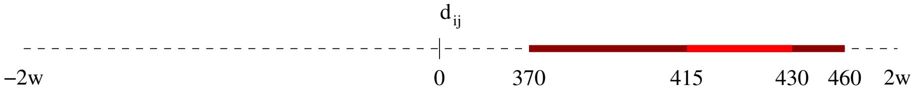


$$t^i_{12} = 1165, [t^9_j = 720 - t^{10}_j = 735], d_{ij} \notin [415, 430] \subseteq [370, 460]$$



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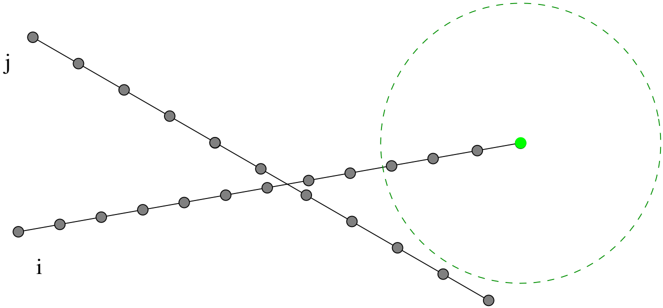

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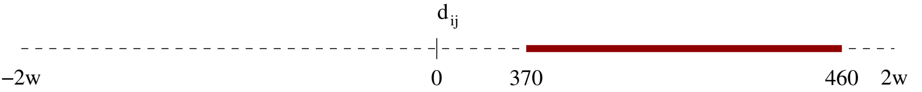
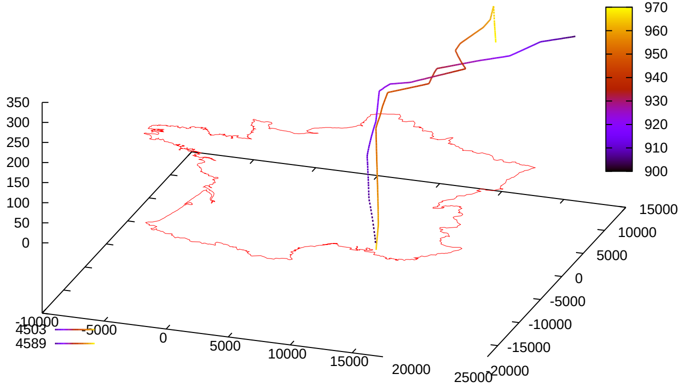


Multiply-Conflicting Flight Pair

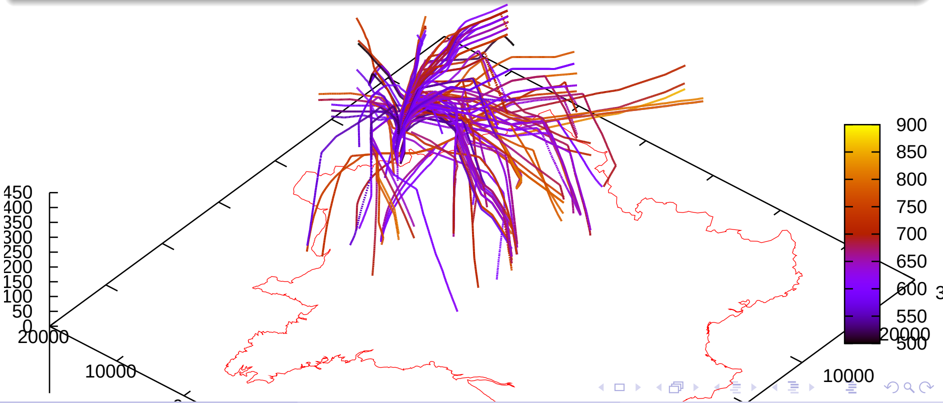


$$d_{ij} = \delta_j - \delta_i \notin [lb_{ij}^1..ub_{ij}^1] \cup \cdots \cup [lb_{ij}^k..ub_{ij}^k]$$

Flight Conflicting with Many Other

Constraint Graph of High Degree

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



Data

Simulator

- Date of the day of traffic
- **Standard** or **direct** routes
- Trajectories sampled every 15s

Further Instance Conditioning

- TMA: trajectories cut around airports (10 NM) for takeoff/landing
- **Maximal delay**: problem size grows as more conflicts may occur
- **Minimal flight level** (usually upper airspace $\geq$ FL290)
- Time unit (1 min): scaled with strict enclosure of conflicting intervals
- Flights without any conflict are discarded

Robustness Towards 4D-Contract Uncertainties

- **Extension of the conflicts** by $\pm\frac{ext}{2}$ min

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Search and Optimization

Search Strategy

- Directly labelling the delay decision variables often inefficient
- High-order decision scheme by analogy with **disjunctive** tasks in **scheduling** problems
- Order conflicting flights by **branching within the disjoint intervals** of their d_{ij} domain
- Dynamic variable ordering: choose d_{ij} with **highest sparsity** first
- Choose interval **closest to zero** first (low cost heuristic)
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Optimization

- Cost = **maximum delay**: equity, easiest for optimality proof
- Sum/Mean: exponentially harder
- Leximin? might be too propagation-costly

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Results

Instance Figures

- Traffic from 2007 within french airspace
- Demand up to 9 500 flights (6 600 once processed)
- Up to 630 000 conflicting pairs
- Best solvable volume of airspace down to FL0 (except TMA) for the easiest instances
- Disjoint conflicts for the same pair: up to 50 after processing
- Difference domains with up to 90% sparsity

Limitations

- Instance size limited by memory usage (4 GB)
- Running times: a few seconds to 1 min (Core 2 Duo @ 2.4 GHz)
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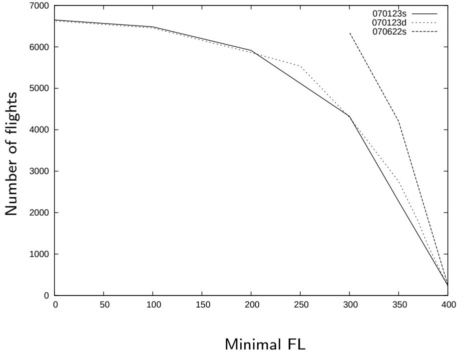
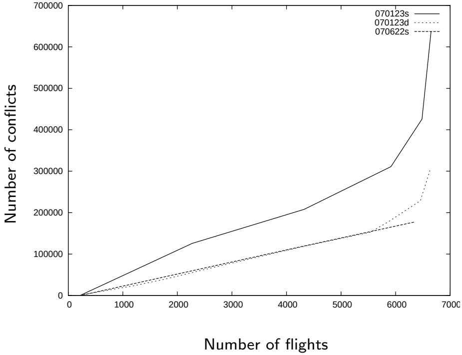
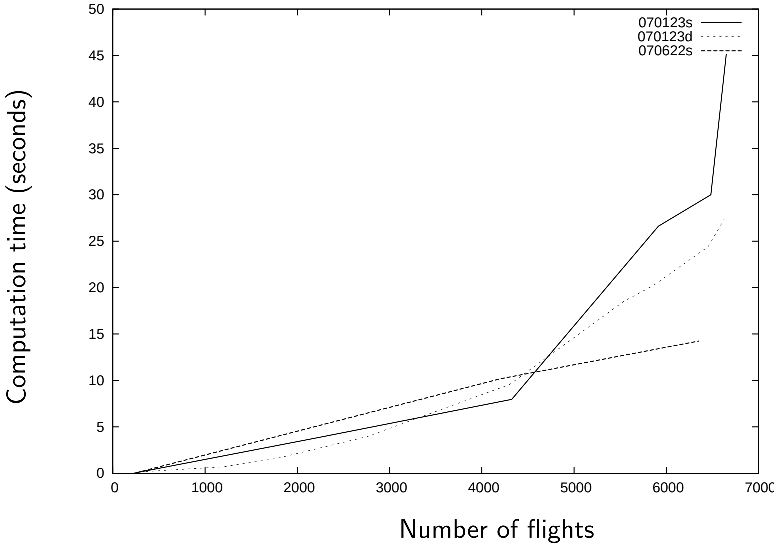
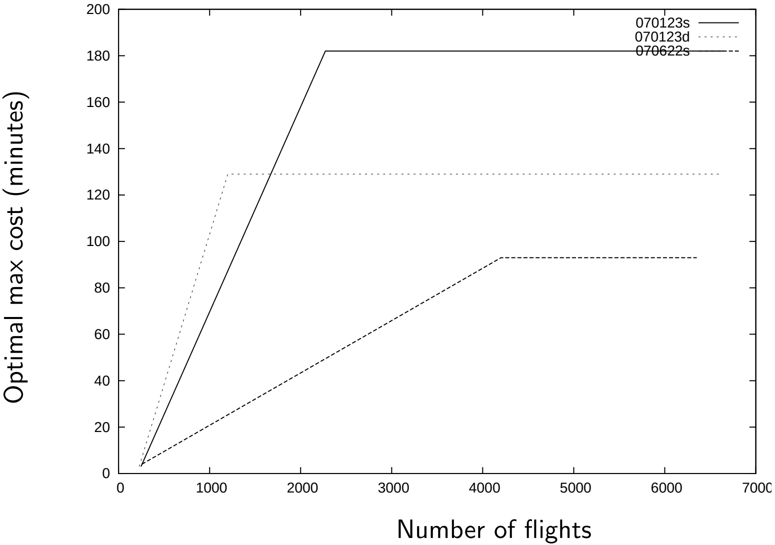




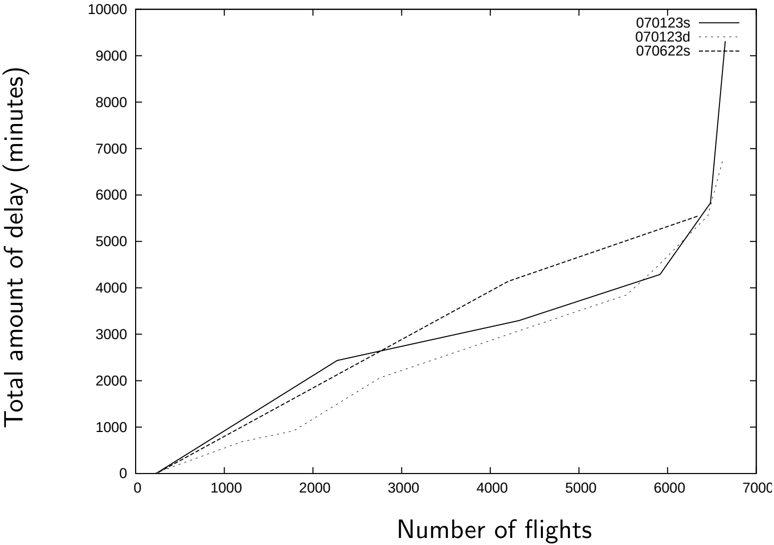
Number of Flights vs Computation Time (Proof)



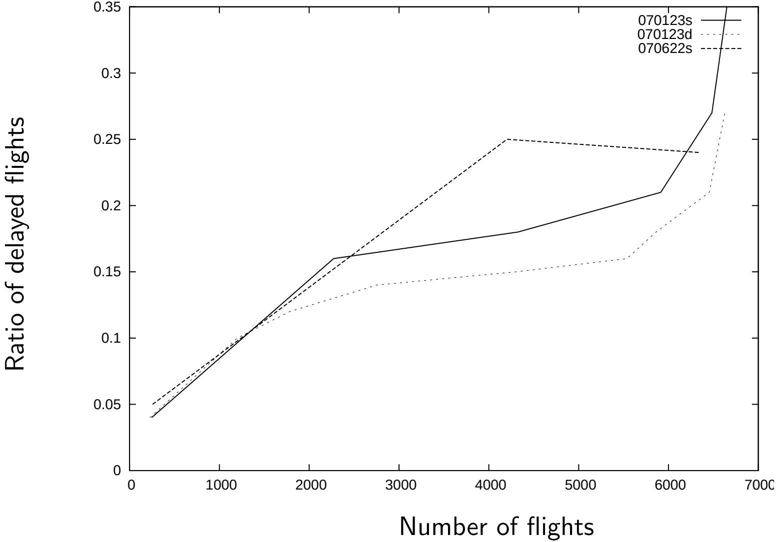
Number of Flights vs Optimal Cost



Number of Flights vs Total Amount of Delay



Number of Flights vs Ratio of Delayed Flights



Robustness

Validation

- Results checked with CATS
- Only unhandled conflicts remain (non-ECAC and below minimal FL)

4D-Contract Uncertainties

- Each end of **conflicts extended** by $\frac{ext}{2}$ min
- Departure time uncertainties uniformly chosen in $[-\frac{err}{2}, +\frac{err}{2}]$ during validation with CATS

Results

- No conflicts when $ext \geq err$ as expected
- Dramatic increase of the total amount of delay with ext (≥ 3 min)

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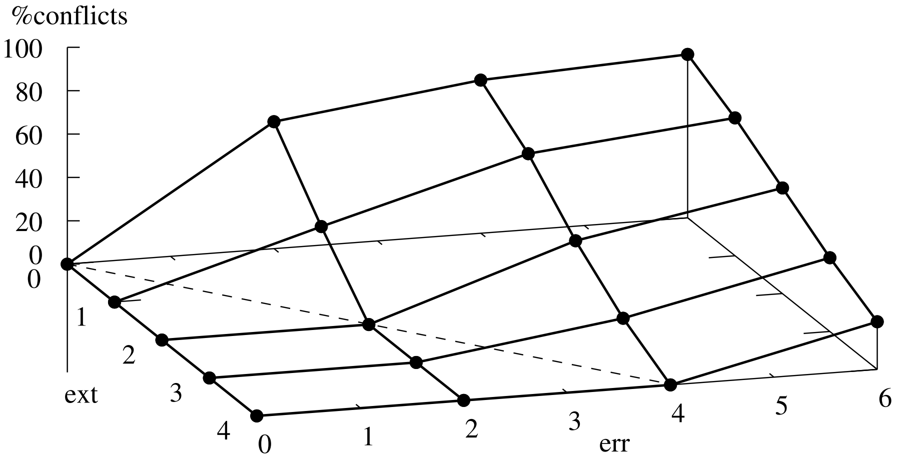
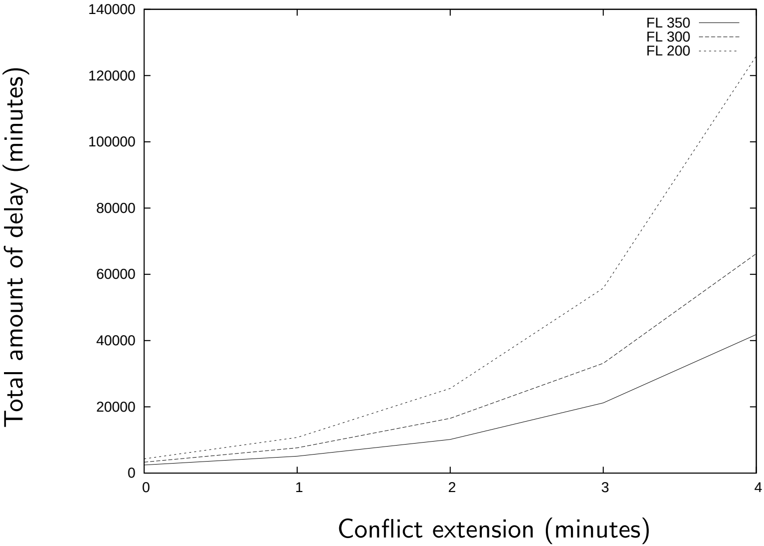
Remaining Conflicts vs Conflict Extension and 4D-Contract Uncertainty



Total Amount of Delay vs Conflict Extension



Further Works

Larger Instances

- European instances up to 30 000 flights
- Search paradigms that better scale to the instance size: local search, meta-heuristics, combination with CP (e.g. LNS)

More Realistic Modelling

- Aircraft rotation constraints: easy to implement but lack of data
- Uncertainties: vertical and ground speed
- Real-time: reactive planning with sliding time windows

Degrees of Freedom

- Prior FL allocation: pre-deconfliction, lower delay costs [CP-AI-OR'02]
- Handling remaining conflicts with CATS resolution modules [Granger, Durand, Alliot 2001] (horizontal manœuvres, speed adjustment)

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ATM

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- Amount of allocated **delay compatible with typical CFMU figures**
- **Better** results with **direct routes** (tractable?)
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- Still scalable to European instances?
- May be **combined** with other search paradigms: LS to solve CSP, CP to speed up LS...

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