Air Traffic Deconfliction Using Sum Coloring

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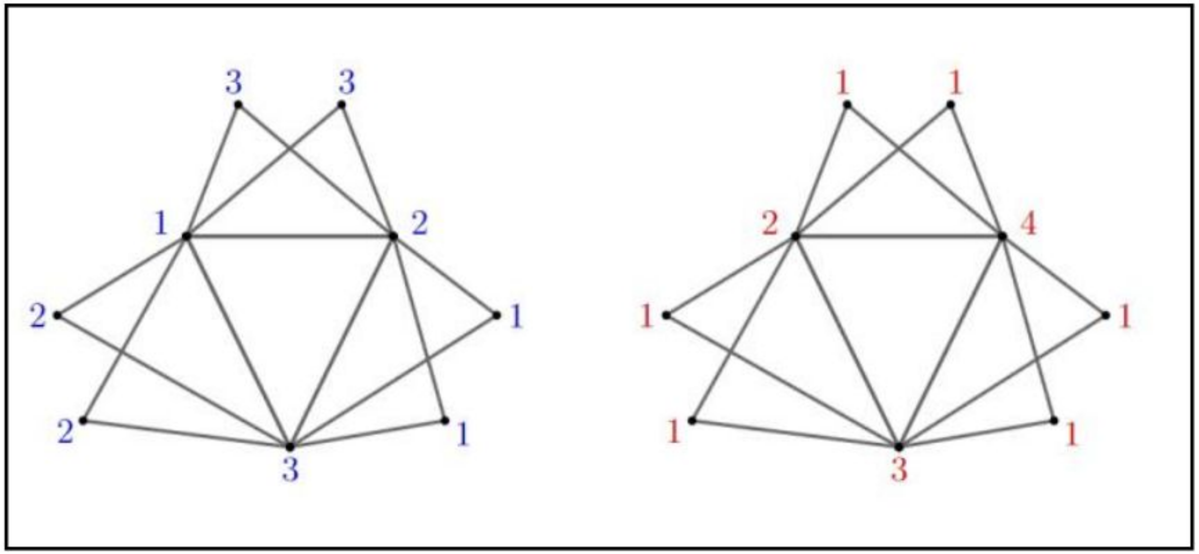
Motivation

- There is a need to **alleviate the ATCs workload** and to **avoid** the **unnecessary costs of solving conflicts** that could have been anticipated

- In **unmanned aviation**, drones are expected to do **numerous short flights**, requiring a **higher level of automation** to solve conflicts

- **Objective**: **Strategically solve conflicts** with an **optimal resource allocation** method modelled as a **weighted sum coloring problem**

Minimum Sum Coloring Problem



- **Graph vertex coloring** involves assigning a **color** to **each vertex** so that two adjacent vertices feature different colors; the goal is finding the **minimum number of colors** needed to color the graph

- In the **Minimum Sum Coloring Problem** (MSCP) each color is identified with a **positive integer**, called the **cost** of the color, and the goal is to **minimize the total cost**

Deconfliction model (I)

- **Input**: set of **aircraft entering** the sector at the **same time slot**
- Graph **G=(V,E)** where **vertices** (V) are the **planes** and **edges** (E) are the **conflicts**
- **Colors** are assigned to the aircraft (**time slots** for the **planes** and **vertical layers** to the **drones**)
- Vertices connected by an edge cannot be assigned the same color → **conflict**!!

Deconfliction model (II)

- Users have **preferences** over colors (first time slot, particular layers,...)
- c_v is the **cost** incurred by user v in the coloring of the graph (**delay** in **ATM** and **cost of the layer** in **UTM**)
- w_v is the **weight** of each user v → value of time (i.e. **cost of delay**) in **ATM** and **UTM**

$$TotalDelay = \sum_{v \in V} c_v \qquad TotalCost = \sum_{v \in V} c_v w_v$$

Deconfliction model (III)

- An **Integer Programming** (IP) formulation of MSCP is used *

- The IP is solved using **Gurobi** on a server with two Intel(R) Xeon(R) Gold 6132 2.60GHz CPU nodes, 64 RAM and 2.59TB temporary disk space

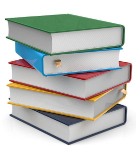
- In all cases finding the **optimal IP solution** in one instance completed within **few minutes**

$$min \sum_{v \in V} \sum_{c \in \mathbb{N}} w_v X_{vc} c$$

$$\sum_{c \in \mathbb{N}} X_{vc} = 1 \quad \forall v \in V$$

$$X_{ic} + X_{jc} \leq 1 \quad \forall (i,j) \in E, \forall c \in \mathbb{N}$$

$$X_{vc} \in \{0,1\} \quad \forall v \in V, \forall c \in \mathbb{N}$$

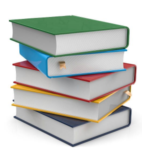


* F. Furini, E. Malaguti, S. Martin, and I.-C. Ternier, "ILP models and column generation for the minimum sum coloring problem,"Electronic Notes in Discrete Mathematics, vol. 64, no. 1, pp. 215–224,2018

Cost of delay

Aircraft	Low scenario	Base scenario	High scenario
B733	2 280	3 200	4 370
B734	2 360	3 290	4 540
B735	2 130	2 950	4 040
B738	2 590	3 650	5 330
B752	3 110	4 210	5 640
B763	4 600	6 230	9 070
B744	8 890	10 950	14 030
A319	2 400	3 420	4 840
A320	2 480	3 490	5 090
A321	2 950	4 130	5 770
AT43	580	900	1 350
AT72	830	1 270	1 890
DH8D	1 110	1 630	2 420
E190	1 920	2 750	3 950
A332	5 330	7 220	10 470

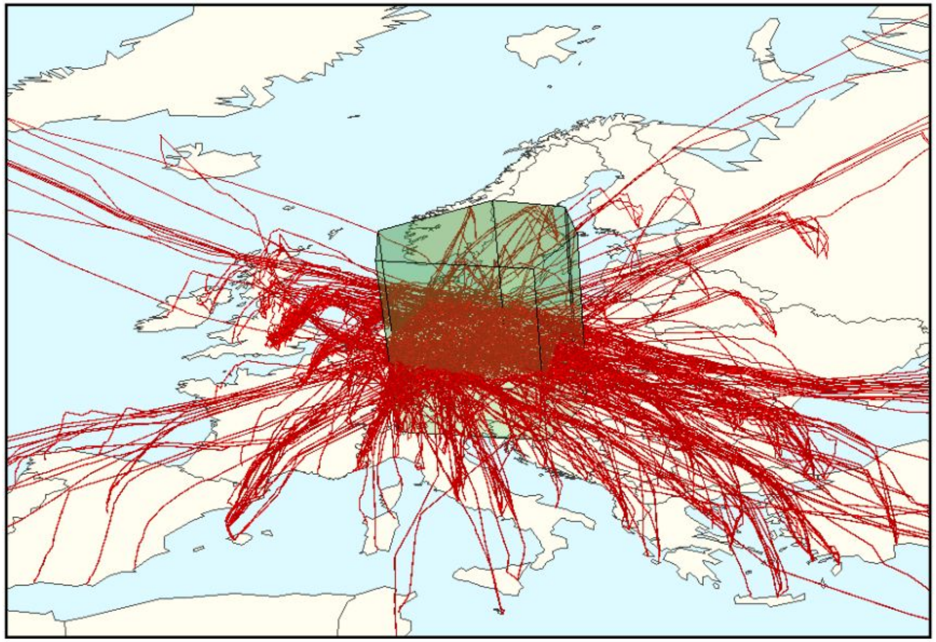
- The **financial values of time** were used as **weights** for the sum coloring *
- **Strategic cost of delay** for different aircraft models
- **Fuel costs** → **major source of cost** in en-route phase
- **UTM**: **random weights** with most of drones having **small weights** (delay does not create high cost)



* A. Cook, "European airline delay cost reference values," University of Westminster, Tech. Rep., 2015.

Scenario (I)

- **ATM**: planes flying inside LOCCAOI sector during 1 hour (source: **DDR2**) → force same sector entry time
- **UTM**: stochastic traffic during one hour over Norrköping (source: **Cal model***)



* V. Bulusu, R. Sengupta, and Z. Liu, “Unmanned aviation: To be free or not to be free?” in 7th International Conference for Research in Air Transportation (ICRAT), 2016

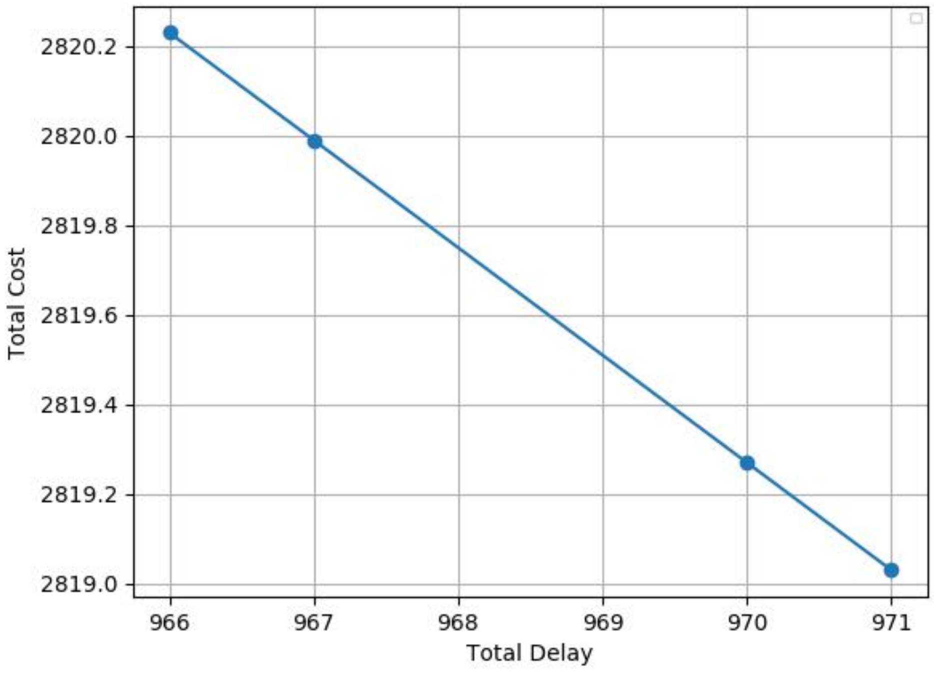
Scenario (II)

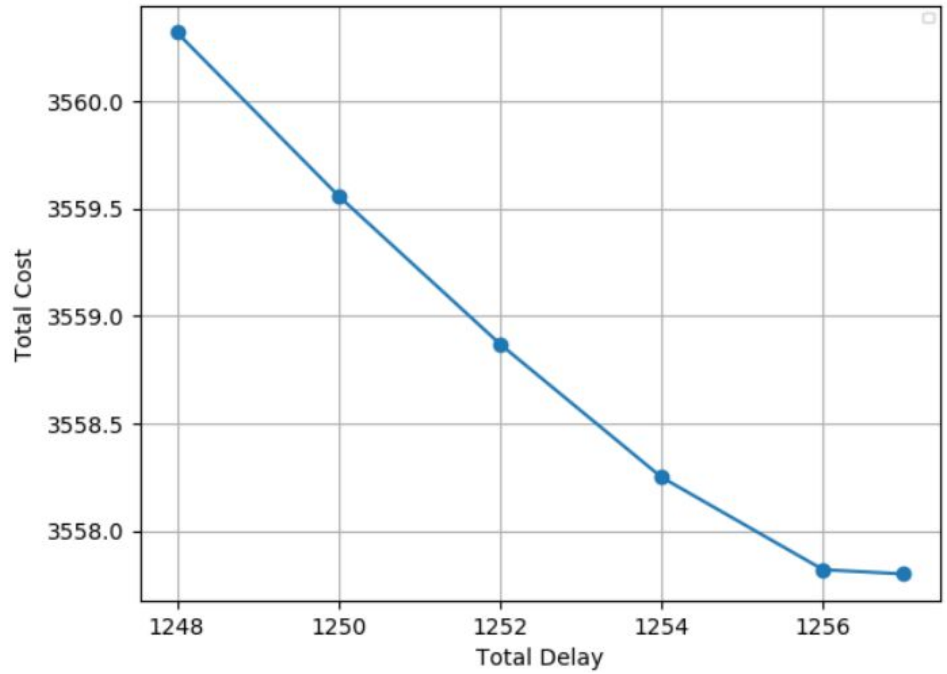
- **ATM**: 2 test cases:
    - **Case 1**: 02/06/2018 from 12am to 1pm, with 450 planes (vertices) and 1399 conflicts (edges)
    - **Case 2**: 06/06/2018 from 12am to 1pm, with 462 planes and 770 conflicts

- **UTM**: 2 test cases:
    - **Case 1**: 800 drones and 663 conflicts
    - **Case 2**: 1000 drones and 770 conflicts

Results (I)

- **Pareto frontiers** in **ATM** were computed with respect to the two objectives:
  - Minimizing **total delay**
  - Minimizing **total cost**





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Results (II)

- Results were compared with **20 random orders** and **FCFS** (First Come First Served) **time slot attribution** in **ATM** and **vertical layer attribution** in **UTM**

	ATM (case1/case2)	FCFS (case1/case2)	UTM (case1/case2)	FCFS (case1/case2)
Total delay	Pareto frontier	1423.9 / 1416	-	-
Total cost	Pareto frontier	4959.5 / 4450.8	1788 / 1791	8830.55 / 9430.85

UTM Payment mechanism

- A market-based economic mechanism specifies how to allocate resources and how much every user has to pay for the allocation
- **Resource allocation** should **maximize benefit to the society** (finding **optimal solution** to the **weighted MSCP**)
- Drone operators report **higher values of time** (weights) → need for a **truthful mechanism** *
- **Vickrey-Clarke-Groves** (VCG) mechanism is used to determine the **payments** for the users **

$$p_v = \sum_{j \in V \setminus \{v\}} c_j^v w_j - \sum_{j \in V \setminus \{v\}} c_j^{V \setminus \{v\}} w_j$$

* T. Granberg and V. Polishchuk, "Socially optimal allocation of atm resources via truthful market-based mechanisms," in 2nd SESAR Innovation Days (SIDs), 2012

** N. Nisan, T. Roughgarden, E. Tardos, and V. Vazirani, "Algorithmic game theory," in Cambridge University Press, 2007.

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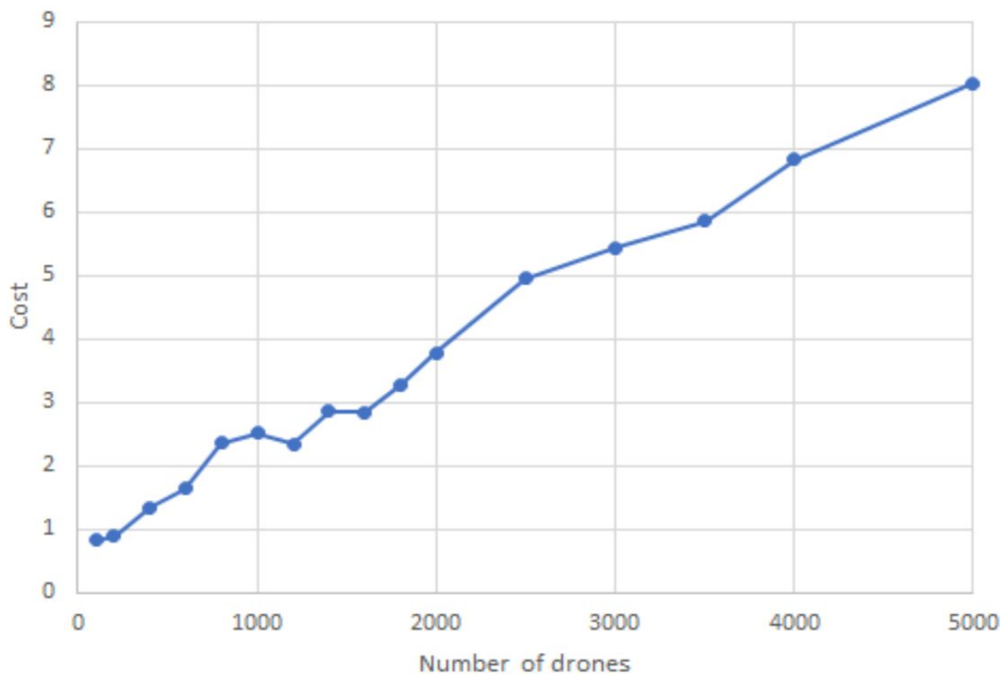
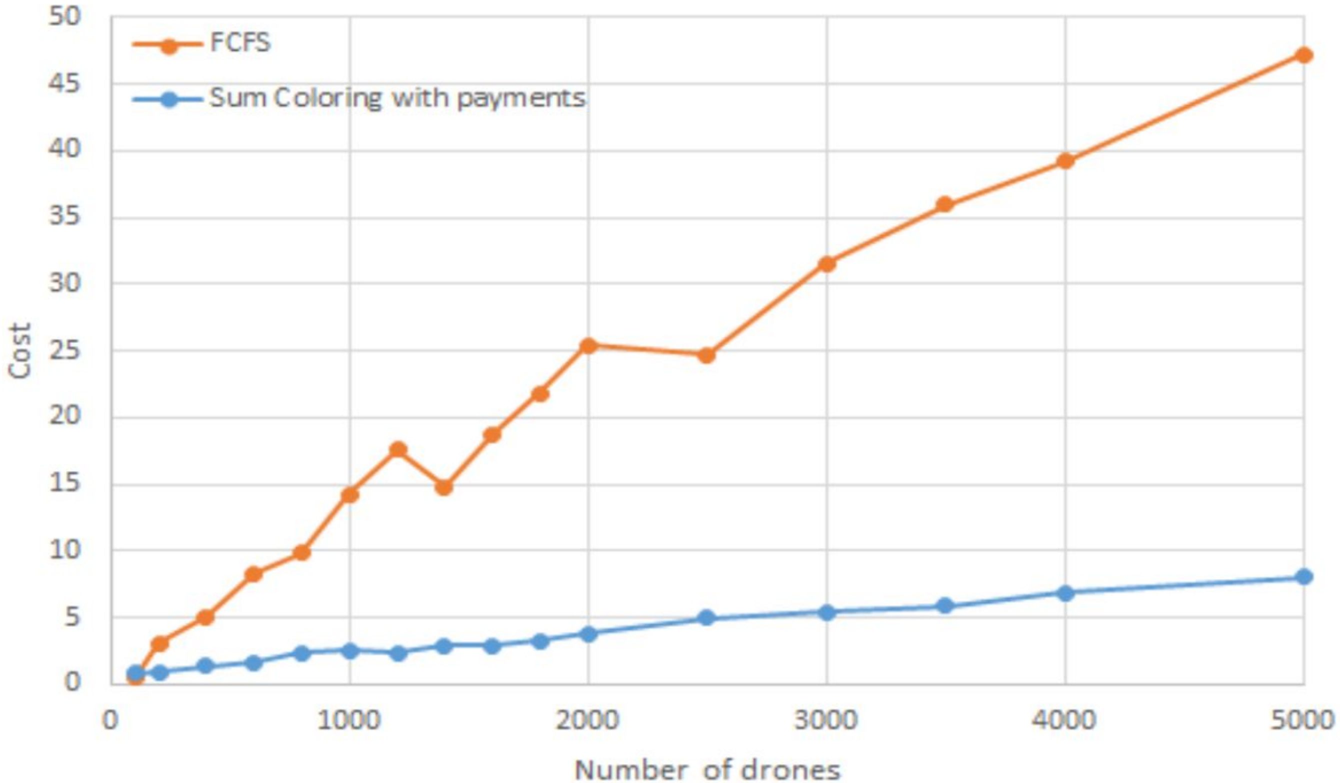
Cost of drone flights

- Figure below shows the **mean cost of a drone flight** as a function of the **number of drones** flying during **one hour**
- **Average** of **5 runs** of traffic simulation, with **100m** as the **separation loss distance**



Cost of drone flights

- Results were compared with **FCFS** strategy, which involves **no payments** (but **costs** are **higher**!)



Conclusions

- **Strategic deconfliction** using **sum coloring** works **better** than the **FCFS allocation**
- **Uncertainty** is not considered (**real-time adjustments** might be needed)
- **Unlimited number of layers** is considered
- **Computing time** to get he payments in the **VCG** mechanism **grows** with the **number of drones**