Consideration of contrails by air navigation services and their impact on the network

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Introduction

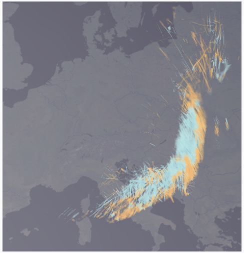
Introduction

Context and motivations

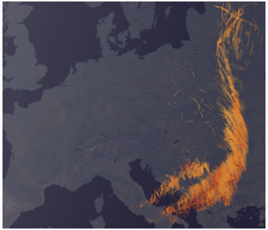
Climate impact of air transportation

A particular non-CO_2 effect: condensation trails

- Cold and humid areas
- Can persist and become cirrus clouds
- Warming and cooling effects



01/08/2023, 13:55 UTC, https://map.contrails.org/.



01/08/2023, 18:00 UTC, https://map.contrails.org/.

A brief overview of contrails over the French airspace

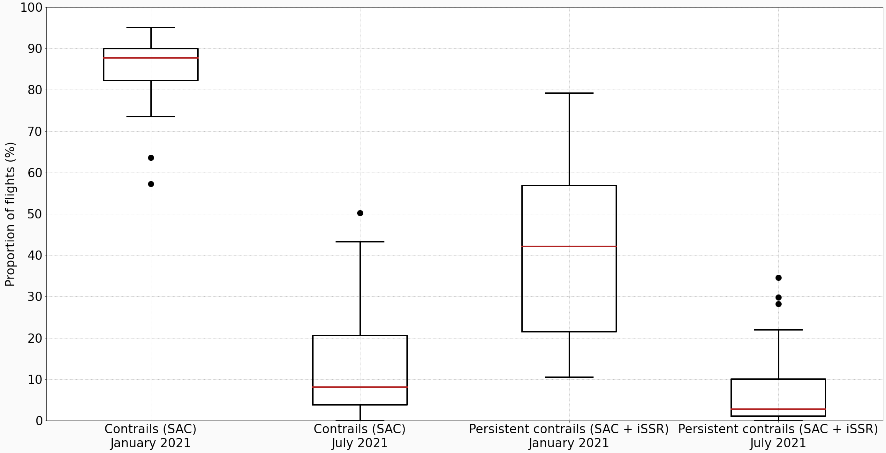


Figure 1: Proportion of flights flying in a contrail or persistent-contrail favorable areas over France in January and July 2021.

A brief overview of contrails over the French airspace

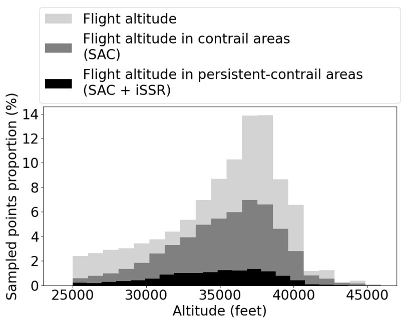


Figure 2: Altitudes of sampled points (light gray), in contrail areas (gray) or in persistent contrail areas (dark gray) in January 2021.

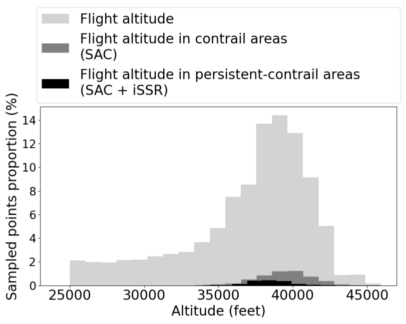
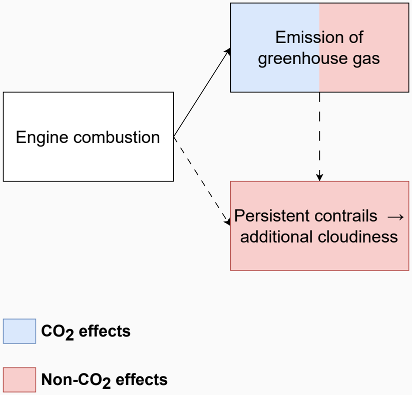


Figure 3: Altitudes of sampled points (light gray), in contrail areas (gray) or in persistent contrail areas (dark gray) in July 2021.

How to measure the impact of two criteria?



Adapted from Simorgh *et al.*, 2022.

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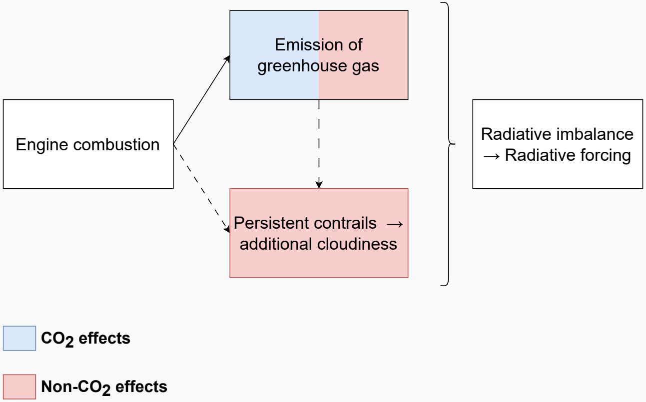

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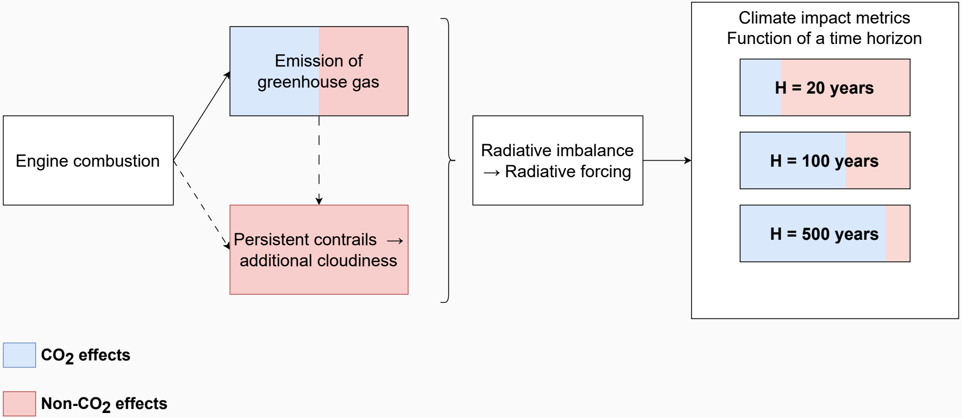
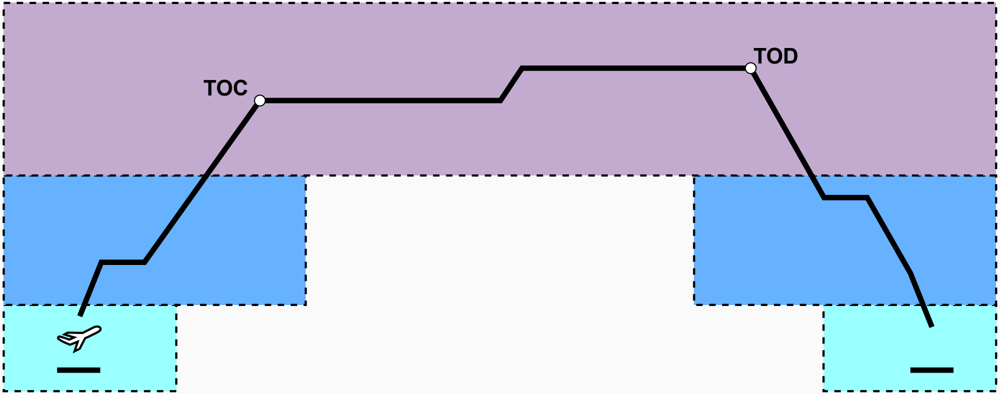
How to measure the impact of two criteria?

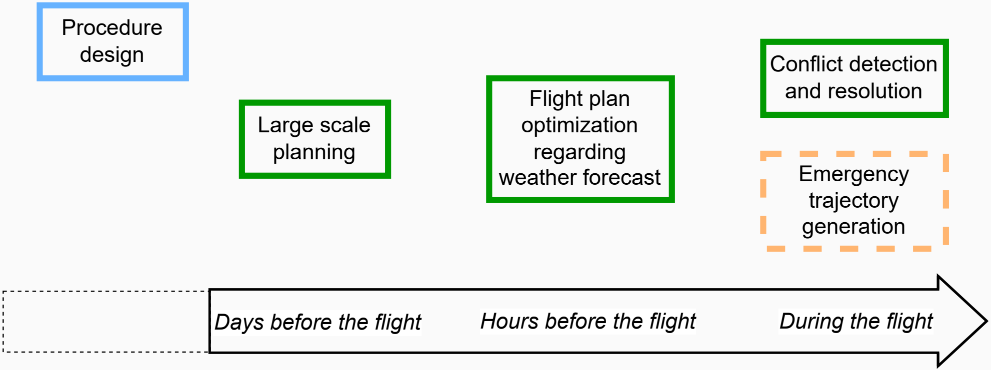


Adapted from Simorgh *et al.*, 2022.

Operational context



Operational context

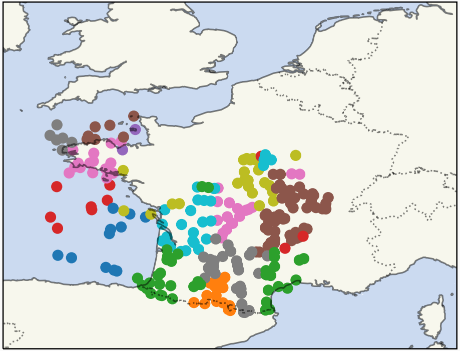


Airspace context

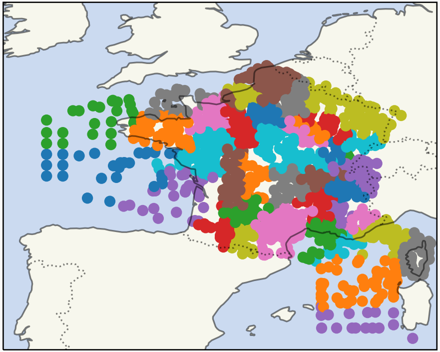
$$G = (V, A)$$

$$A = \left\{(u, v) \mid u \in V,\ v \in V,\ \underline{D} \leq d_{u,v} \leq \overline{D}\right\}$$

$$\mathit{1\ color} = \mathit{1\ sector}$$



Current (2023) FRA points over France.

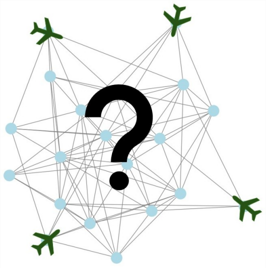


Realistic simulated FRA points over France.

Introduction

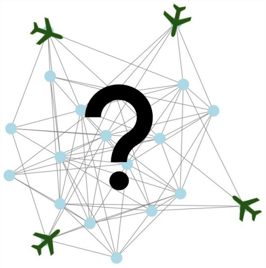
Research objectives

Research objectives



Propose new models and methods to take into account contrails at the network scale

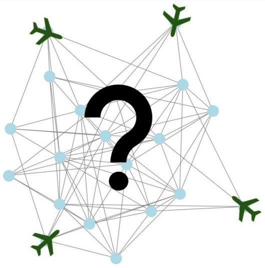
Research objectives



Propose new models and methods to take into account contrails at the network scale

- Compute trajectories for whole traffic

Research objectives



Propose new models and methods to take into account contrails at the network scale

- Compute trajectories for whole traffic
- Simulate the impact of various policies

Contributions

Literature review on contrails and related flight-by-flight optimization

Contributions

Literature review on contrails and related flight-by-flight optimization

New flight-by-flight optimization method

Contributions

Literature review on contrails and related flight-by-flight optimization

New flight-by-flight optimization method

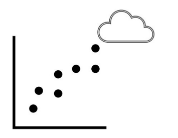
New network-scale optimization models and methods

Contributions

Literature review on contrails and related flight-by-flight optimization

New flight-by-flight optimization method

New network-scale optimization models and methods



Contrail-related uncertainties

The classical Air Traffic Flow Management problem

Not a network flow problem

Objective functions

Sum of delays, number of cancellations, ...

Decisions

Departure times, routes (2D or 3D), speed modulations

Constraints

Infrastructure and airspace capacity (number of flights per time period)

The classical Air Traffic Flow Management problem

Seminal papers: ILP

Odoni, 1987

Bertsimas and Patterson, 1998

Multi-agent approach

Weigang *et al.*, 2010

Pre-processing (graph pruning) + MILP

Agustin *et al.*, 2012a

MILP + Column generation

Richard *et al.*, 2011

Balakrishnan and Chandran, 2014

Diao and Chen, 2018

A model adapted to environmental impact consideration

Objective functions

Total environmental impact

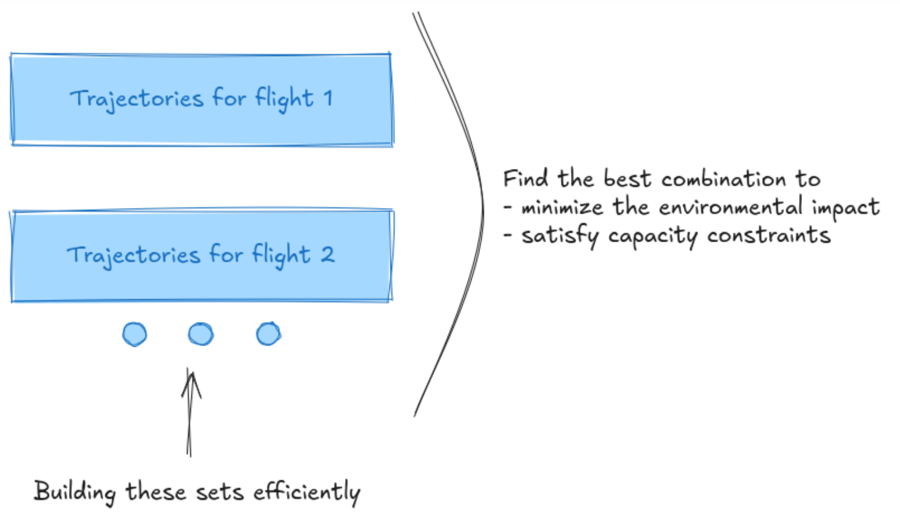
Decisions

Find a trajectory for each flight (2D, 3D, 4D)

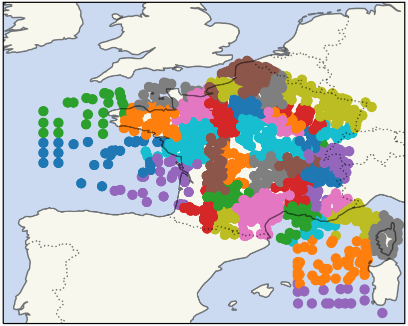
Constraints

Sector capacity, demand satisfaction

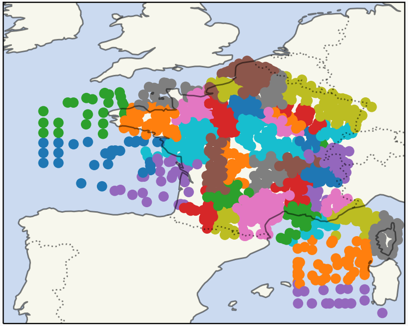
A few words on the resolution approach



Instance



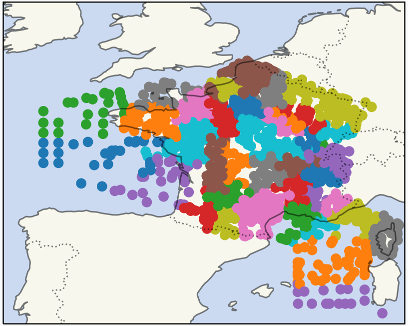
Instance



Weather and contrail data

Extracted from ERA5 reanalysis data and processed with ClimACCF library.

January 1st, 2022, 00:00 UTC



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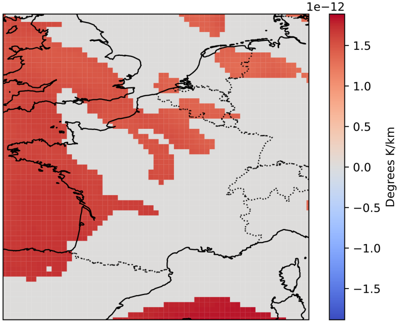
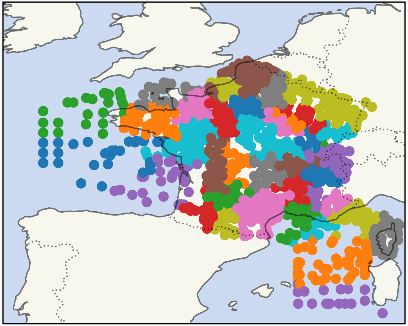


Instance



Weather and contrail data

Extracted from ERA5 reanalysis data and processed with ClimACCF library.

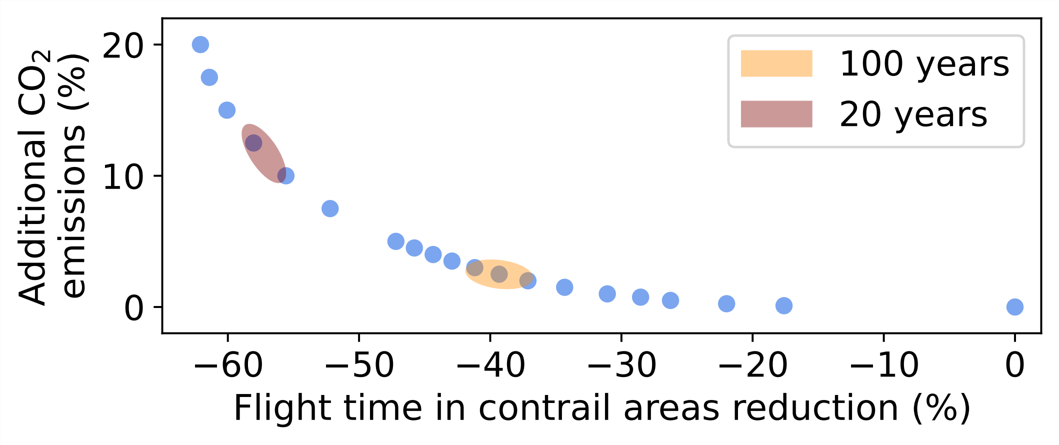
January 1st, 2022, 00:00 UTC

Traffic data

Extracted from Eurocontrol R&D historical data.

March 5th, 2019, 15:00 UTC (1 hour, 474 flights)

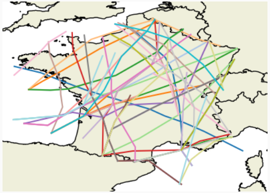
Results



Additional CO_2 emissions (%)
20
10
0
−60
−50
−40
−30
−20
−10
0
Flight time in contrail areas reduction (%)
100 years
20 years

Conclusion

Demouge, C., Mongeau, M., Couellan, N., & Delahaye, D. (2024).**Climate-aware air traffic flow management optimization via column generation.** Transportation Research Part C: Emerging Technologies, *166*, 104792



Summary

- A new model for climate-aware ATFM, solved via an efficient method
- 2D or 3D optimization, with or without speed modulations and ground delays
- Comparison of various metrics and their impact on the network
- Realistic instances from public data

Perspectives

- Numerical experiments on a **larger geographical scale**
- Numerical experiments when considering **other non-CO_2 effects**
- Consideration of **uncertainties**

Uncertainties taken into account

Aircraft-related

- Mass estimation: Wickramasinghe *et al.*, 2016
- Departure time forecast: Sandamali *et al.*, 2020
- Positioning errors and speed uncertainties: Kuzmenko *et al.*, 2018

Uncertainties taken into account

Aircraft-related

- Mass estimation: Wickramasinghe *et al.*, 2016
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Airspace-related

- Capacity and demand forecasts: Agustin *et al.*, 2012b; Balakrishnan and Chandran, 2014

Uncertainties taken into account

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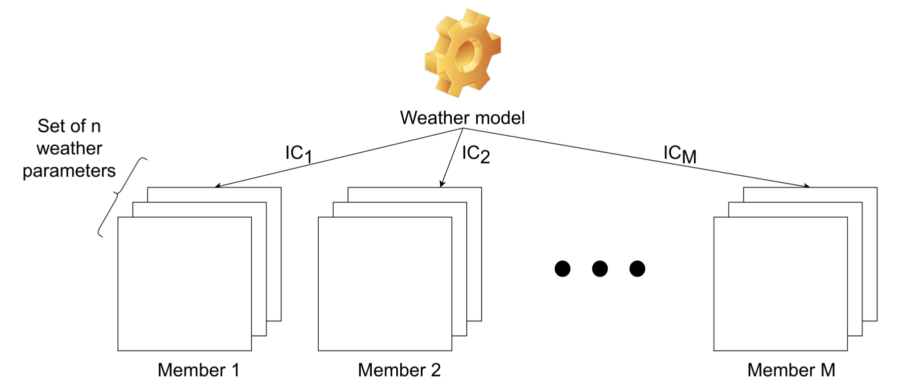
Airspace-related

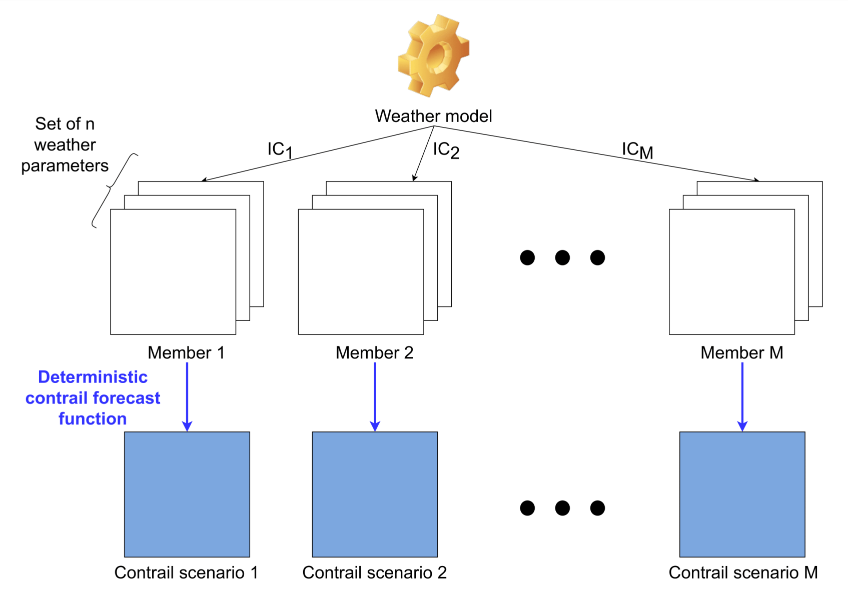
- Capacity and demand forecasts: Agustin *et al.*, 2012b; Balakrishnan and Chandran, 2014

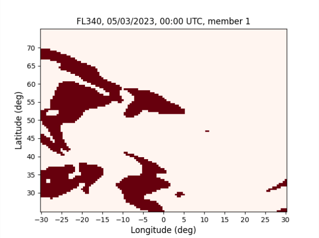
Weather-related

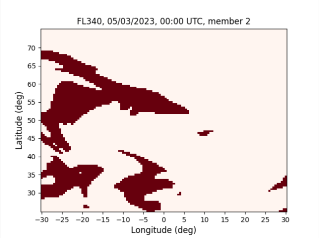
- Wind forecast: Legrand *et al.*, 2018
- Non-CO_2 effect impact forecast: Simorgh *et al.*, 2024

Ensemble forecast




Weather model
Set of n weather parameters
IC1
IC2
ICM
Member 1
Member 2
Member M
Deterministic contrail forecast function
Contrail scenario 1
Contrail scenario 2
Contrail scenario M


FL340, 05/03/2023, 00:00 UTC, member 1
Latitude (deg)
Longitude (deg)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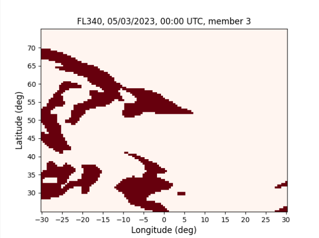
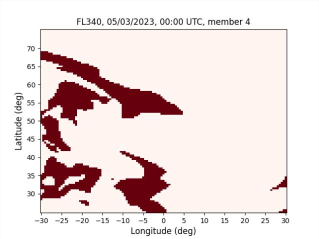
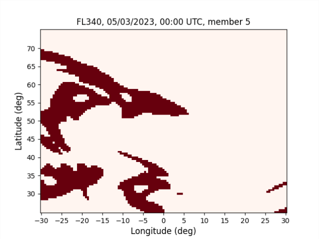
Latitude (deg)
Longitude (deg)


FL340, 05/03/2023, 00:00 UTC, member 3
Latitude (deg)
Longitude (deg)


FL340, 05/03/2023, 00:00 UTC, member 4
Latitude (deg)
Longitude (deg)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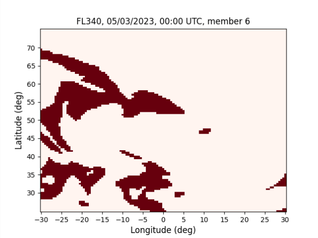
Latitude (deg)
Longitude (deg)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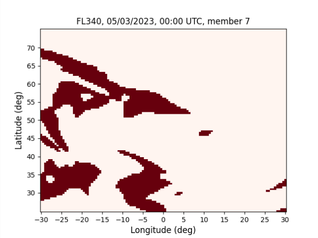
Latitude (deg)
70 65 60 55 50 45 40 35 30
−30 −25 −20 −15 −10 −5 0 5 10 15 20 25 30
Longitude (deg)


FL340, 05/03/2023, 00:00 UTC, member 7
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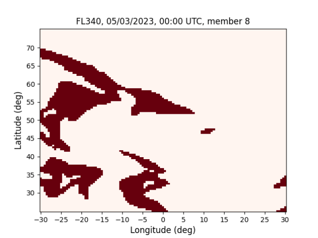
−30 −25 −20 −15 −10 −5 0 5 10 15 20 25 30
Longitude (deg)


FL340, 05/03/2023, 00:00 UTC, member 8
Latitude (deg)
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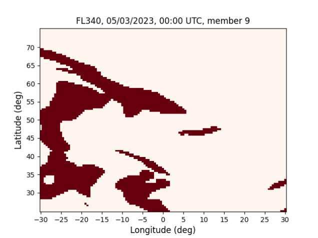
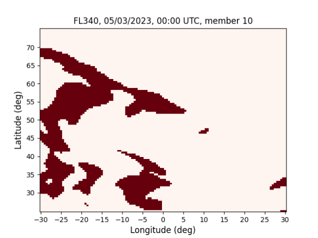
−30 −25 −20 −15 −10 −5 0 5 10 15 20 25 30
Longitude (deg)

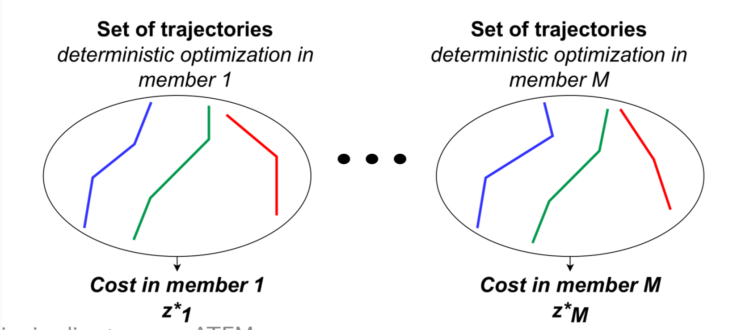

FL340, 05/03/2023, 00:00 UTC, member 9
Latitude (deg)
70 65 60 55 50 45 40 35 30
−30 −25 −20 −15 −10 −5 0 5 10 15 20 25 30
Longitude (deg)


FL340, 05/03/2023, 00:00 UTC, member 10
Latitude (deg)
70 65 60 55 50 45 40 35 30
−30 −25 −20 −15 −10 −5 0 5 10 15 20 25 30
Longitude (deg)

A key indicator: (Relative) regret

(Relative) regret

$$\chi_m = \frac{z^{(m)} - z_m^*}{z_m^*}$$



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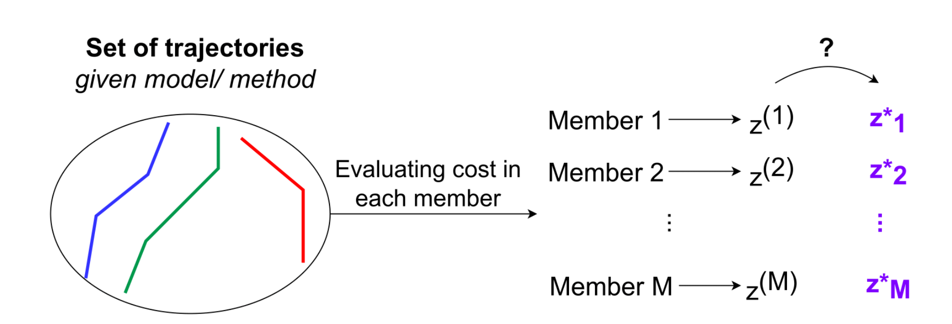
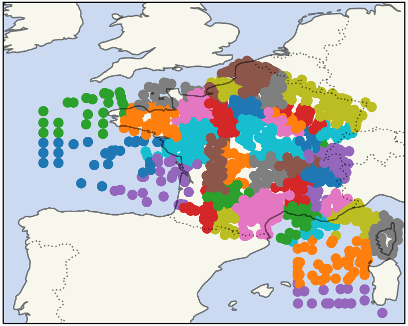




Weather and contrails data

Extracted from ERA5 reanalysis data and processed with ClimACCF library.

January 26th, 2019, 00:00 UTC

Traffic data

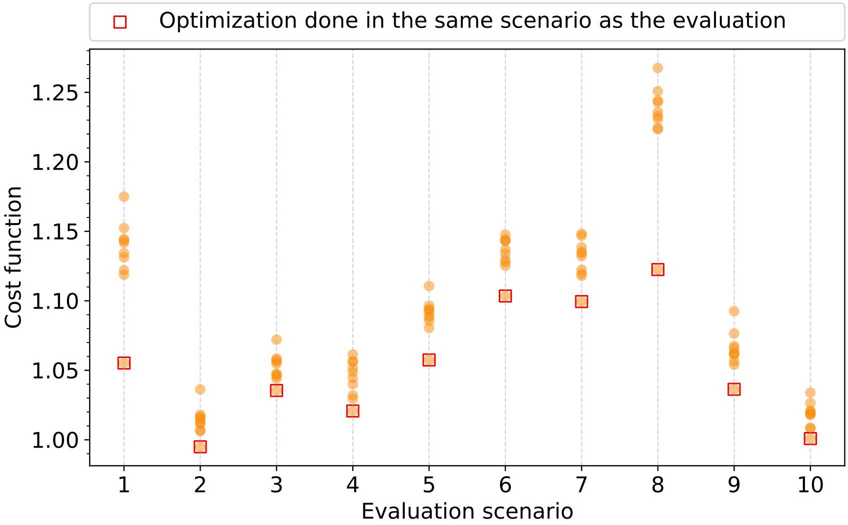
Extracted from Eurocontrol R&D historical data.

March 5th, 2019, 12:00 UTC (1 hour, 518 flights)

Results

Optimization scenario \ Evaluation scenario	1	2	3	4	5	6	7	8	9	10	Mean regret	Max regret
1	0.00%	2.08%	1.00%	2.75%	5.03%	3.58%	4.44%	12.92%	3.87%	2.00%	3.77%	12.92%
2	8.20%	0.00%	2.11%	3.04%	3.41%	3.63%	3.25%	11.43%	2.42%	1.93%	3.94%	11.43%
3	6.02%	1.18%	0.00%	0.87%	3.02%	2.20%	2.08%	10.73%	1.96%	0.74%	2.88%	10.73%
4	8.36%	1.66%	0.83%	0.00%	3.33%	3.05%	1.69%	9.68%	2.44%	0.78%	3.18%	9.68%
5	8.46%	2.32%	2.22%	3.48%	0.00%	1.98%	3.56%	8.99%	2.54%	1.72%	3.53%	8.99%
6	6.33%	2.17%	2.01%	3.98%	2.18%	0.00%	2.98%	10.10%	3.00%	2.55%	3.53%	10.10%
7	7.50%	1.92%	1.14%	1.10%	3.70%	2.74%	0.00%	9.83%	1.71%	1.76%	3.14%	9.83%
8	11.35%	4.15%	3.54%	3.51%	3.46%	4.00%	3.17%	0.00%	5.42%	3.30%	4.19%	11.35%
9	7.20%	1.70%	1.15%	1.88%	2.89%	2.36%	1.84%	9.09%	0.00%	1.76%	2.99%	9.09%
10	9.20%	1.15%	1.86%	2.32%	2.66%	3.68%	4.31%	10.84%	2.84%	0.00%	3.89%	10.84%

Results



Optimization done in the same scenario as the evaluation
Cost function
1.25
1.20
1.15
1.10
1.05
1.00
1
2
3
4
5
6
7
8
9
10
Evaluation scenario

Proposition of new cost functions

$$w_{f,(u,v),(t_u,t_v)} = \boxed{\textbf{Mean cost} \quad \frac{1}{M}\sum_{m=1}^{M} w^{(m)}_{f,(u,v),(t_u,t_v)}}$$

Proposition of new cost functions

$$w_{f,(u,v),(t_u,t_v)} = \boxed{\begin{array}{c}\textbf{Mean cost}\\ \frac{1}{M}\sum_{m=1}^{M} w^{(m)}_{f,(u,v),(t_u,t_v)}\end{array}}$$

$$w_{f,(u,v),(t_u,t_v)} = \boxed{\begin{array}{c}\textbf{Mean cost}\\ \frac{1}{M}\sum_{m=1}^{M} w^{(m)}_{f,(u,v),(t_u,t_v)}\end{array}} + \boxed{\begin{array}{c}\textbf{Risk function}\\ \kappa\ \sigma^{c}_{f,(u,v),(t_u,t_v)}\end{array}}$$

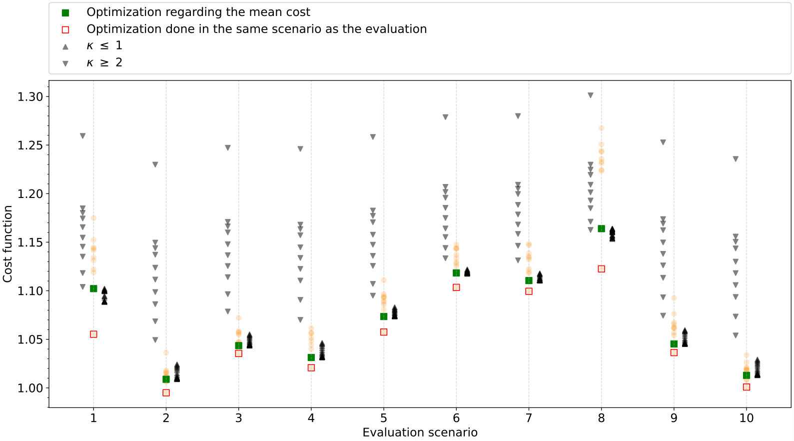
Results

$$w_{f,(u,v),(t_u,t_v)} = \frac{1}{M}\sum_{m=1}^{M} w^{(m)}_{f,(u,v),(t_u,t_v)} + \kappa\ \sigma^{c}_{f,(u,v),(t_u,t_v)}$$

κ \ Evaluation scenario	1	2	3	4	5	6	7	8	9	10	Mean regret	Max regret
0.0	4.45%	1.4%	0.775%	1.03%	1.51%	1.35%	1.01%	3.69%	0.859%	1.2%	1.73%	4.45%
0.01	4.39%	1.41%	0.787%	1.05%	1.52%	1.35%	1.01%	3.69%	0.845%	1.22%	1.73%	4.39%
0.02	4.31%	1.43%	0.799%	1.05%	1.55%	1.38%	1.01%	3.66%	0.867%	1.24%	1.73%	4.31%
0.03	4.26%	1.44%	0.807%	1.06%	1.57%	1.39%	1.02%	3.62%	0.876%	1.25%	1.73%	4.26%
0.1	4.17%	1.55%	0.901%	1.13%	1.63%	1.38%	1.04%	3.34%	0.959%	1.37%	1.75%	4.17%
0.2	3.72%	1.65%	0.999%	1.31%	1.79%	1.27%	1.13%	3.36%	1.11%	1.54%	1.79%	3.72%
0.3	3.71%	1.81%	1.14%	1.43%	1.82%	1.26%	1.2%	3.1%	1.23%	1.69%	1.84%	3.71%
0.4	3.55%	2.01%	1.19%	1.53%	1.9%	1.33%	1.21%	3.03%	1.39%	1.86%	1.9%	3.55%
0.5	3.24%	2.32%	1.34%	1.74%	2.01%	1.46%	1.28%	3.01%	1.65%	2.11%	2.02%	3.24%
0.6	3.2%	2.5%	1.51%	1.98%	2.11%	1.53%	1.42%	2.84%	1.86%	2.31%	2.13%	3.2%
0.7	3.21%	2.64%	1.64%	2.18%	2.17%	1.55%	1.54%	2.73%	2.06%	2.46%	2.22%	3.21%
0.8	3.19%	2.75%	1.77%	2.36%	2.23%	1.54%	1.6%	2.79%	2.13%	2.62%	2.3%	3.19%
0.9	3.15%	2.87%	1.83%	2.43%	2.35%	1.62%	1.64%	2.83%	2.16%	2.75%	2.36%	3.15%
1.0	3.14%	2.95%	1.91%	2.52%	2.42%	1.69%	1.69%	2.83%	2.25%	2.84%	2.42%	3.14%
2.0	4.62%	5.46%	4.17%	4.83%	3.54%	2.72%	2.9%	3.58%	3.67%	5.31%	4.08%	5.46%
3.0	5.97%	7.39%	5.89%	6.84%	4.69%	3.68%	4.26%	4.33%	5.49%	7.25%	5.58%	7.39%
6.0	9.43%	11.7%	9.77%	11.1%	8.5%	6.48%	7.19%	7.02%	9.81%	11.7%	9.27%	11.7%
7.0	10.4%	12.9%	10.9%	12.1%	9.48%	7.42%	8.09%	7.72%	10.9%	12.9%	10.3%	12.9%
8.0	11.3%	14.3%	12%	13.4%	10.7%	8.37%	9.11%	8.62%	12.2%	14.3%	11.4%	14.3%
9.0	11.8%	15%	12.6%	14%	11.3%	8.9%	9.6%	9.1%	12.8%	14.9%	12%	15%
10.0	12.3%	15.5%	13.1%	14.4%	11.8%	9.38%	9.98%	9.56%	13.3%	15.5%	12.5%	15.5%
20.0	19.3%	23.6%	20.4%	22.1%	19%	15.9%	16.4%	15.9%	20.9%	23.5%	19.7%	23.6%

Results

$$w_{f,(u_i,u_{i+1}),t_i} = \frac{1}{M}\sum_{m=1}^{M} w^{(m)}_{f,(u_i,u_{i+1}),t_i} + \kappa\ \sigma^{c}_{f,(u_i,u_{i+1}),t_i}$$



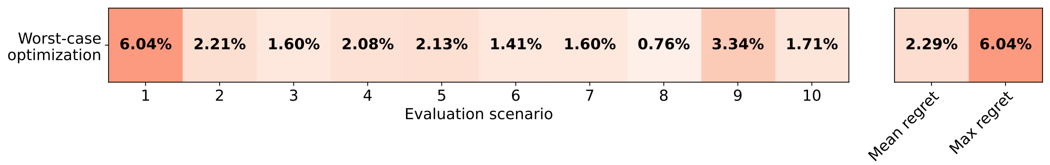
General idea

Minimize the maximum cost over the given scenarios

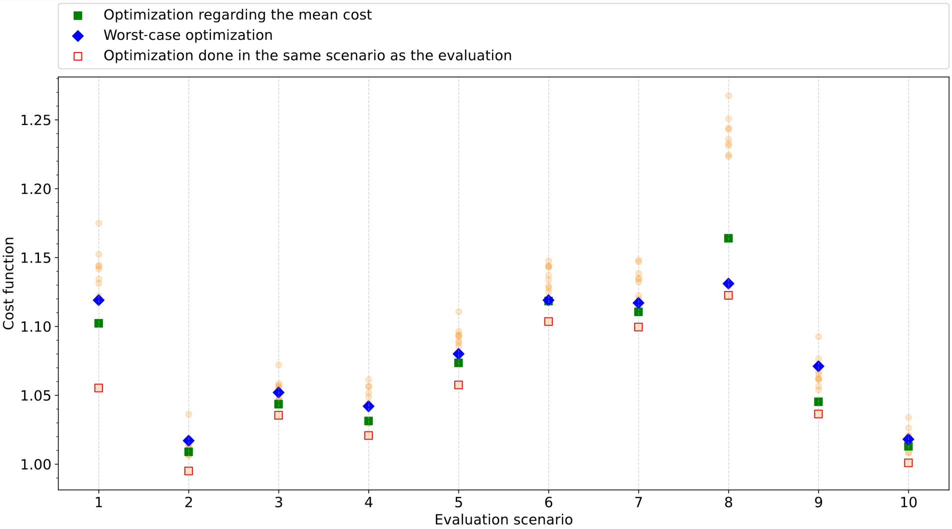
Find the trajectories that offer the best compromise to minimize the worst-case cost obtained by evaluating the trajectories in each scenario.

$\rightarrow$ Using an analogous method for resolution to the deterministic one

Results


Worst-case optimization
6.04%
2.21%
1.60%
2.08%
2.13%
1.41%
1.60%
0.76%
3.34%
1.71%
2.29%
6.04%
1
2
3
4
5
6
7
8
9
10
Evaluation scenario
Mean regret
Max regret

Results



Optimization regarding the mean cost
Worst-case optimization
Optimization done in the same scenario as the evaluation
Cost function
1.25
1.20
1.15
1.10
1.05
1.00
1
2
3
4
5
6
7
8
9
10
Evaluation scenario

Conclusions and perspectives

Conclusions

- New cost functions for risk mitigation
- Model adapted for worst-case optimization using an approach similar to that of the deterministic case
- Heuristics for a chance-constrained approach considering ensemble forecast

Conclusions and perspectives

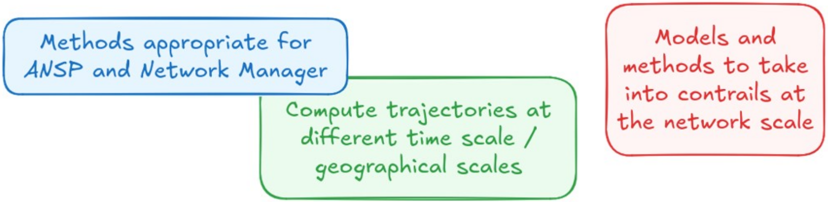
Conclusions

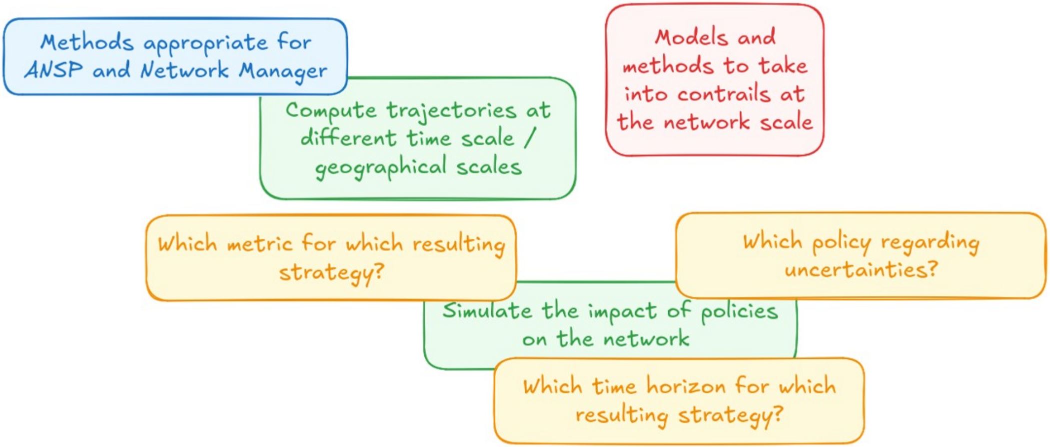
- New cost functions for risk mitigation
- Model adapted for worst-case optimization using an approach similar to that of the deterministic case
- Heuristics for a chance-constrained approach considering ensemble forecast

Perspectives

- Consider data with more members
- Considering continuous probabilistic model
- Considering other contrail-related uncertainties (*e.g.*, ML-forecast model uncertainties)

Models and methods to take into contrails at the network scale


Methods appropriate for ANSP and Network Manager
Compute trajectories at different time scale / geographical scales
Models and methods to take into contrails at the network scale


Methods appropriate for ANSP and Network Manager
Compute trajectories at different time scale / geographical scales
Models and methods to take into contrails at the network scale
Which metric for which resulting strategy?
Which policy regarding uncertainties?
Simulate the impact of policies on the network
Which time horizon for which resulting strategy?

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