Deconfliction with Constraint Programming

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Outline

Introduction

Congested European Sky

- Traffic still growing by a yearly 5%
- Increasing regulation delays 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 - WP3

Pre-tactical Deconfliction with Constraint Programming

- Deconfliction by ground-holding
- Highly combinatorial/disjunctive 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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ATC and ATFM

Objectives

1. **Safety** : maintaining aircraft separated
2. **Efficiency** : expedite the flow of traffic

Layered Filters with Decreasing Time Horizon

1. **Strategic** (several months) : AirSpace Management (ASM), design of routes, sectors and procedures
2. **Pre-tactical** (a few days to a few hours) : Air Traffic Flow Management (ATFM), sector openings and capacities, flow regulation by delaying and rerouting (Central Flow Management Unit)
3. **Tactical** (5-15 min) : Air Traffic Control (ATC), surveillance, coordination, conflict resolution
4. **Emergency** (< 5 min) : safety nets, ground-based (STCA, MSAW) and airborne (TCAS, GPWS)

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Ground-Holding

Pre-tactical Flow Regulation

- **Safest** than handling the traffic while airborne
- **Costly** for airlines and passengers, snowball 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) at CFMU

CASA

- Greedy algorithm : optimality, consistency
- "First-come, first-served" questionable principle
- Operational setting, real-time updates

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Slot Allocation with CP

Optimize upon CASA Solutions

- SHAMAN : CP model over 30 min periods (CENA/RFM)
- ISA : CP and LP [Junker et al]
- Marabout : sort constraint with FaCiLe to smooth the entry rate [ATM'01]

"Complexity" of Traffic

- **Relevance** of sector capacity to model **controller workload** ?
- Discrepancies between planned schedule and actual openings
- More pertinent metrics w.r.t. real-time merge/split decision [Giannazza, Guittet 06]

Prior Opening Schedule Optimization

- Optimize upon FMP's opening schedule
- Multiple partitioning problem, possibly with side transition constraints [Barnier 02]
- Lower cost for slot allocation
- With other workload metrics [Giannazza 07]

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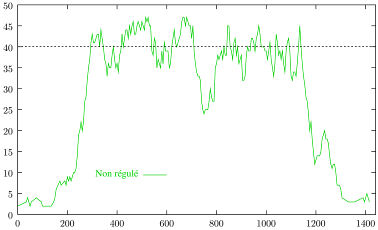
Results

Standard Model



Entries within the next δ min

Results

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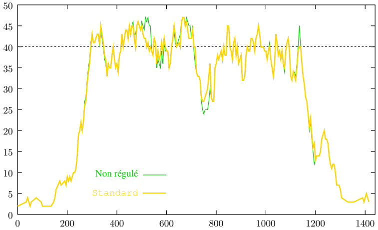

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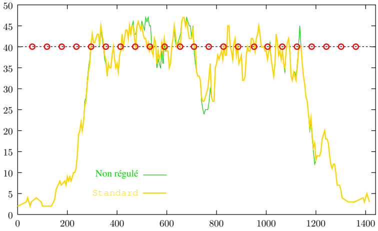

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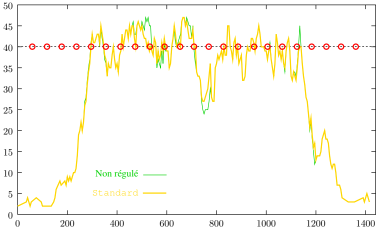

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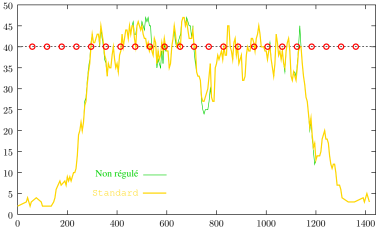

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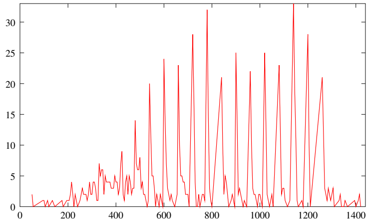

Flights in the sector

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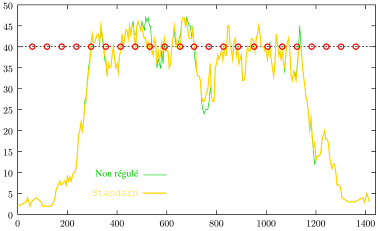

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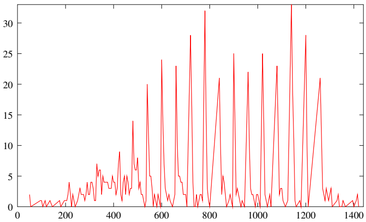
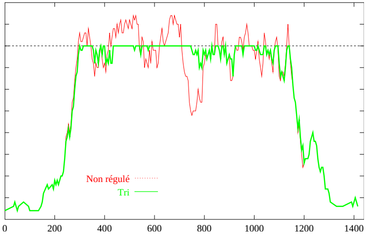
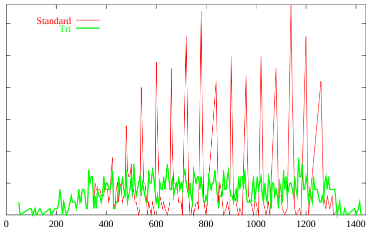


Flights in the sector

Marabout





Conflict-Free 4D Tubes

4D Trajectory Planning

- European Commission Episode 3 project (WP3)
- 4D trajectory planning to reduce conflicts number and controller workload
- Many opportunities : flight level, speed, rerouting...
- Large scale combinatorial optimization problem

Deconfliction by Ground-Holding

- Finest grain vs aggregated model (sector capacity)
- Same degree of freedom than slot allocation
- **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 precisely...

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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 15s (shortest conflicts not missed) 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

Non European Flight

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

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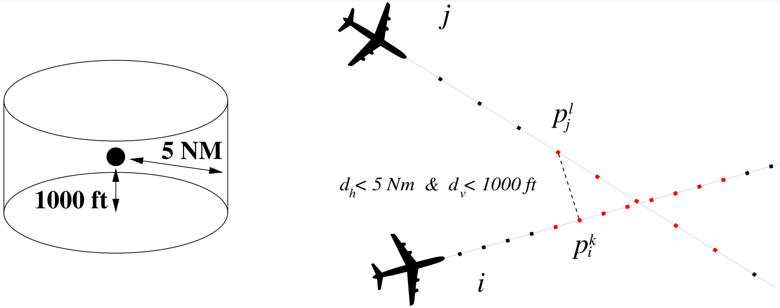
Conflict Detection

Conflicting Points Detection



Naïve 3D Conflicting Segments

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

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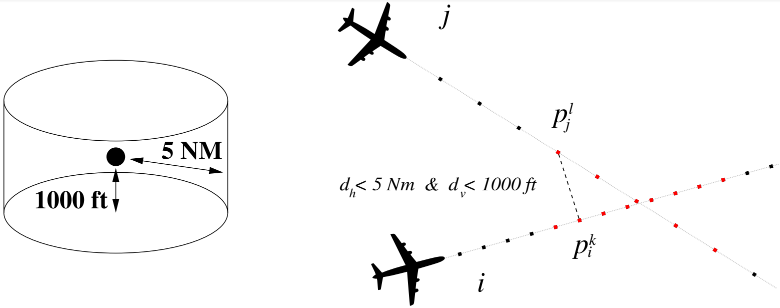

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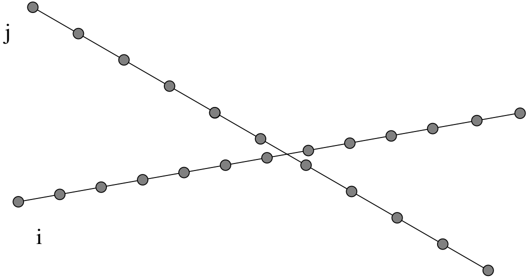
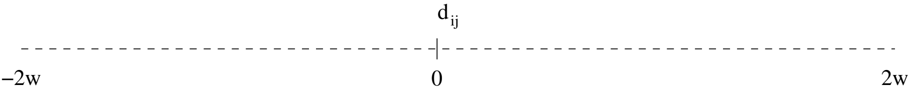
4D-Conflict Constraints



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



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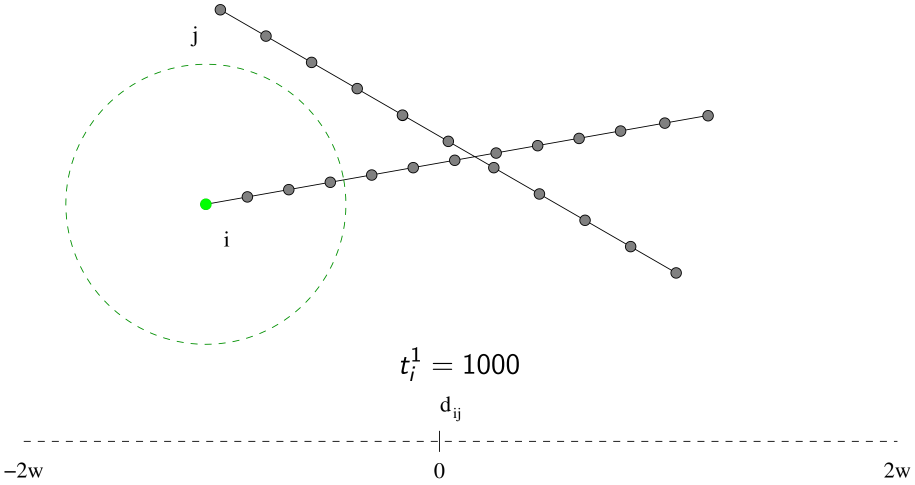

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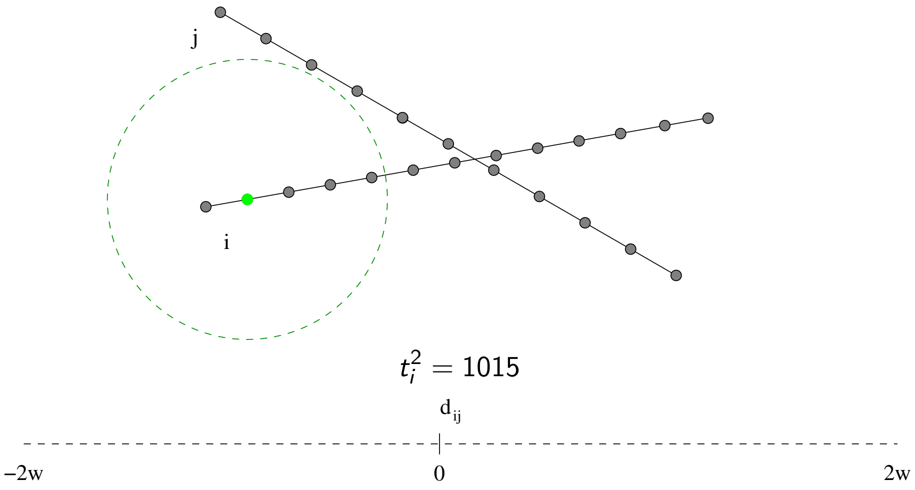

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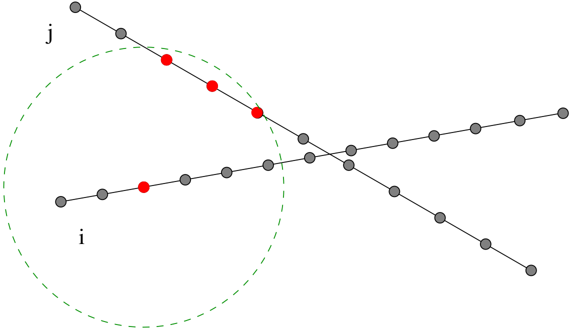
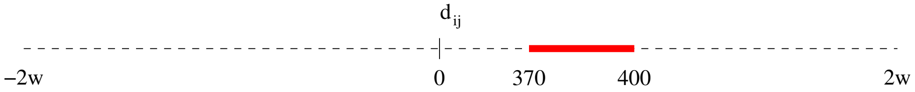


$$t_i^3 = 1030, [t_j^3 = 630, t_j^5 = 660], d_{ij} \notin [370, 400]$$



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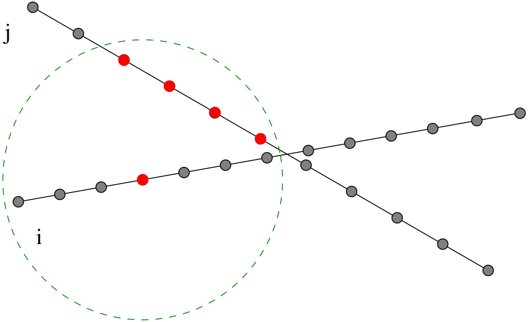
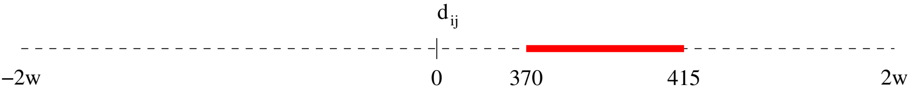


$$t_i^4 = 1045, [t_j^3 = 630 - t_j^6 = 675], d_{ij} \notin [370, 415] \subseteq [370, 415]$$



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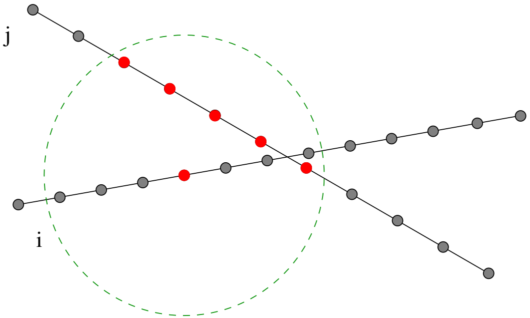
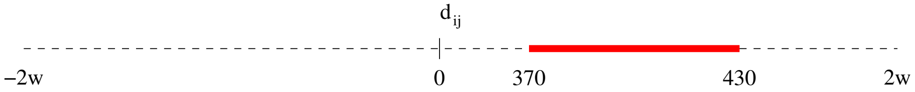


$$t_i^5 = 1060, [t_j^3 = 630 - t_j^7 = 690], d_{ij} \notin [370, 430] \subseteq [370, 430]$$



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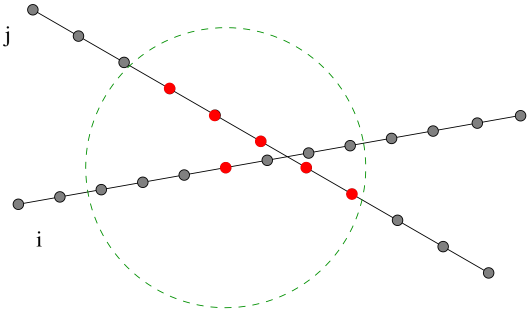
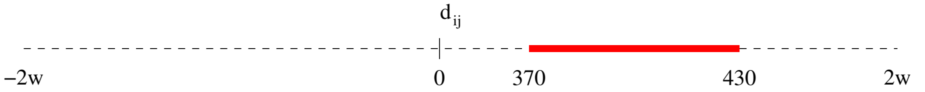


$$t_i^6 = 1075, [t_j^4 = 645 - t_j^8 = 705], d_{ij} \notin [370, 430] \subseteq [370, 430]$$



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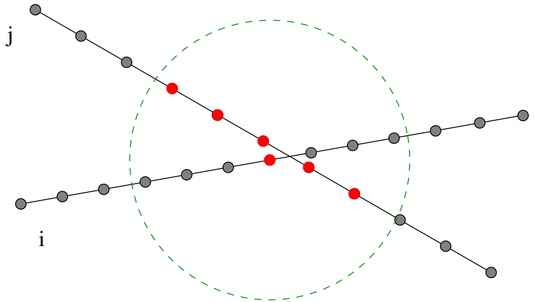
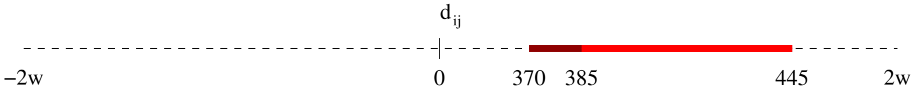


$$t_i^7 = 1090, [t_j^4 = 645 - t_j^8 = 705], d_{ij} \notin [385, 445] \subseteq [370, 445]$$



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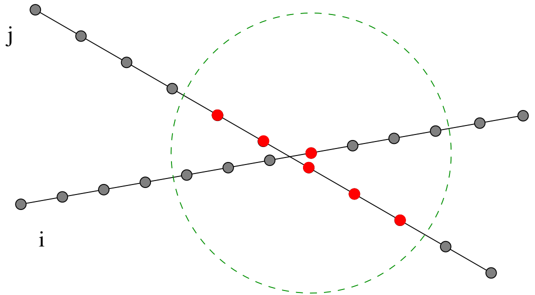
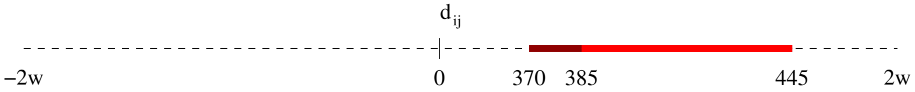


$$t_i^8 = 1105, [t_j^5 = 660 - t_j^9 = 720], d_{ij} \notin [385, 445] \subseteq [370, 445]$$



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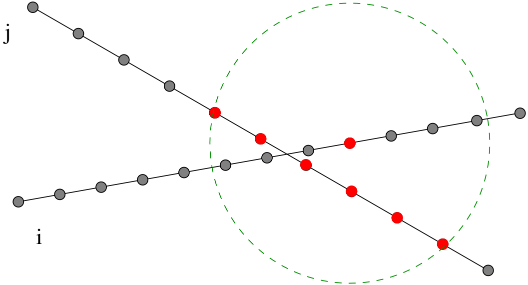
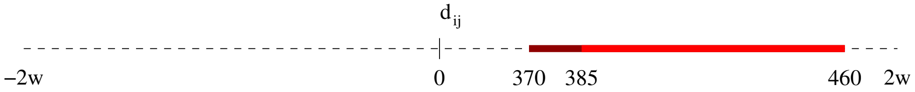


$$t_i^9 = 1120, [t_j^5 = 660 - t_j^{10} = 735], d_{ij} \notin [385, 460] \subseteq [370, 460]$$



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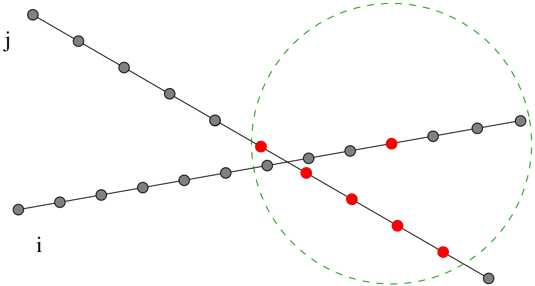
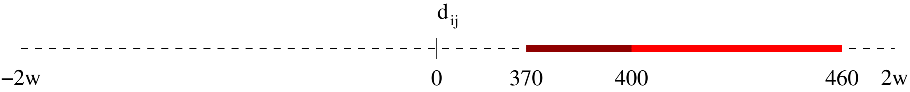


$$t_i^{10} = 1135, [t_j^6 = 675 - t_j^{10} = 735], d_{ij} \notin [400, 460] \subseteq [370, 460]$$



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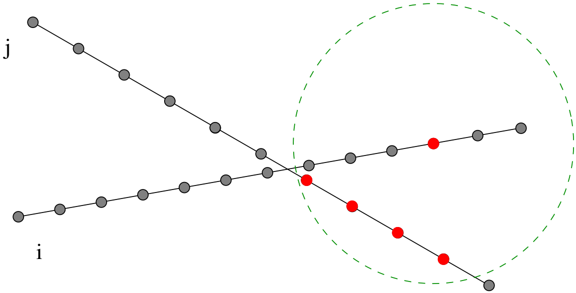
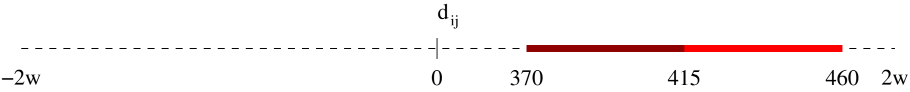


$$t^i_{11} = 1150, [t^7_j = 690 - t^{10}_j = 735], d_{ij} \notin [415, 460] \subseteq [370, 460]$$



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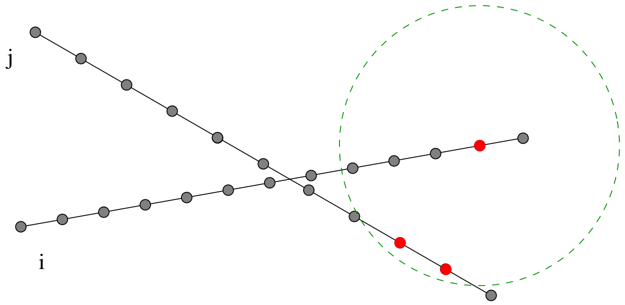
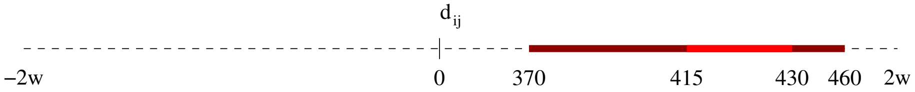


$$t^i_{12} = 1165, [t^9_j = 720 - t^{10}_j = 735], d_{ij} \notin [415, 430] \subseteq [370, 460]$$



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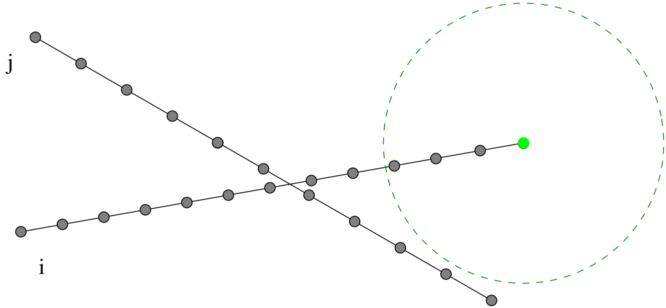
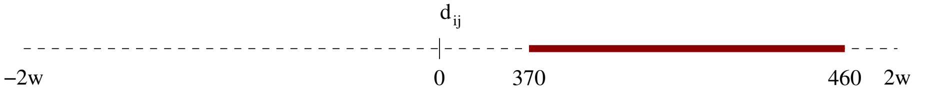
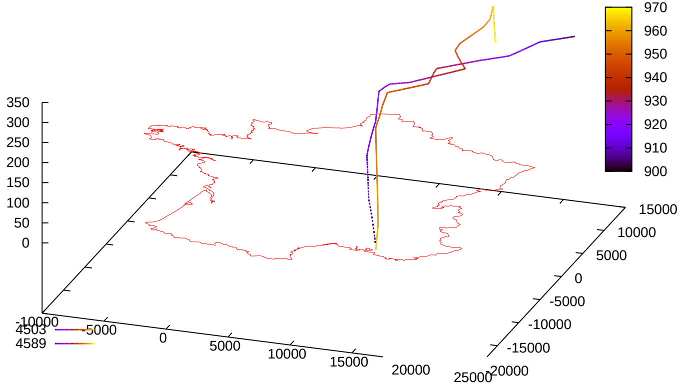


$$d_{ij} = \delta_j - \delta_i \notin [370, 460]$$



Mutliply-Conflicting Flight Pair

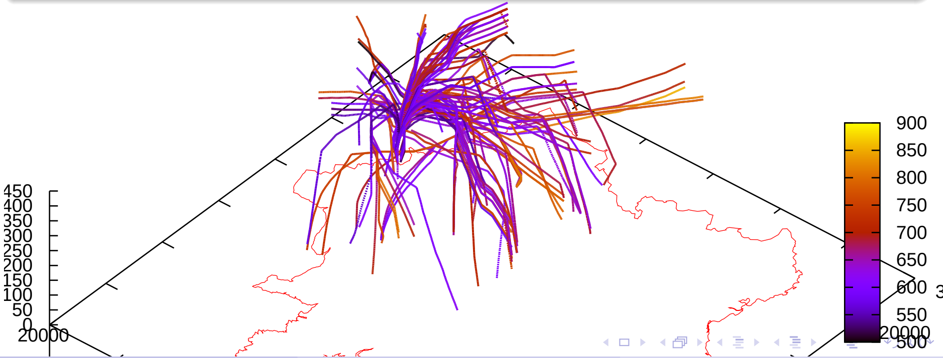


$$d_{ij} = \delta_j - \delta_i \notin [lb_{ij}^1..ub_{ij}^1] \cup \cdots \cup [lb_{ij}^k..ub_{ij}^k]$$

Flight Conflicting with Many Other

Constraint Graph of High Degree

- Maximally delayed flight potentially conflicting with 130 other
- Highest degree > 300
- Large cliques > 60
- One single large connected component



Further Instance Conditioning

Simulator Data

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

Instance Filtering

- 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)
- **Minimal gap** between two disjoint conflicting intervals of the same pair, otherwise merged
- Time unit (1 min) : scaled with strict enclosure of conflicting intervals
- Flights without conflict are withdrawn

Further Instance Conditioning

Simulator Data

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

Instance Filtering

- TMA : trajectories cut around airports (10 NM) for takeoff/landing
- **Maximal delay** : problem size grows as more conflicts may occur
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Search and Optimization

Search Strategy

- Directly labelling the delay decision variables is 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 smaller interval first to maximize propagation
- Then label the delays δ_i by increasing values

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 Size

- Traffic from 2006/2007
- Up to 8000 flights
- Up to 300 000 conflicting pairs
- Best solvable volume of airspace down to FL0 (except TMA) for the easiest day
- Disjoint conflicts for the same pair : up to 26 with raw data, 4 after processing
- Difference domains with up to 97% sparsity

Limitations

- Instance size limited by memory usage (4 GB)
- Running times $<$ 30 min (Core 2 Duo @ 2.4 GHz)
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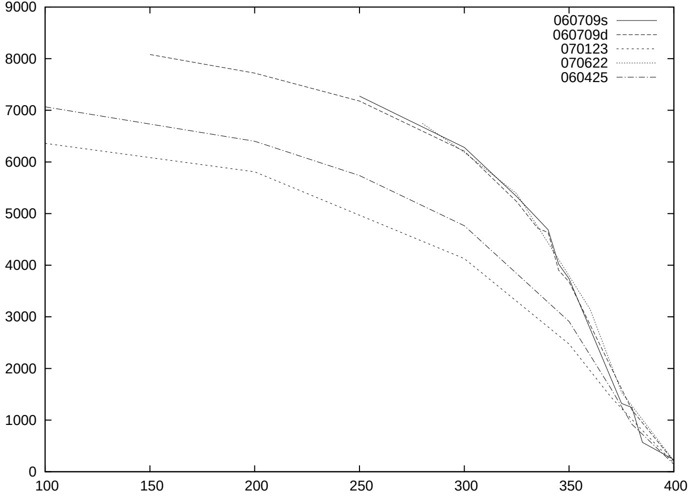
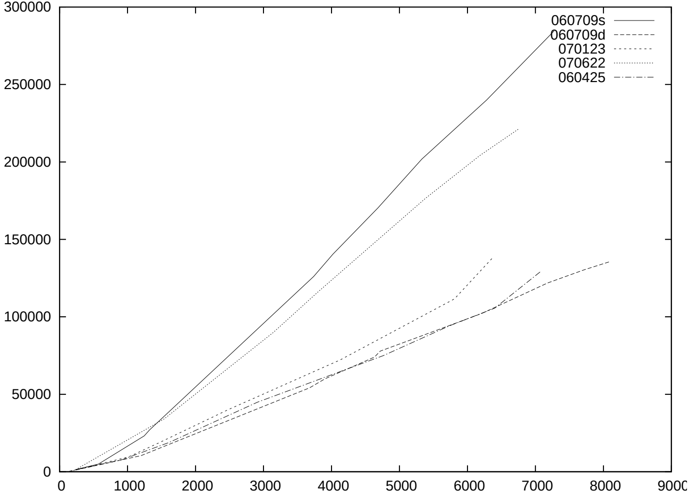
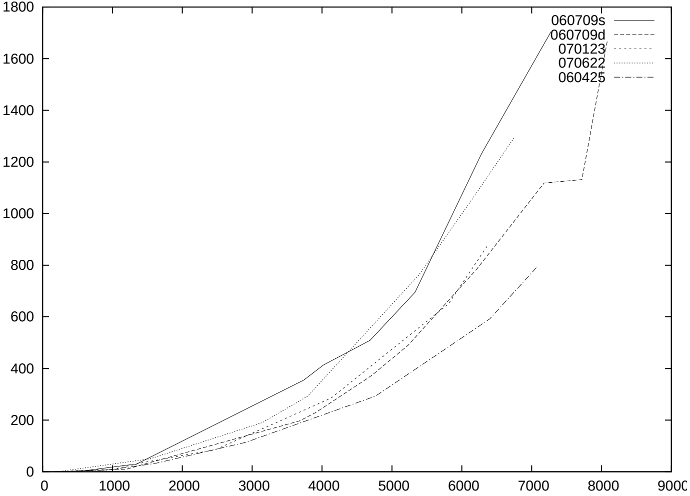
Minimal Flight Level vs Number of Flights



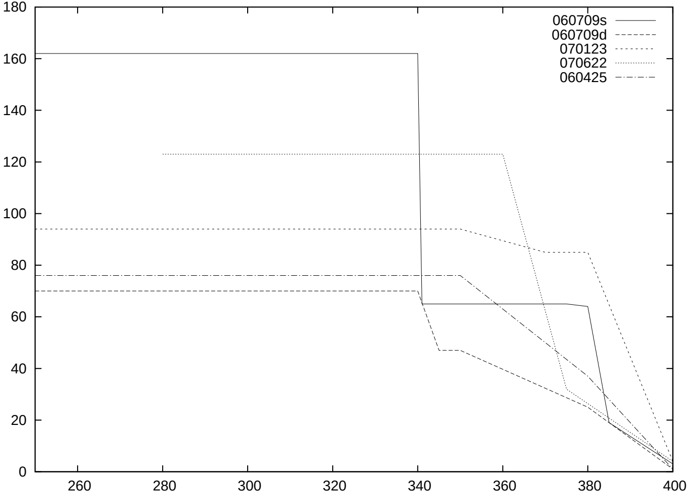
Number of Flights vs Number of Conflicts



Number of Flights vs Computation Time (Proof)



Minimal flight level vs optimal cost



Further Works

Validation and Robustness

- **Validation** of the solutions with the CATS simulator (undergoing)
- **Robustness** of solutions w.r.t. uncertainty : vertical and ground speed, takeoff time

Perspectives

- Rotation constraints : easy to implement but not provided by airlines
- Prior flight level allocation : pre-deconfliction, lower delay costs [CP-AI-OR'02]
- Larger (European) instances with soft constraints and other optimization paradigms : local search (LS), meta-heuristics, combined with CP (LNS)
- Post-optimization of the sum/mean with LS or CP once the maximum delay is bounded

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ATM

- **Ground-Holding for deconfliction** vs macroscopic regulation
- Large problem but **optimality proof** obtained (w.r.t. max) with CP
- Some instances with solution compatible with CFMU figures, **too costly** for some others
- **Better** results with **direct routes**
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- **Uncertainties** : have to be taken into account in the operational setting, until accurate 4D-FMS are designed

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- Still scalable to European instances 20 000-30 000 flights/day ?
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