

Integrating Extended Arrival Management and Network Management for Demand and Capacity Balancing with User Preferences

Junqiang Wan^{a,b,d,e}, Yan Xu^{c,e}, Honghai Zhang^b, Yifei Zhao^a, Xavier Prats^d

^aCollege of Air Traffic Management, Civil Aviation University of China, Tianjin, China

^bCollege of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing, China

^cSchool of Electronics and Information Engineering, Beihang University, Beijing, China

^dDepartment of Physics - Aeronautics Division, Technical University of Catalonia, Barcelona, Spain

^eSchool of Aerospace, Transport and Manufacturing, Cranfield University, Bedford, U.K.

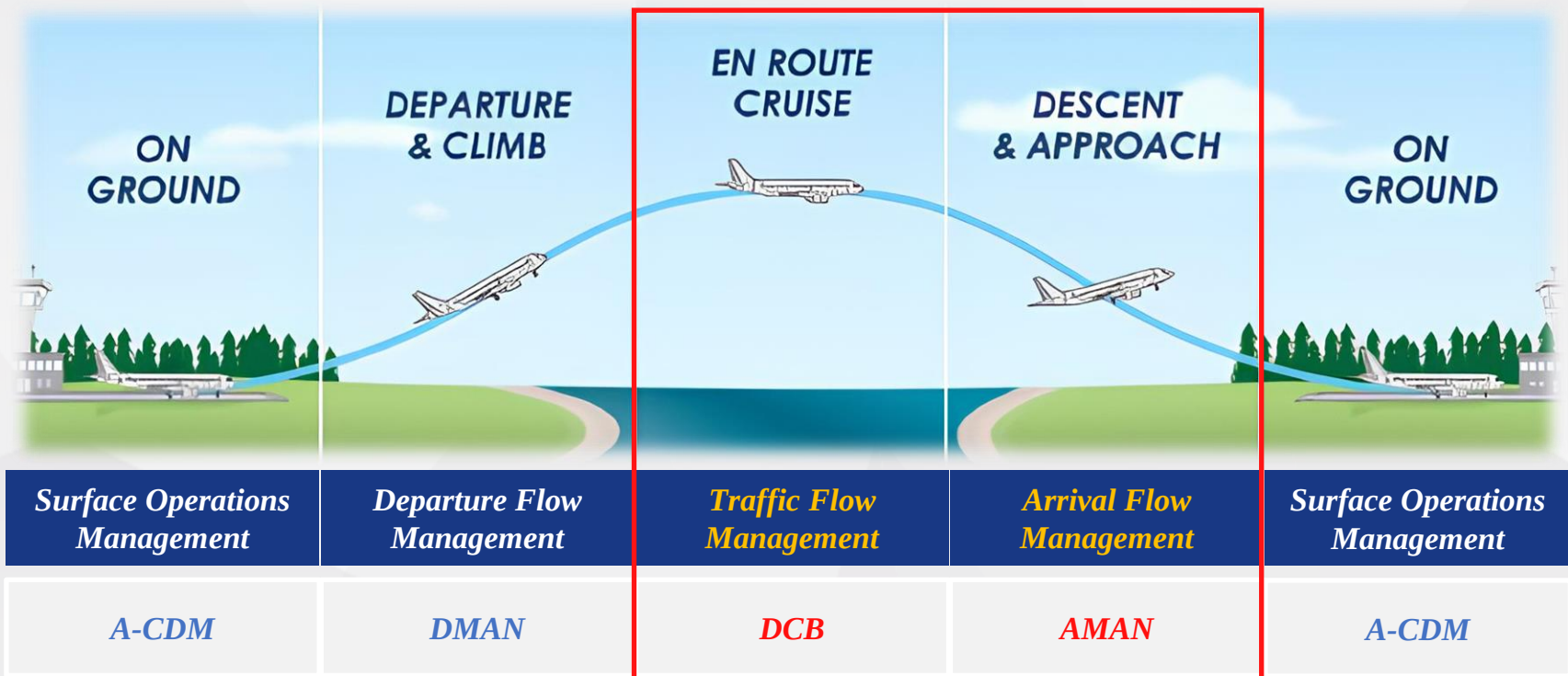
E-mail: jqwan@cauc.edu.cn



Background

ATFM Definition: A service established with the objective of contributing to a *safe, orderly and expeditious* flow of air traffic by ensuring that ATC capacity is utilized to the maximum extent possible, and that the *traffic volume* is compatible with the *capacities declared* by the appropriate ATS authority.

--Source: ICAO Doc 4444 PANS-ATM



Collaborative **DCB** + Extended **AMAN** ???

DCB: Demand and Capacity Balancing, **AMAN:** Arrival Management, **DMAN:** Departure Management, **A-CDM:** Airport collaborative decision making

Background

User-Driven Prioritisation Process (UDPP) Features:

- Fleet Delay Reordering (FDR)**

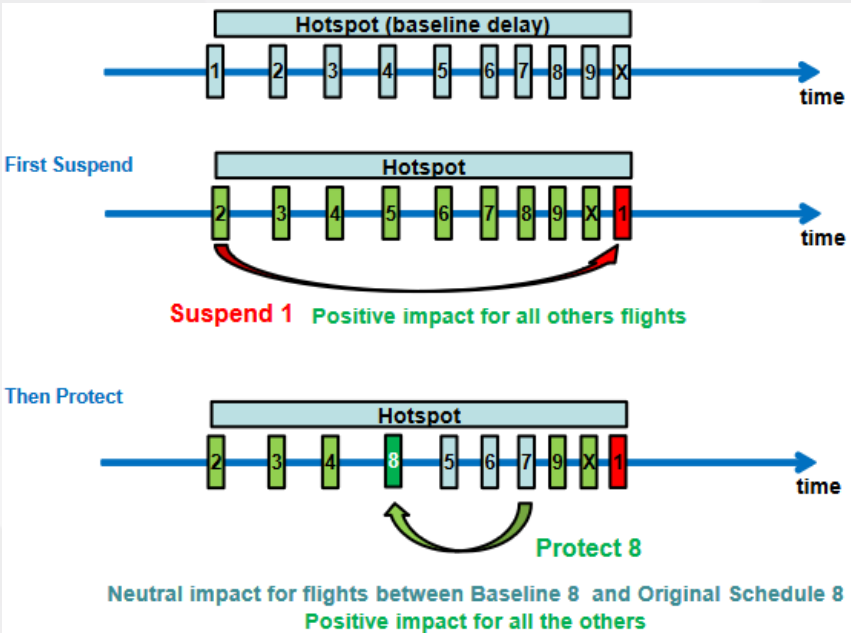
It allows an AU to reprioritize its flights by slot swapping within the UDPP measure, without advancing any flight before its original slot.

- Selective Flight Protection (SFP)**

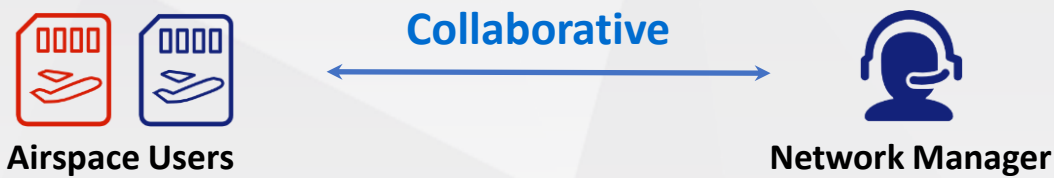
It enables an AU to secure a specific flight’s schedule by shifting another earlier flight, ensuring the protected flight retains its planned slot.

- Margins with Priority Values (MPV)**

It assign flexible time windows (“not before” and “not after”) to flights, used alone or with FDR and SFP, to reflect AU constraints and maintain stable prioritisation under varying ATM conditions.



Selective flight protection high level description



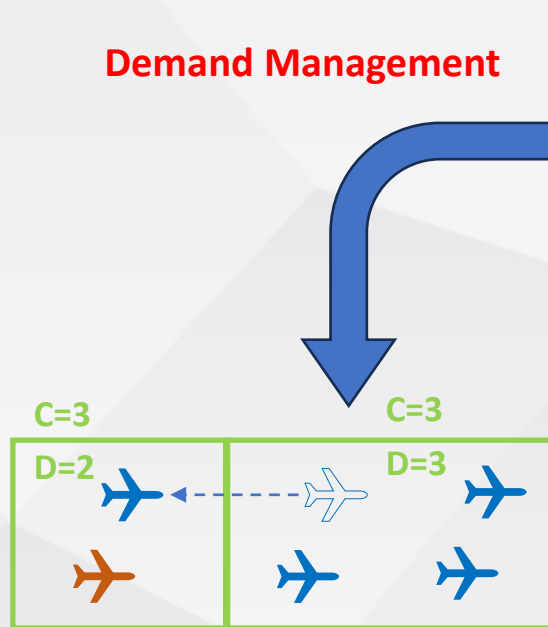
Background

Demand and Capacity Balancing (DCB):

Objective

$$\text{Demand} \leq \text{Capacity}$$

Demand Management

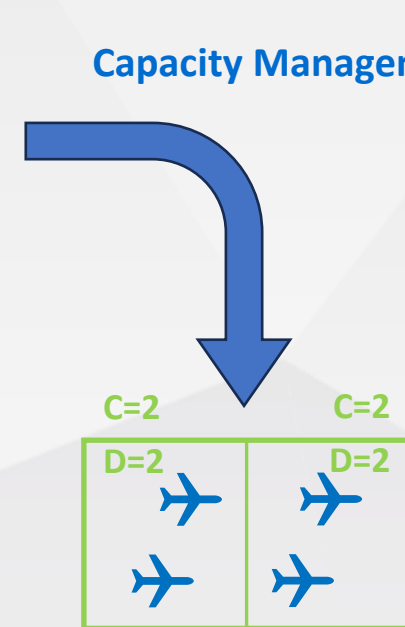


Trajectory management

Ground delay, Rerouting, Speed control

Most common uses

Capacity Management

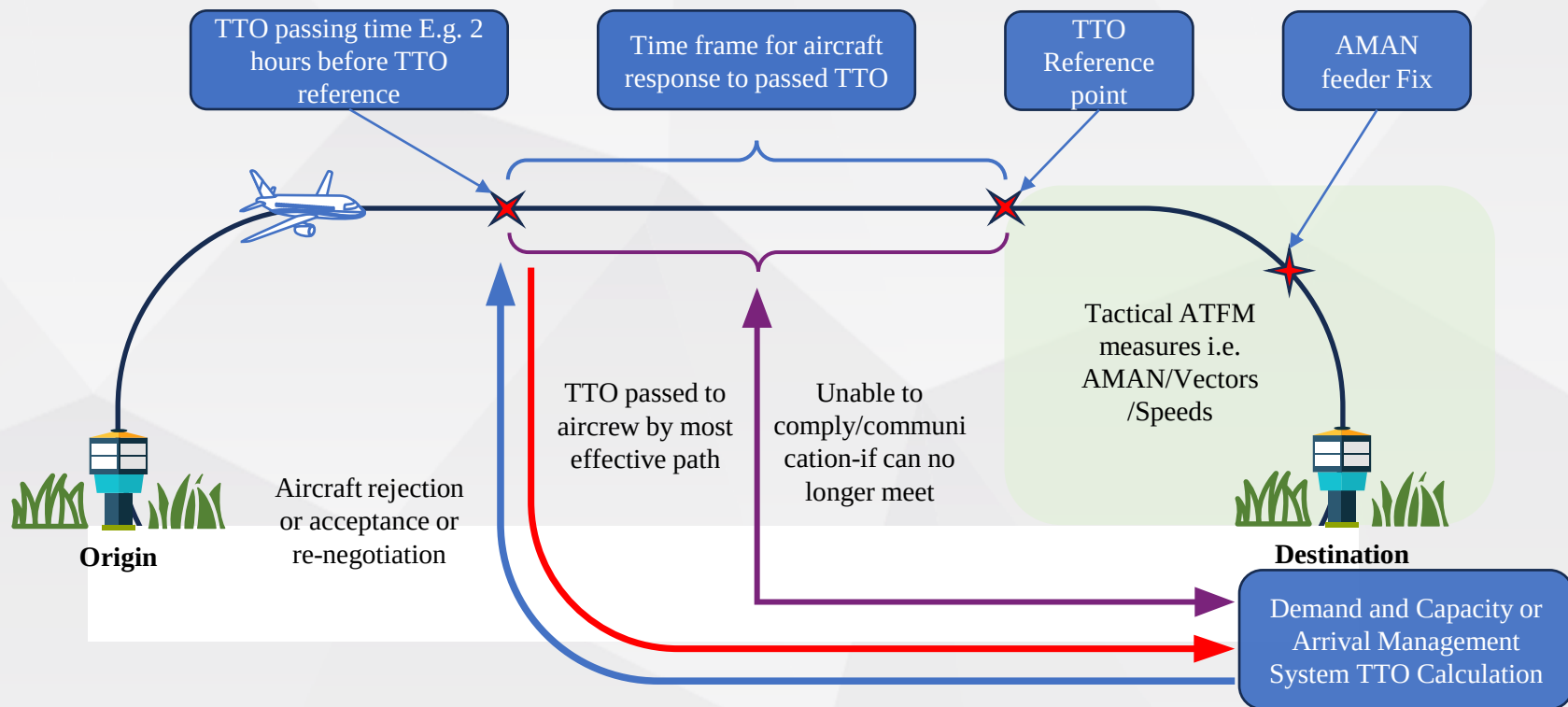


Flexible airspace configuration

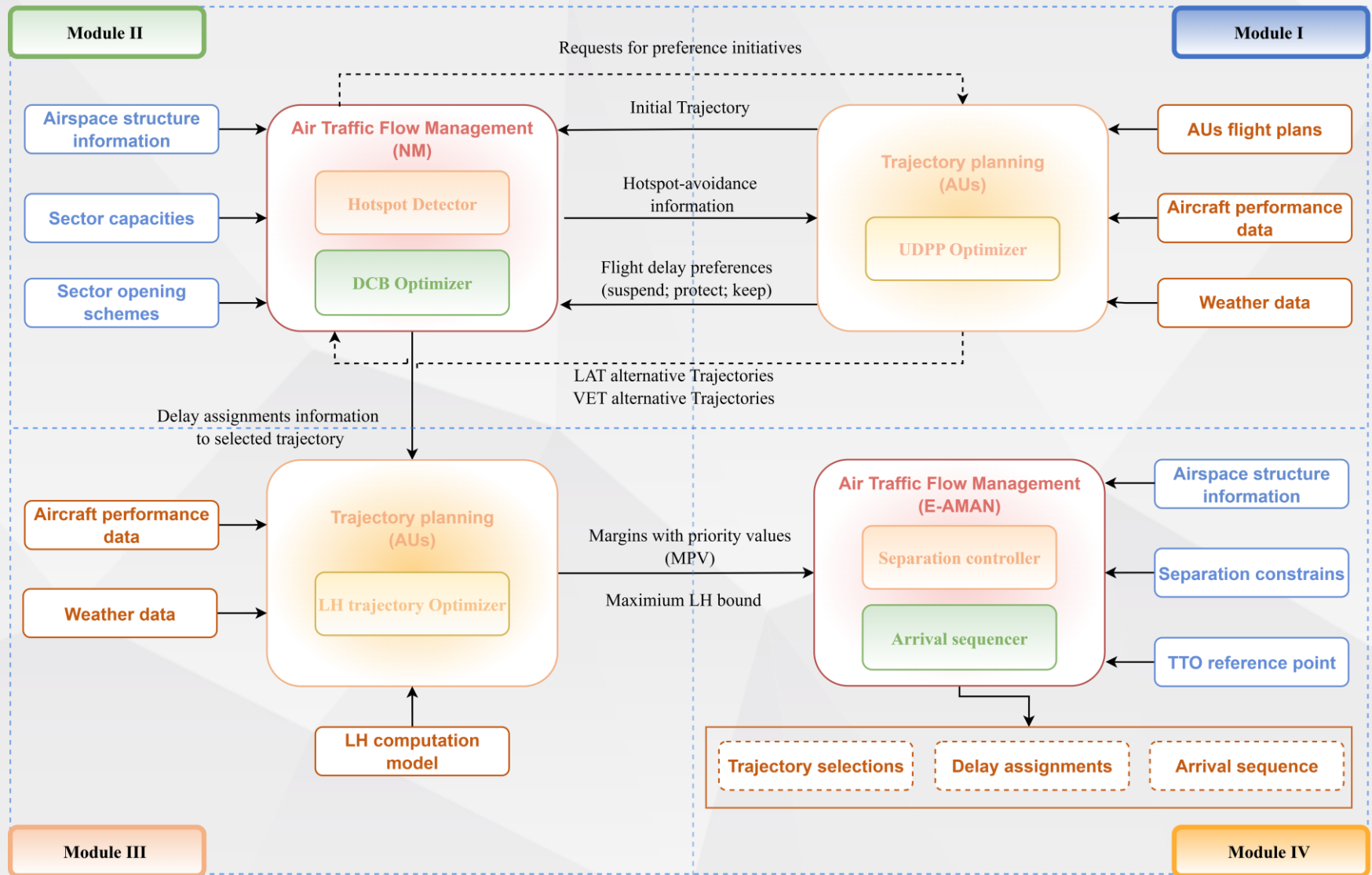
Dynamic sectorization (split/merge sectors)

Background

Extended arrive management (E-AMAN): is an extension of AMAN that shifts arrival-sequence management from the terminal maneuvering area (TMA) into *upstream en route airspace*, enabling *earlier* controller interventions to *adjust their speeds* and improve arrival efficiency.



TTO: Target time over



Methodology

Module I: Scheduling of User-driven preferred greener trajectories

□ Objective Function

Minimize cost: **Ground delay** + **Rerouting** - **the gains from flight prioritization** + **penalty cost for unpunctuality**

$$\min (C_{delay}^g + C_{delay}^r - C_{protect} + C_{penalty})$$

□ Decision Variables

$$p_f^h = \begin{cases} 1, & \text{if flight } f \text{ is protected in hotspot } h \\ 0, & \text{otherwise} \end{cases}$$

$$k_f^h = \begin{cases} 1, & \text{if flight } f \text{ is keeps baseline in hotspot } h \\ 0, & \text{otherwise} \end{cases}$$

$$s_f^h = \begin{cases} 1, & \text{if flight } f \text{ is suspended in hotspot } h \\ 0, & \text{otherwise} \end{cases}$$

$$r_f^h = \begin{cases} 1, & \text{if flight } f \text{ is rerouting in hotspot } h \\ 0, & \text{otherwise} \end{cases}$$

□ Constrains

- Consistency of the total OC of an AU
- The transformational relationship of OC between suspended and protected flights
- The use of the UDPP mechanism has a positive effect on flight delays

Trajectory delay-related cost

Fuel cost

Route charges

Emission charges

- Each flight can only have a single option selected
- Guarantees a unique solution for each flight
- Binary constraint

Methodology

Module II: System-wide optimization to balance demand and capacity

□ Objective Function

Minimize cost: **Ground delay + Rerouting + Suspend cost + penalty cost for additional operating cost**

□ Decision Variable

$$x_{f,t}^{k,j} = \begin{cases} 1, & \text{if flight } f \text{'s } k^{\text{th}} \text{ trajectory enters elementary sector } j \text{ by time } t \\ 0, & \text{otherwise} \end{cases}$$

$$z_f^k = \begin{cases} 1, & \text{if flight } f \text{'s } k^{\text{th}} \text{ trajectory is chosen} \\ 0, & \text{otherwise} \end{cases}$$

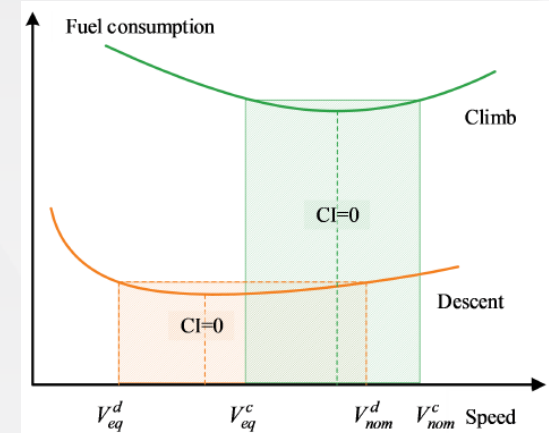
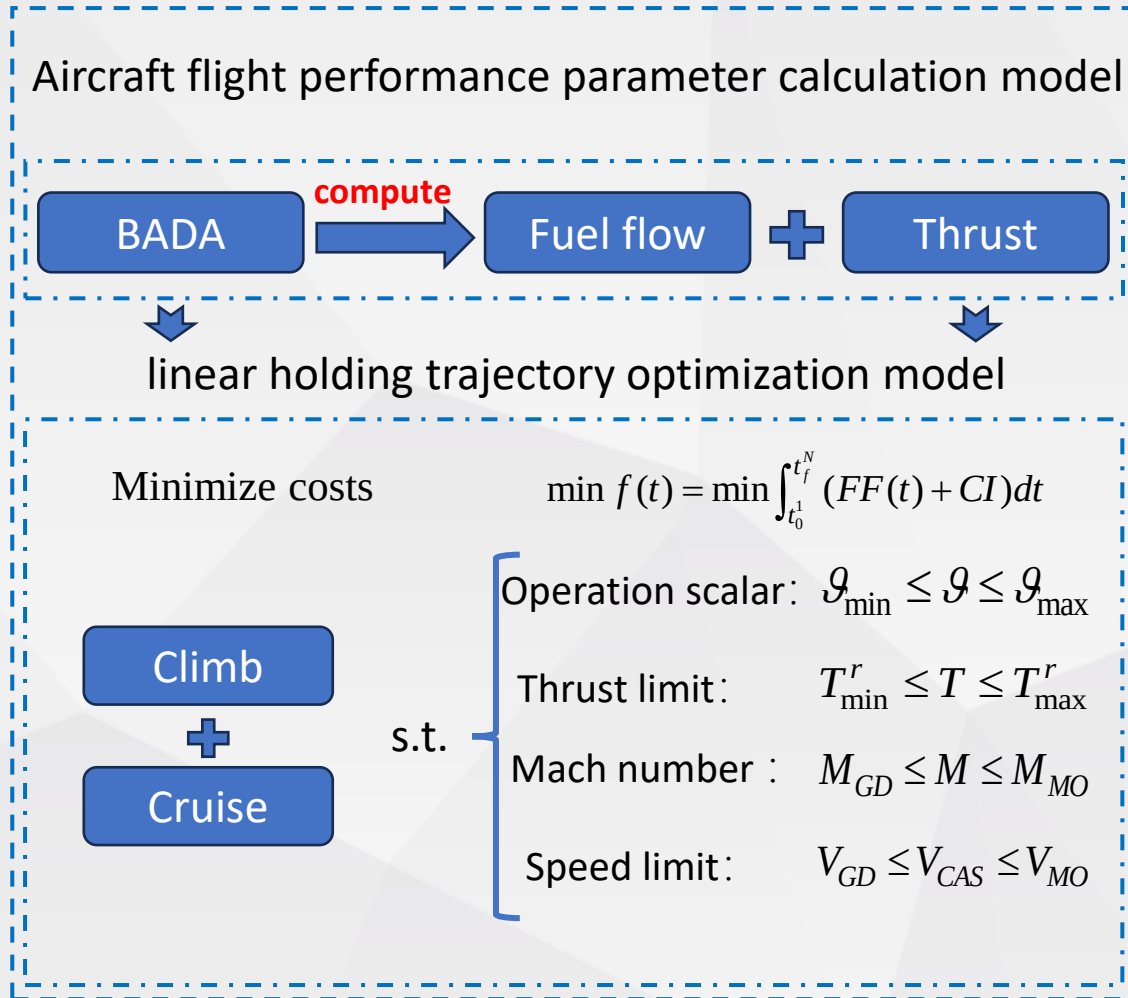
□ Constrains

- Each flight selects a unique trajectory
- Define the feasible CTA range at each control point for each flight
- Enforce continuity of the decision variable timeline under the “**by-time**” concept.
- Binary Constraint.
- Segment flying times remain identical to those in the initial schedule
- Demand not exceed planned capacity.
- Protected flights are punctual within their designated hotspots.

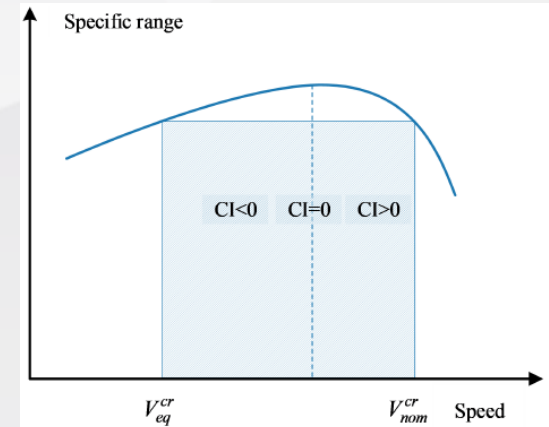
CTA: Controlled time of arrival

Methodology

Module III: Computation of linear holding bound for optimal trajectories



(a) Climb and Descent



(b) Cruise

BADA: Base of aircraft data

Methodology

Module IV: Integrated optimization model for extended arrival management

□ Objective Function

Minimize cost: **Airborne Holding** + **Linear Holding**

□ Decision Variable

$$x_{f,t}^j = \begin{cases} 1, & \text{if flight } f \text{ departs from position } j \text{ by time } t \\ 0, & \text{otherwise} \end{cases}$$

$$y_{f,t}^j = \begin{cases} 1, & \text{if flight } f \text{ arrives at position } j \text{ by time } t \\ 0, & \text{otherwise} \end{cases}$$

$$h_{f,f'}^j = \begin{cases} 1, & \text{if flight } f \text{ arrives at position } j \text{ before flight } f' \\ 0, & \text{otherwise} \end{cases}$$

Depart time

Arrive time

Sequence

□ Constrains

- Each flight f is assigned one departure and one arrival slot at position j
- Maximum Airborne Holding time limit
- Maximum Linear Holding bound between two consecutive waypoints
- Minimum separation interval between aircraft at specific points
- Artificial variable constraints
- Binary Constraint.

Experimental setup and dataset

① Case infor

- ❑ Scheduled flights (6255)
- ❑ 164 elementary sectors, and 224 operating sectors
- ❑ 60min * 24 sector capacity values
- ❑ Unit time step 1 min, time scale for DCB 60 min

② Trajectory

- ❑ initial trajectories (6255)
- ❑ lateral alternative trajectories (1305)
- ❑ vertical alternative trajectories (1379)
- ❑ Total 8939 trajectories

③ Environment

- ❑ GAMS V.24.2 as modelling tool
- ❑ Gurobi V.5.6 optimizer as the solver
- ❑ 64 bit Intel i7-4790 @3.60 GHz quad core CPU, 16 GB RAM, Linux OS

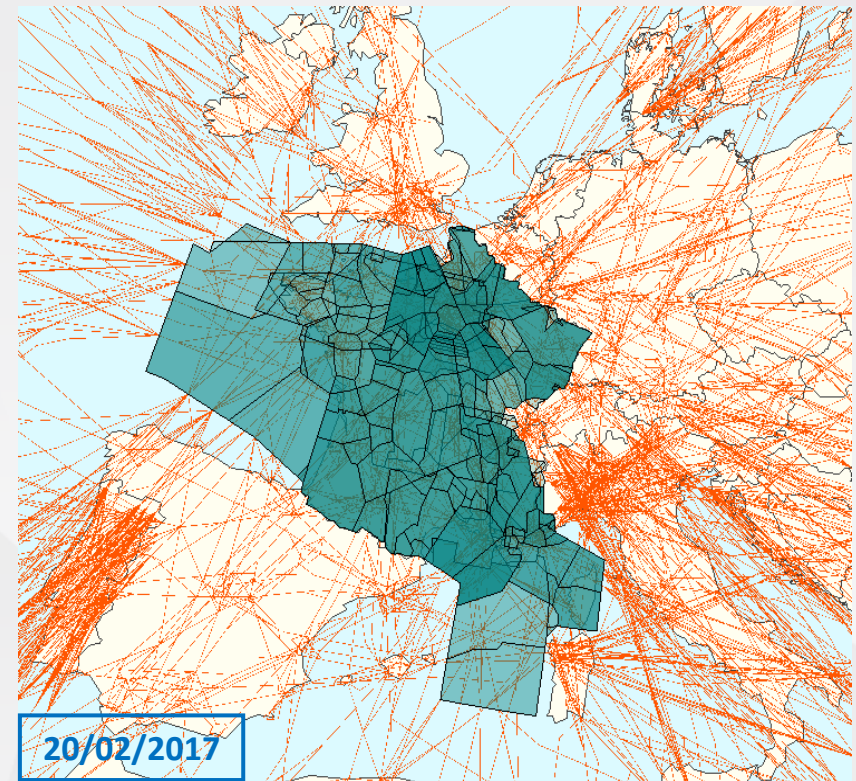


Diagram of French airspace sector structure and flight trajectory dataset

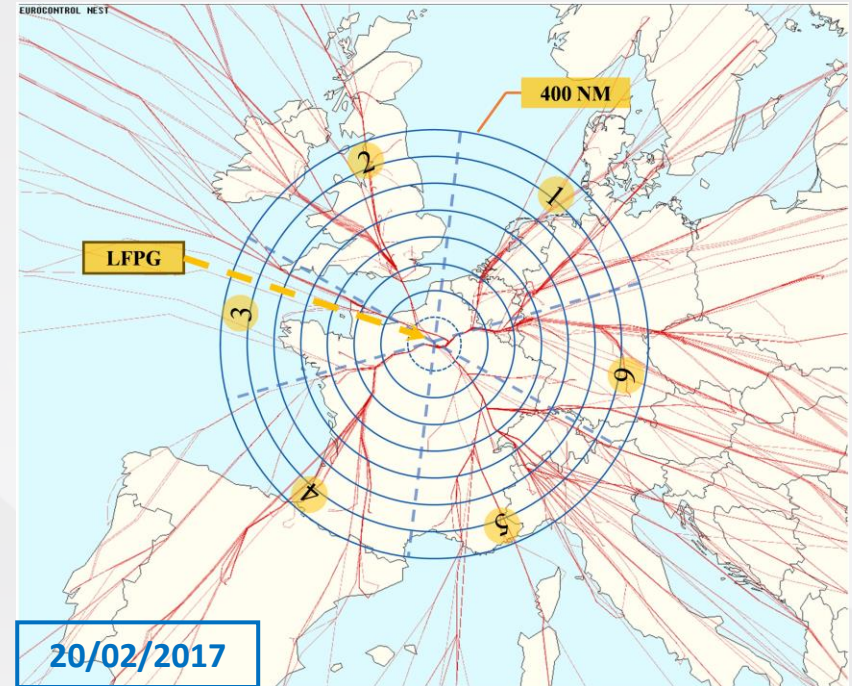
Experimental setup and dataset

Case information

- 677 inbound flights
- 8 terminal-entry points
- Six distinct and independent approach directions
- 70% are medium aircraft, and 30% are heavy aircraft.

Aircraft time-based safety separation

Front aircraft	Rear aircraft	
	Medium	Heavy
Medium	70 S	60 S
Heavy	118 S	82 S

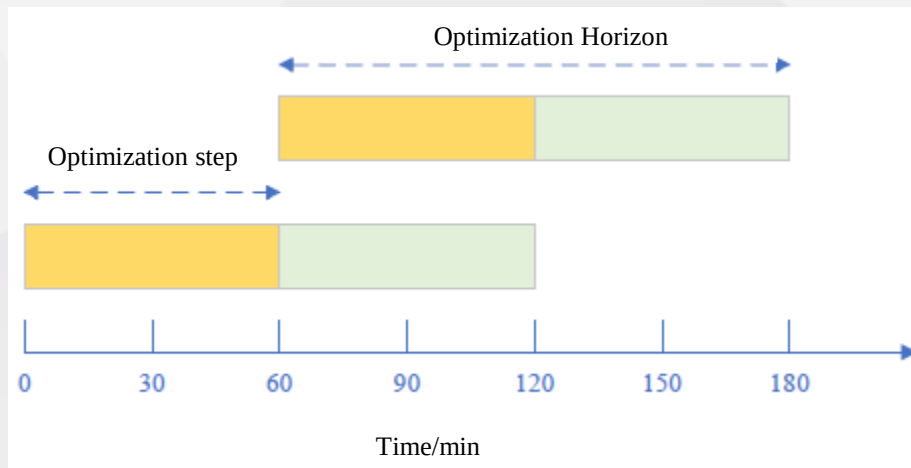


Schematic of airspace slices and approach trajectories near LFPG

Experiment

E-AMAN model Solution algorithm

During data processing, **dividing the experimental data into hourly intervals**, it may break the continuity of flight information at period boundaries. To balance solution quality and computational efficiency, a **sliding time-window approach** was adopted.



Algorithm 1 Sliding Time-Window Based Arrival Pre-Sequencing Algorithm

Input: Flight plan F^{plan} ; optimization horizon O^{time} ; optimization step O^{step} ; airspace structure data D^{airspace}

- 1: Initialize time-window size $W \leftarrow O^{\text{time}}$ and the number of aircraft released per step $N^{\text{step}} \leftarrow O^{\text{step}}$
- 2: Sort the flights inside the initial window based on sequencing criteria determined by D^{airspace}
- 3: Initialize the final arrival sequence list $Q \leftarrow []$
- 4: **for** $k \leftarrow 1$ **to** N^{step} **do**
- 5: Remove the first aircraft from the current window (and from F^{plan})
- 6: Append this aircraft to the final sequence Q
- 7: **end for**
- 8: **while** $\text{len}(F^{\text{plan}}) > W$ **do**
- 9: Sort the flights inside the new window
- 10: **for** $k \leftarrow 1$ **to** N^{step} **do**
- 11: Remove the first aircraft from the current window (and from F^{plan})
- 12: Append this aircraft to the final sequence Q
- 13: **end for**
- 14: **end while**
- 15: **if** $\text{len}(F^{\text{plan}}) > 0$ **then**
- 16: Sort the remaining flights in the last window
- 17: **for** $k \leftarrow 1$ **to** $\text{len}(F^{\text{plan}})$ **do**
- 18: Remove the first aircraft from the current window (and from F^{plan})
- 19: Append this aircraft to the final sequence Q
- 20: **end for**
- 21: **end if**

Output: Final arrival sequence Q

Experiment

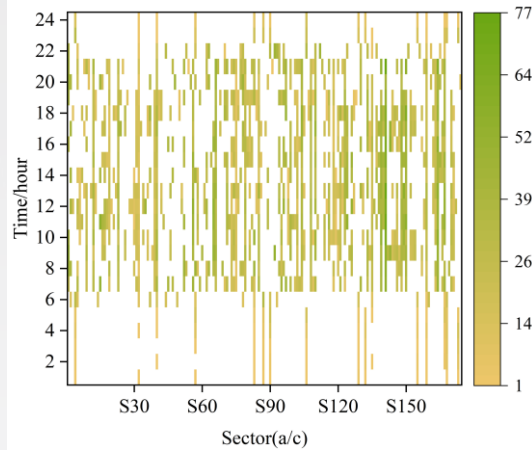
Problem dimensions and computational times

Summary	DCB (Baseline)	UDPP-DCB(i)	UDPP-DCB(ii)	E-AMAN
Time window	360 min	360 min	120 min	6 min
Variables	12,392,347	16,434,401	16,002,524	275,483
Equations	22,459,267	27,056,519	21,580,388	707,498
Non-zeros	47,518,810	56,592,773	44,456,969	6,085,613
Presolved variables	147,048	74,313	69,627	2,004
Presolved equations	141,785	77,966	75,793	26,057
Presolved non-zeros	496,032	295,066	297,593	19,186
Generation time	2 min	2 min	1 min	5 sec
Solution time	4 min	4 min	2 min	7 sec

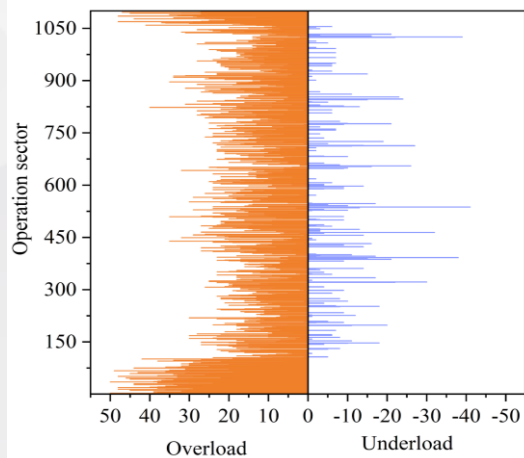
- The solution time for **UDPP-DCB** is in the **minutes range**.
- The solution time for **E-AMAN** is in the **seconds range**.

Experiment

Stage I: Module I (UDPP Optimizer) & Module II (DCB Optimizer)



(a) Initial demand in operating sector



(b) Imbalance of demand and capacity

Information of operating sectors. (15 Hotspots)

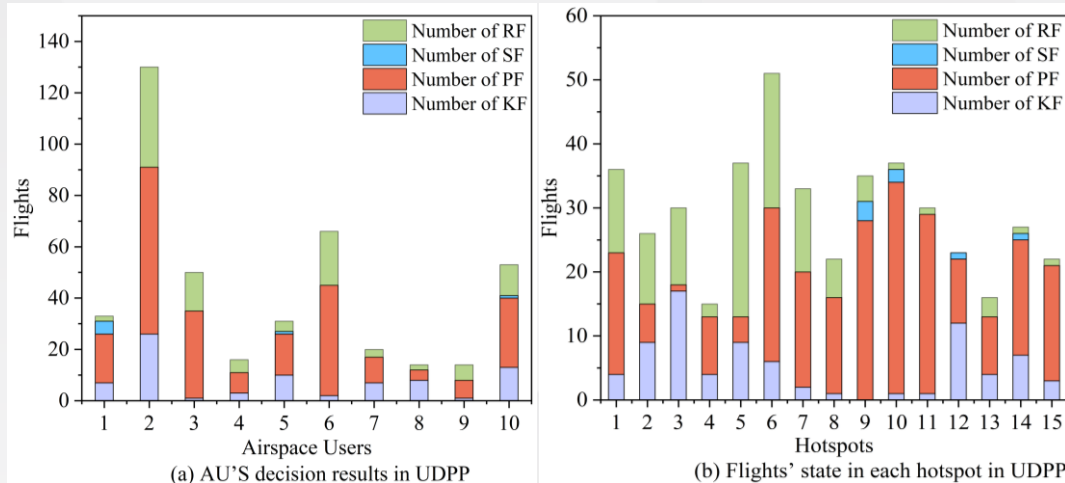
Time period	Sector	Capacity	Demand	Operating index	Max delay(min)
8:00-9:00	LFMMZL	54	56	104	119
10:00-11:00	LFBBLM	50	55	110	119
10:00-11:00	LFMMZL	54	66	122	119
...	...	...	...	...	...
21:00-22:00	LFBBLM	50	55	110	119
21:00-22:00	LFMMZL	54	75	139	119
21:00-22:00	LFBBL4	57	59	104	118

Information of AUs involved in UDPP. (10 AUs)

AUs	Number of flights	Cost scenario	Type of operation	AUs	Number of flights	Cost scenario	Type of operation
AU1	33	High	Full service	AU6	66	Low	Low-cost
AU2	130	Low	Low-cost	AU7	20	High	Full service
AU3	50	High	Full service	AU8	14	Regional	Full service
AU4	16	High	Full service	AU9	14	High	Full service
AU5	31	High	Full service	AU10	53	High	Full service

Experiment

Module I (UDPP Optimizer) results



- **Suspend flights (SF)** are relatively few, because rerouting is more cost-effective and also releases operating credits.
- Hotspot with lower operating indexes make SF a more favorable option.

AU's decision results in UDPP optimization model

Indicators	Total delays(min)	Delayed flights(a/c)	Initial trajectory(a/c)	Lateral alternative(a/c)	Vertical alternative(a/c)
Baselines	23,780	548	6255	\	\
UDPP-DCB(i)	27,483	442	6255	\	\
UDPP-DCB(ii)	219	48	6065	39	151

Experiment

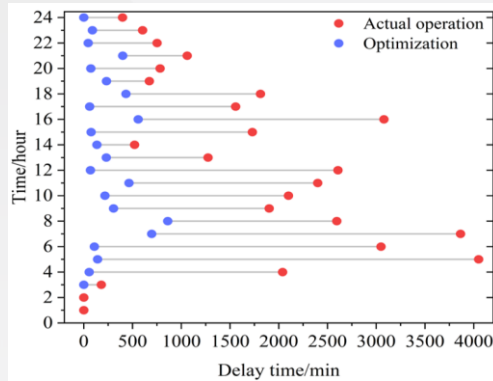
Module I (DCB Optimizer) results

Benefits obtained by AUs after the implementation of UDPP

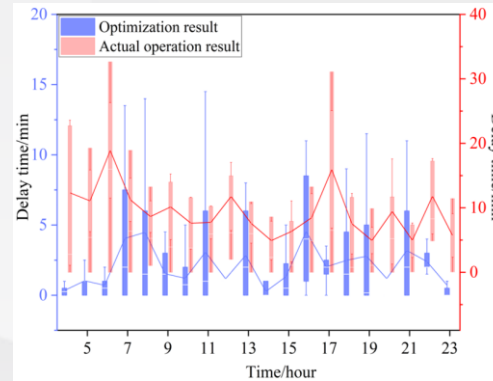
AU	Flights(a/c)	Baselines delay indicator		UDPP-DCB (i) delay indicator			UDPP-DCB(ii) delay indicator		
		Time(min)	Flights(a/c)	Time(min)	Flights(a/c)	Cost reduction(€)	Time(min)	Flights(a/c)	Cost reduction(€)
AU1	33	675	14	995	4	40495	3	1	64042
AU2	130	1903	65	2024	26	118040	24	3	192526
AU3	50	596	16	729	6	41160	13	2	63364
AU4	16	302	7	387	2	18370	2	1	29973
AU5	31	402	9	426	3	27495	8	2	39605
AU6	66	771	30	952	13	39870	11	2	76284
AU7	20	236	7	320	2	16770	3	1	28422
AU8	14	104	3	138	2	1270	2	1	10329
AU9	14	135	3	168	3	1530	5	1	13567
AU10	53	883	31	959	15	55535	22	2	83705

- **UDPP-DCB (i)**: although total system delay was increase, but result shows lower delay costs for each AU.
- **UDPP-DCB (ii)**: further lowers each AU's total delay compared with both UDPP-DCB(i) and the baseline, with greater savings for AUs that include more flights.

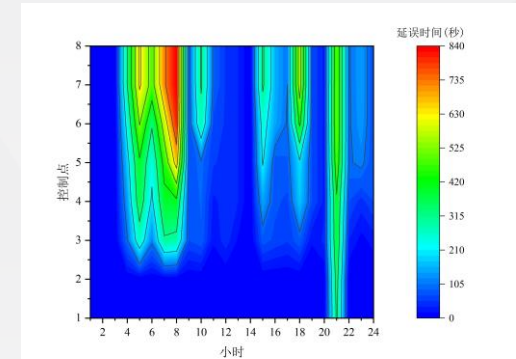
Module I (DCB Optimizer) results



Total delay time



Distribution of delay time



Delay results for control points

E-AMAN VS. Actual Operation

Indicator	Delay(min)	Flights(a/c)	LH(a/c)	LH Delay(min)
E-AMAN	113.83	158	208	27.15
Actual	2783.26	391	\	\

E-AMAN delay VS. Actual Operation (min) ↓ **95.91%**

E-AMAN delay VS. Actual Operation (a/c) ↓ **59.59%**

Delays are concentrated mainly within the three inner circles (50-150 nautical miles).

Conclusions and future work

- ✓ Integrating **UDPP** into network-level DCB expands the decision space and enables AUs to **dynamically reprioritize flights**, resulting in significant reductions in total delay and operational costs.
- ✓ The **E-AMAN** optimization enhances predictability and mitigates arrival congestion through **dynamic sequencing** at terminal entry.
- ✓ The coordinated operation of all four functional modules shows that combining **pre-tactical network management** with **tactical sequencing** delivers overall improvements in operational efficiency, fairness, and environmental performance within the collaborative ATM framework.
- Incorporating **stochastic** demand and weather **uncertainty** into large-scale simulations to enhance robustness;
- Improving **computational efficiency** to enable scalability for multi-airport and cross regional traffic management applications.

Thank you for your attention!!! Questions?

Junqiang Wan

E-mail: jqwan@cauc.edu.cn