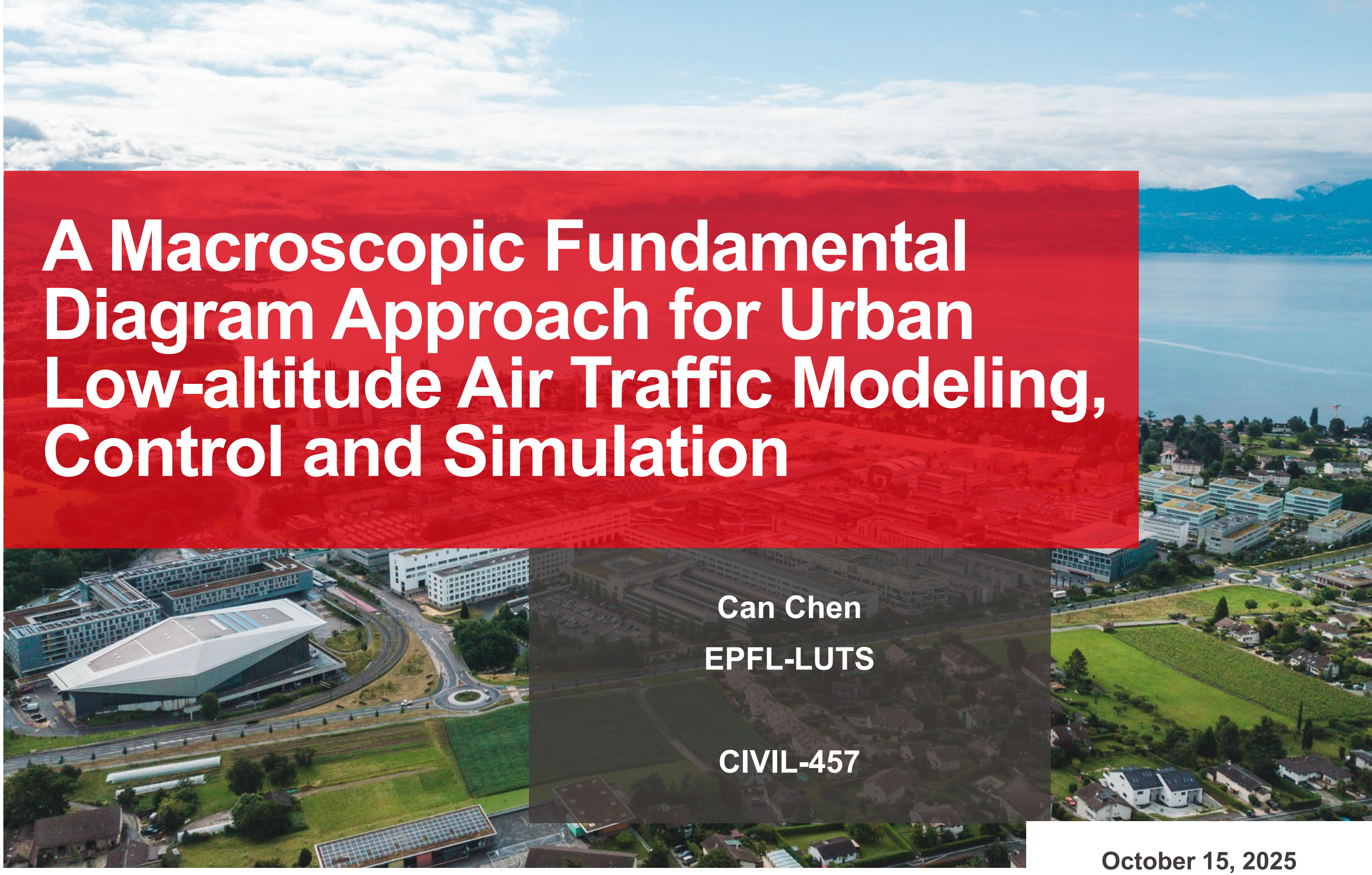


A Macroscopic Fundamental Diagram Approach for Urban Low-altitude Air Traffic Modeling, Control and Simulation

Can Chen
EPFL-LUTS

CIVIL-457

October 15, 2025

Introduction to Urban Air Mobility (UAM)

Urban Air Mobility (UAM) has emerged and received increasing attention for its potential to alleviate roadway traffic congestion by point-to-point air travel.

- ☺ Low-altitude airspace – Underused resource
- ☺ eVTOLs[1] – Safe, clean, and affordable mobility

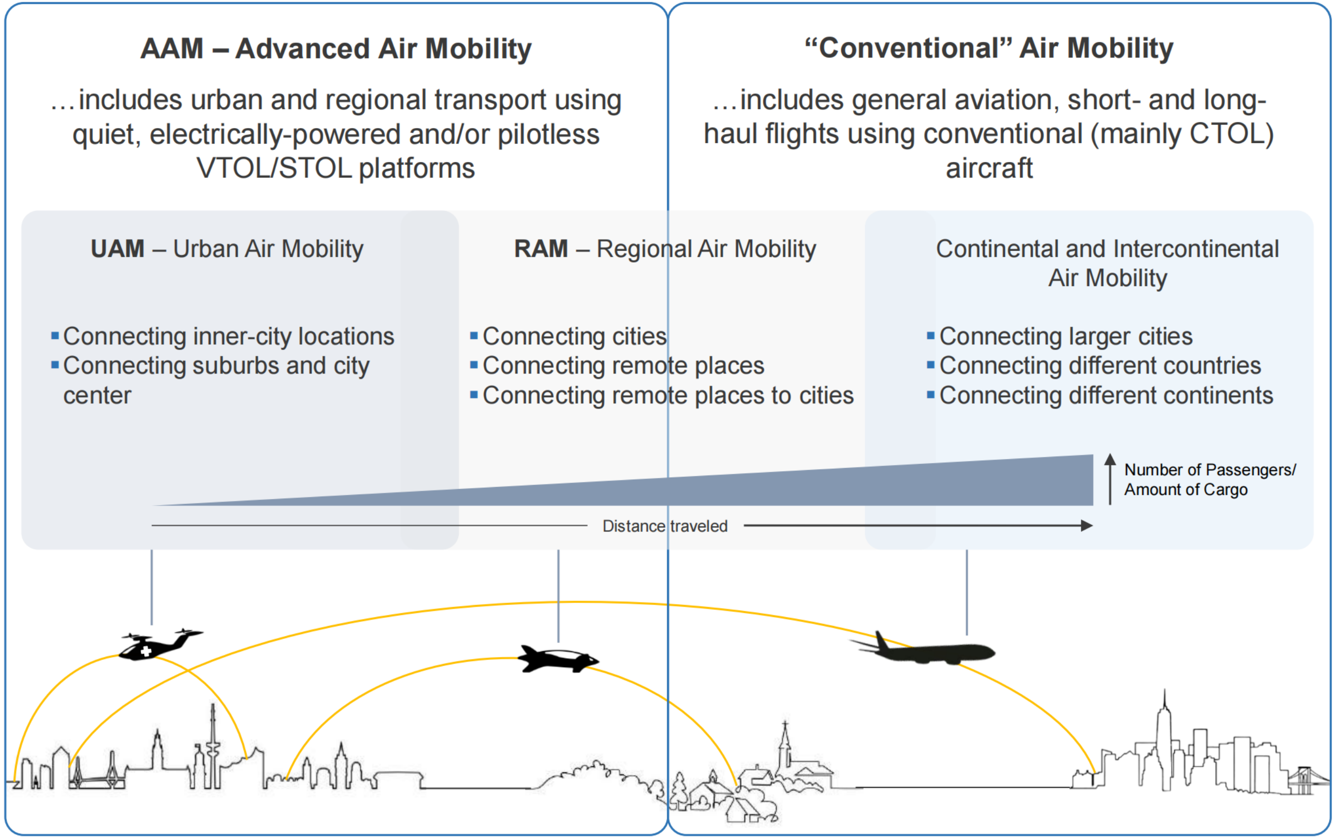
- ☹ Saturated network capacity
- ☹ Recurrent traffic congestion

- ❖ $32 billion market (2035)
- ❖ Large-scale UAM

---

[1] eVTOLs : Electric vertical take-off and landing vehicles

1.1 What is UAM ?



AAM – Advanced Air Mobility

…includes urban and regional transport using quiet, electrically-powered and/or pilotless VTOL/STOL platforms

“Conventional” Air Mobility

…includes general aviation, short- and long-haul flights using conventional (mainly CTOL) aircraft

UAM – Urban Air Mobility

- Connecting inner-city locations
- Connecting suburbs and city center

RAM – Regional Air Mobility

- Connecting cities
- Connecting remote places
- Connecting remote places to cities

Continental and Intercontinental Air Mobility

- Connecting larger cities
- Connecting different countries
- Connecting different continents

Figure 1. The relationship between “air mobility” concepts[1].

- VTOL: vertical take-off and landing (**no runway**)
- STOL: short take-off and landing (**short runway**)
- CTOL: conventional take-off and landing (**long runway**)

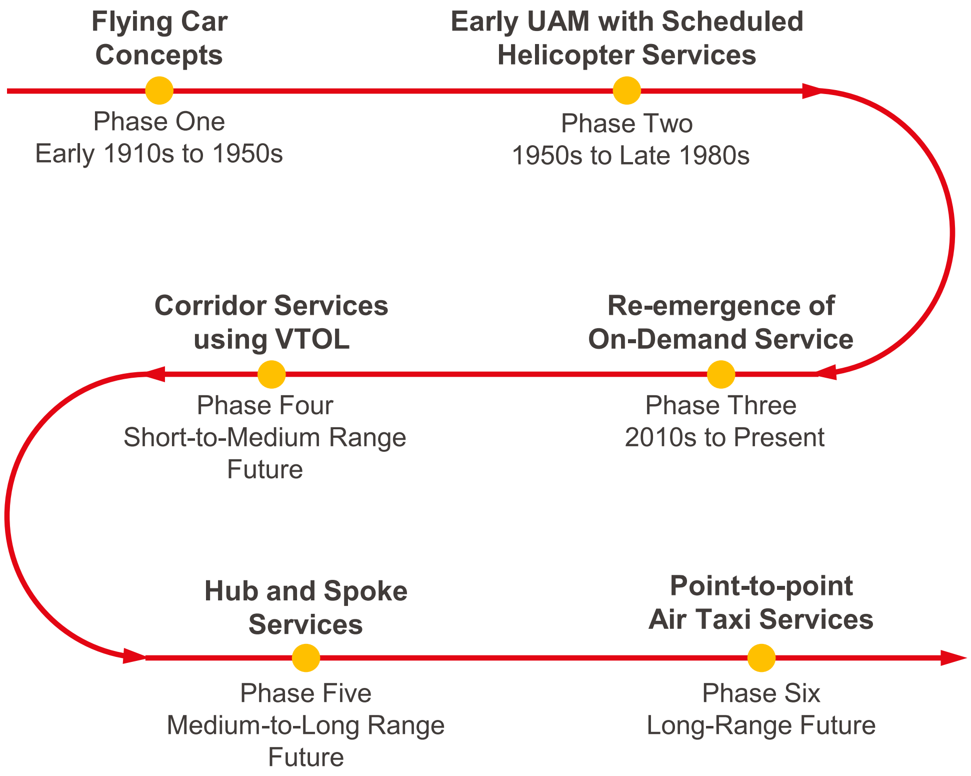
1.2 Why do we need UAM?

- Traffic congestion causes headaches for people in metropolises.
- UAM is expected to provide convenient, cheap, clean, and safe air transportation services.
- UAM is appealing for cities separated by rivers, mountains, or spread across islands.

Rank of 2023	City	Avg. Comm. Time (min)	Compared with 2022
1	Beijing	44.47	↑ 3.91%
2	Shanghai	39.60	↑ 11.06%
3	Nanjing	37.40	↑ 5.95%
4	Tianjin	37.11	↓ 1.10%
5	Dalian	36.22	↑ 3.00%
6	Chengdu	35.88	↓ 0.62%
7	Wuhan	35.86	↑ 1.68%
8	Shenzhen	35.40	↑ 3.65%
9	Shenyang	35.27	↑ 2.21%
10	Guangzhou	35.25	↓ 4.44%

Table 1. Commute time consumption in Chinese cities in 2023[2].

1.3 UAM history[3]



Flying Car Concepts

Phase One
Early 1910s to 1950s

Early UAM with Scheduled Helicopter Services

Phase Two
1950s to Late 1980s

Re-emergence of On-Demand Service

Phase Three
2010s to Present

Corridor Services using VTOL

Phase Four
Short-to-Medium Range Future

Hub and Spoke Services

Phase Five
Medium-to-Long Range Future

Point-to-point Air Taxi Services

Phase Six
Long-Range Future

- **Phase One** – Several inventors develop “flying car” concepts. Over the years, several are built and delivered. However, none achieved commercial viability.
- **Phase Two** – Several companies provide early UAM services using helicopters in major U.S. cities. However, safety and fuel costs create challenges for mainstreaming.
- **Phase Three** – On-demand aviation services re-emerge around the world. These services typically provide on-demand access to helicopters booked through a smartphone app.
- **Phase Four** – Planned “air shuttle services” that take place along specific air routes (e.g., between an airport and downtown) using VTOL aircraft.
- **Phase Five** – Increased infrastructure investments occur to support “air metro services” comprised of multiple flights per day between numerous vertiports in an urban area.
- **Phase Six** – Potential “air taxi services” provide on-demand, decentralized service using numerous vertipads and small vertiports dispersed throughout a region.

1.4 Potential challenges[4,5]

Challenges

Privacy and Community Acceptance

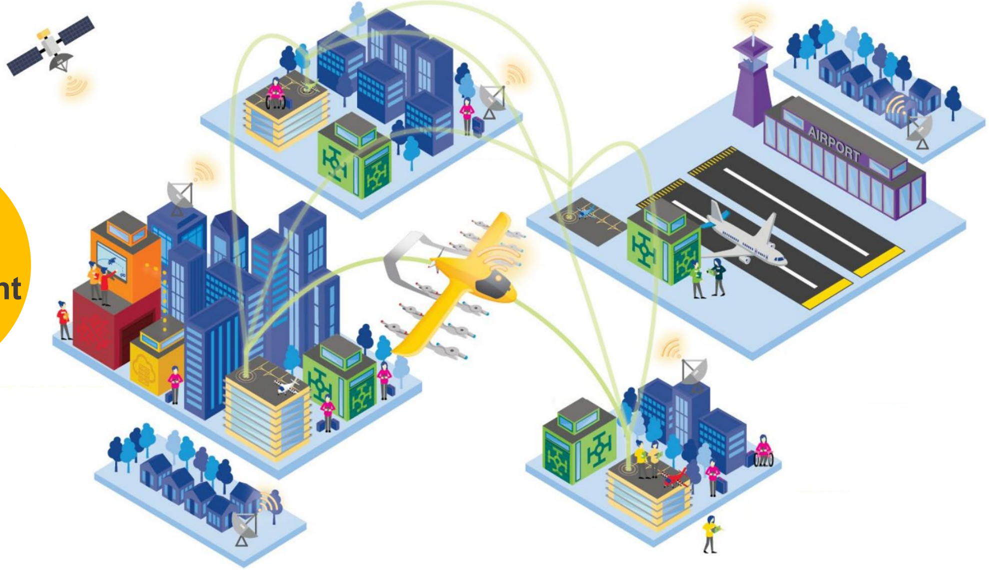
Noise and Environmental Impacts

Safety and Regulatory

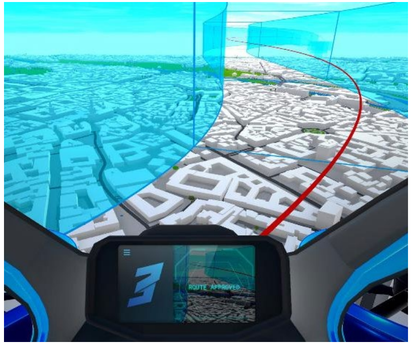
Air Traffic Management

Weather

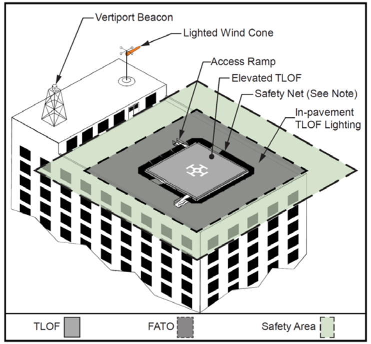
Infrastructure



2 UAM system components



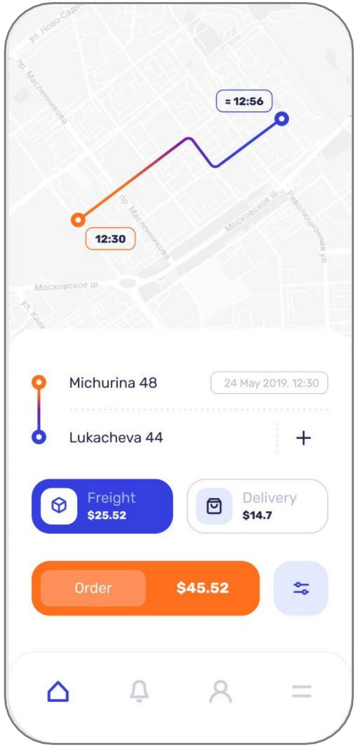
Airspace



Vertiport

Aircraft

Air Traffic Management



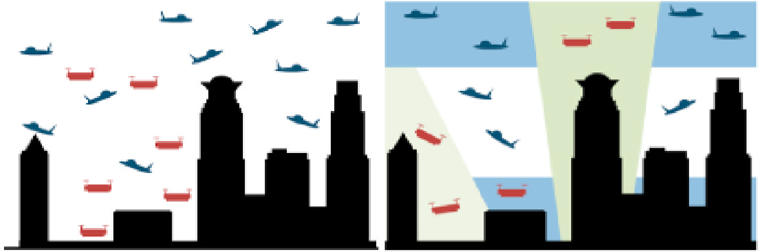
Michurina 48 24 May 2019, 12:30

Lukacheva 44

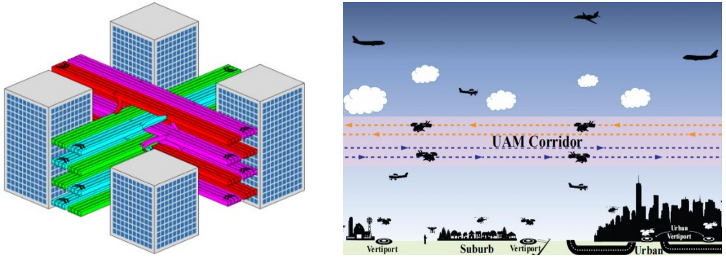
User

2.1 UAM airspace

- Airspace structure design[6]



(a) Full mix (b) Zone



(c) Layer (d) Corridor

Figure 2. The representative airspace structure designs[6].

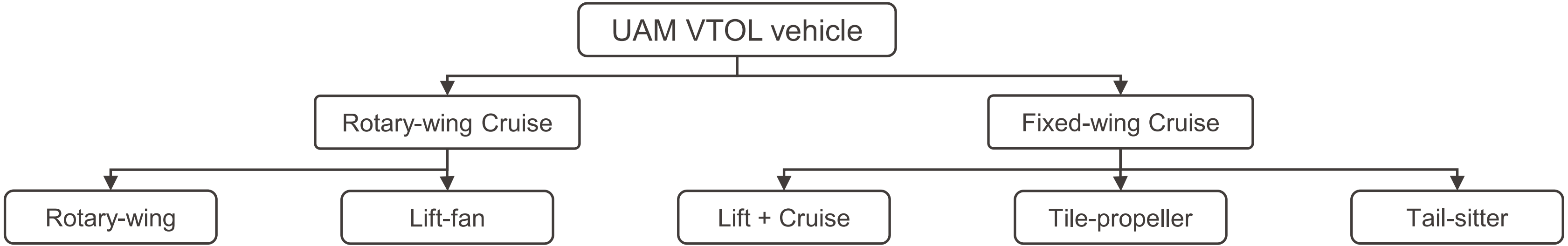
- ✓ **Full mix** (free flight) – Airspace is shared by all aircraft, which have four degrees of freedom (XYZV).
- ✓ **Zones** – Airspace is partitioned into zones for different types of aircraft (e.g., speed, directions, level of autonomy) for separation.
- ✓ **Layers** – Airspace is divided into layers where every altitude band corresponds to a heading range.
- ✓ **Corridor** – Corridors connect two UAM vertiports to support point-to-point operations.

	Full mix	Zone	Layer	Corridor
Safety	2	3	1	4
Capacity	1	3	2	4
Efficiency	1	3	2	4
Noise	2	4	1	3

Table 2. Comparison of airspace structures by ranked characteristics. 1-best, 4-worst

2.2 UAM aircraft

- Aircraft classification[7]



UAM VTOL vehicle
- Rotary-wing Cruise
  - Rotary-wing
  - Lift-fan
- Fixed-wing Cruise
  - Lift + Cruise
  - Tile-propeller
  - Tail-sitter

Volocopter 2X

Neva AirQuadOne

Autoflight (峰飞) v2000cg

Joby S2 (VTOL/Cruise)

Opener Blackfly

- ✓ **Rotary-wing** aircraft have excellent hover and VTOL performance but limited cruising speed.
- ✓ **Lift-Fan** concepts offer compact dimensions but produce loud noise.
- ✓ **Lift + Cruise** aircraft have two separate power trains for VTOL and cruise.
- ✓ **Tilting-propeller** aircraft have a single propulsion system and use tilting mechanisms for VTOL and cruise.
- ✓ **Tail-sitter** aircraft stand upright at takeoff and gradually tilt toward horizontal flight.

2.3 UAM vertiport

- Vertiport definition and types[9]
  - ✓ Vertiports will be fixed locations where UAM aircraft will take off, land, load and unload passengers, and receive services (e.g., energy replenishment).

(a) Vertistop (b) Vertiport (c) Vertihub

Figure 3. Current types of vertiport.

	Number of landing sites	Charging infrastructure	Vertiport management support	Gate infrastructure	Aircraft servicing	Base maintenance	Hangar space
Vertistop	1	√	√		√		
Vertiport	2+	√	√	√	√		
Vertihub	2+	√	√	√	√	√	√

Table 3. Vertiports Key Features.

2.3 UAM vertiport

2.3 UAM vertiport

- ➢ Vertiport management (VM)

- ✓ **Allocating resources** – oversee the allocation of landing sites, taxiways, gates, hangars, ramps, cargo and passenger processing, loading and unloading facilities.
- ✓ **Controlling surface traffic** – determine taxiway, gate, or FATO availability; manage aircraft movement; and provide surface movement authorizations.
- ✓ **Replenishing energy and cooling batteries** – charge aircraft batteries and perform associated cooling procedures.
- ✓ **Verifying aircraft are ready for flight** – complete all of the relevant preflight checks, e.g., battery charge levels and aircraft system security.
- ✓ **Assisting with passenger embarking and disembarking**

2.3 UAM vertiport

- Vertiport network

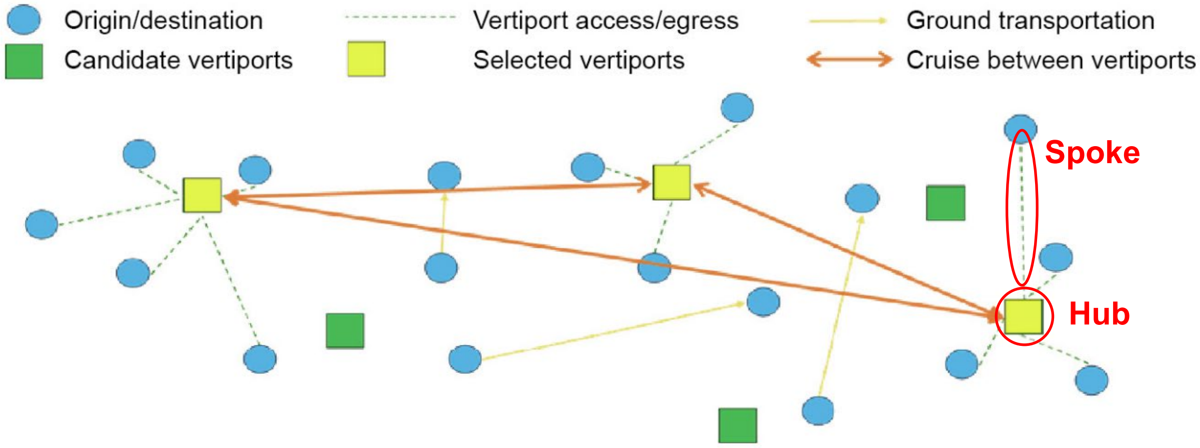


Figure 3. Vertiport network is modeled as a p-median hub-and-spoke network.

Candidate Locations Identification

- ☐ Lidar data (3D map), Land use data, Regulation requirement
- ☐ GIS tool

Demand pattern recognition

- ☐ Origin and Destination (OD), Travel time, Value of time (cost)

Network optimization

- ☐ Traffic assignment model (minimize total travel cost)
- ☐ Integer programming solution

2.4 Air traffic management

- European version (Urban Space, U-space)[12]

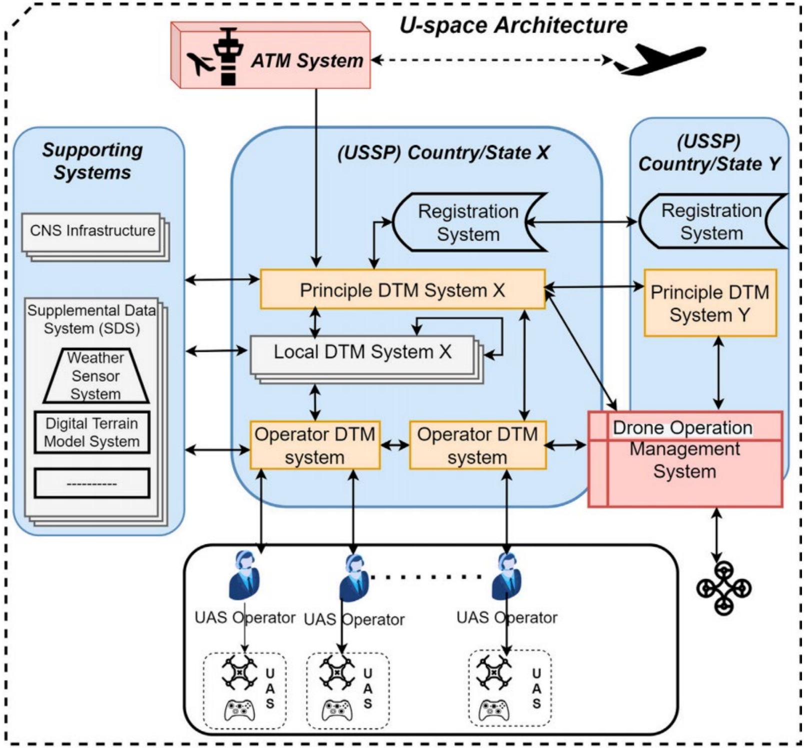


Figure 4. U-space architecture.

- ✓ **CNS** – Communications, Navigation, Surveillance
- ✓ **SDS** (Supplemental Data system) – provides information about meteorological conditions, land environment, cellular coverage, navigation, and terrain.
- ✓ **USSP** (U-space Service Providers) – similar to UTM's USS that provides access services to UAV Operators in uncontrolled low airspace.

	Difference between architectures
UTM	• FAA maintains regulatory, authority, and traffic operation for airspace. • The central FAA interacts with UTM for information/data exchange and has access to data at any time (via FIMS).
U-space	• Civil Aviation Authority and local regulatory authorities evaluate and then authorize or deny drone operations. • There is no specific centralized or federated architecture with U-space as a whole, but it depends on service by service.

2.4 Air traffic management

- European version (Urban Space, U-space)

- ☐ **U1** (Foundation Services) – Allow manned and unmanned aircraft operations in low traffic density locations, involving e-registration, e-identification, and geo-awareness.
- ☐ **U2** (Initial Services) – safe and secure management for BVLOS operations, e.g., geofencing, crisis management, tactical deconfliction, UAV information management.
- ☐ **U3** (Advanced Services) – improving applications for dense and complex environment, e.g., automatic detection and avoidance, dynamic geofencing and capacity management.
- ☐ **U4** (Full Services) – incorporate U-space with ATM completely, involving high degree of computerization, networking, and automation.

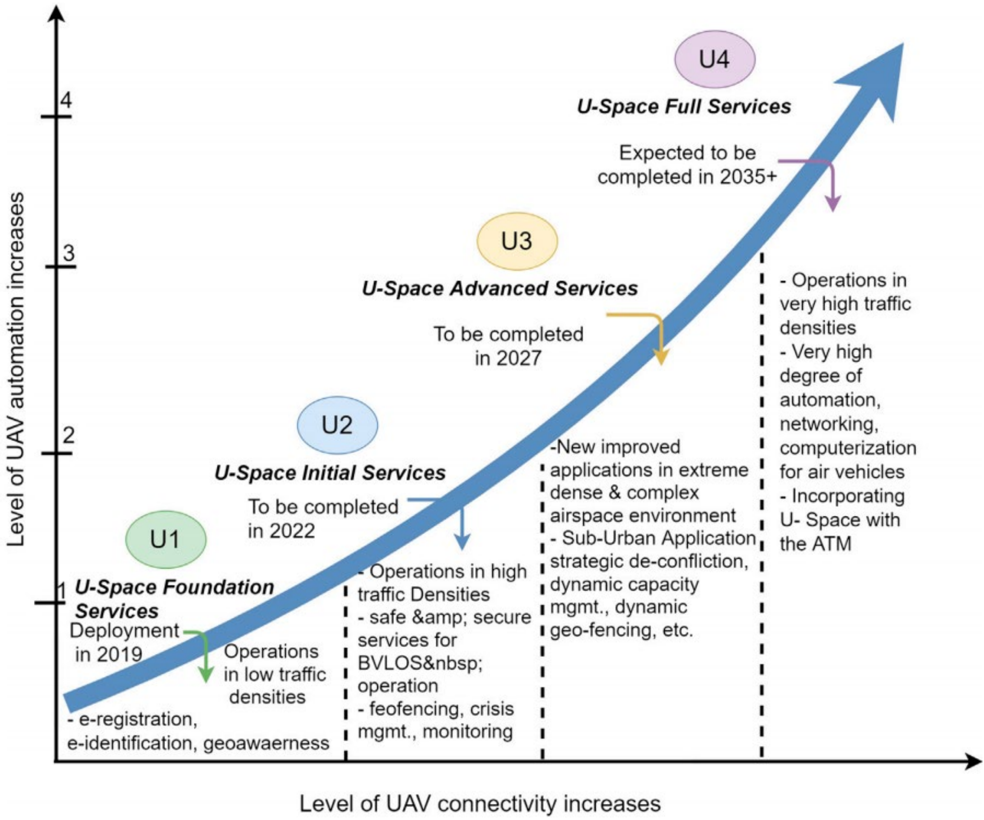


Figure 5. U-space automation levels.

2.5 UAM user

- UAM passenger operations

Figure 6. Passenger-Centric Autonomous UAM Journey.

- ☐ **Booking** – booking flights through online applications; rescheduling or cancelling flights.
- ☐ **Check In** – verify booking and conduct security and weight checks.
- ☐ **Boarding** – assist passengers in loading their luggage and taking their seats.
- ☐ **Disembark** – assist passengers in disembarking and retrieving their luggage.
- ☐ **Exit** – If booking multimodal services, passengers can transfer to ground transport.

2.5 UAM market[13]

- UAM is likely to be a commercially viable market with both parcel delivery and air metro use cases.

Last-mile parcel delivery

- Projecting a potentially profitable market by 2030
- A significant ramp-up of UAS delivery in the years prior to profitability is likely as e-commerce players "lean in" to the market

Air metro

- Could potentially be profitable by 2030 assuming that regulations are in place to accommodate this market
- In anticipation of profitability by 2030, larger-scale "entry into service" may occur in prior years
- Piloted air metro services may be a stepping stone to large-scale autonomous operations

Air taxi (limited)

- High investment costs make a widespread air taxi market with ubiquitous vertiports unlikely in 2030
- There may be concentrated areas of high net worth individuals and businesses served by an air taxi solution (e.g., Manhattan to suburbs)

UAM simulation and control

3 UAM simulation framework

- UAM traffic simulation

Individual aircraft simulation

- × Single aircraft simulation
- × Fixed aircraft routes and schemes
- × Unable to input traffic flow

UAM traffic simulation

- ✓ Multi-agent simulation
- ✓ Flexible aircraft flights
- ✓ Traffic network analysis and application

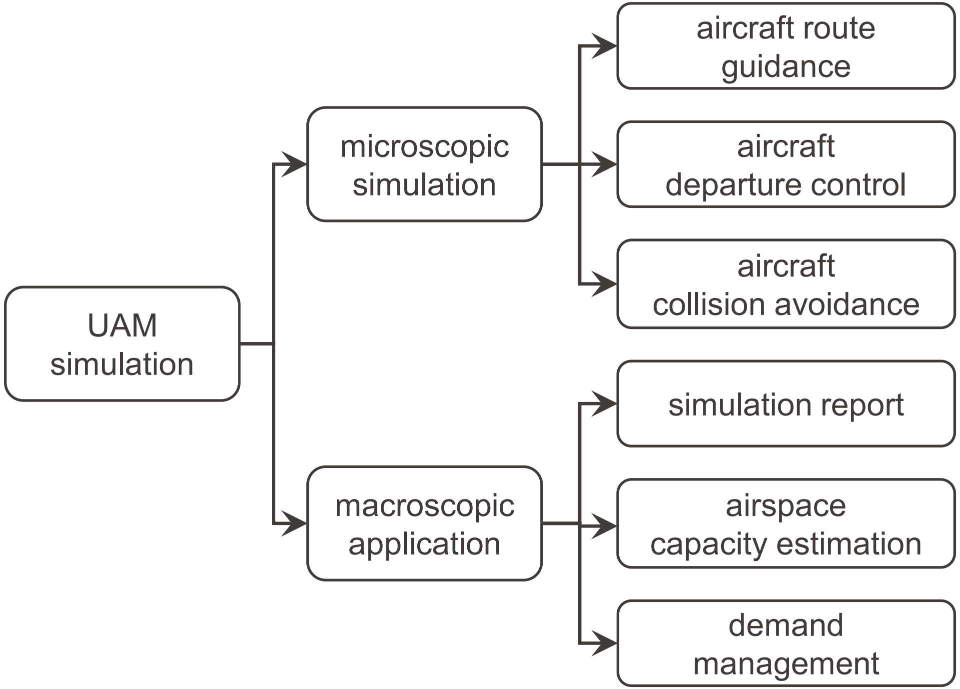


Figure 7. The framework of the UAM simulation platform.

3 UAM simulation framework

- Airspace capacity estimation

☞ *System characteristics* (Macroscopic)

Generalized traffic flow definitions

☞ *Individual behaviors* (Microscopic)

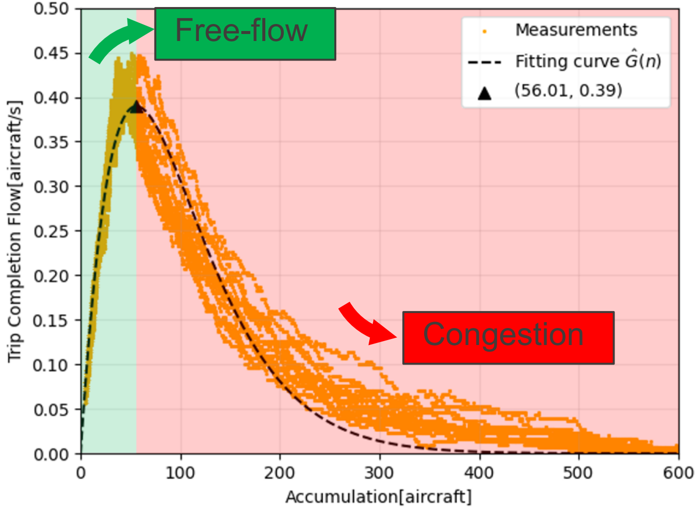


Figure 8. The airspace Macroscopic Fundamental Diagram (MFD) reveals the capacity of a given airspace region.

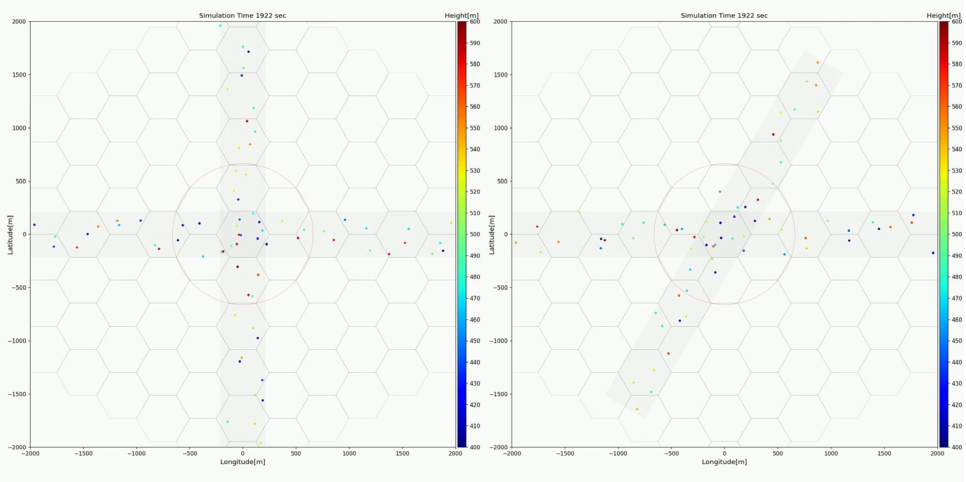


Figure 9. Simulations of airspace capacity (left: orthogonal air corridors; right: oblique air corridors)

3.1 Scenario setting

- Multi-layer regional airspace network
  - ☐ The low-altitude airspace is partitioned into multiple layers along the altitude (z) axis
  - ☐ Each layer is further subdivided into regions based on longitude (x) and latitude (y)
  - ☐ Within each region, the full-mix structure is employed, allowing aircraft to freely select their flight directions.

- Assumptions on control
  - ☐ Deterministic
  - ☐ Observability
  - ☐ Controllability

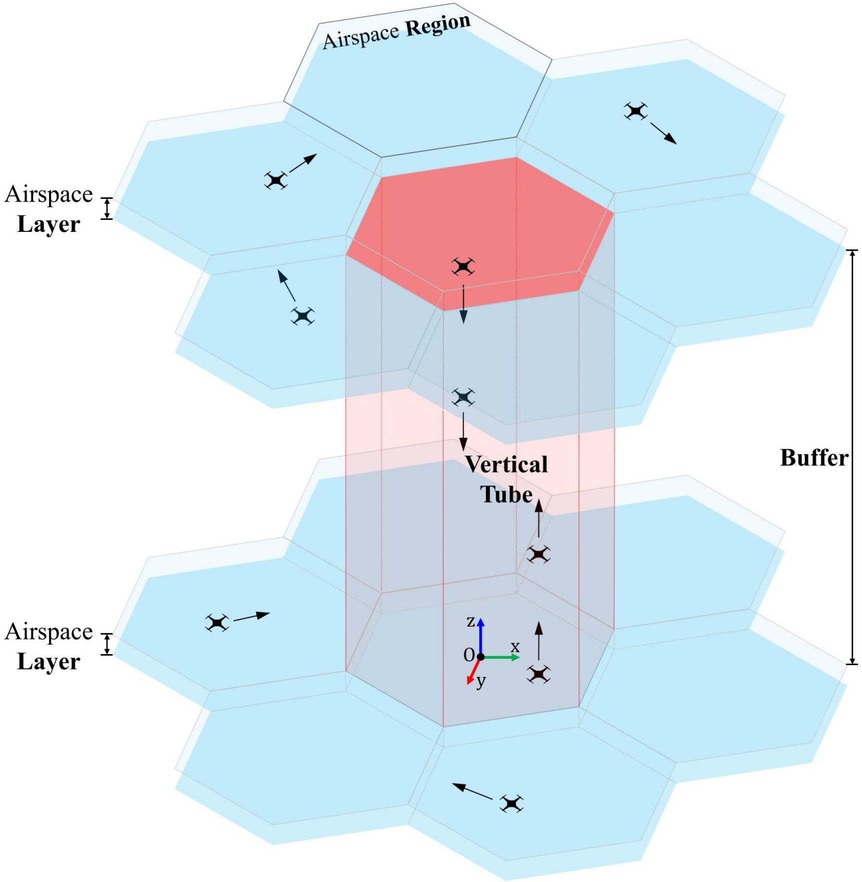
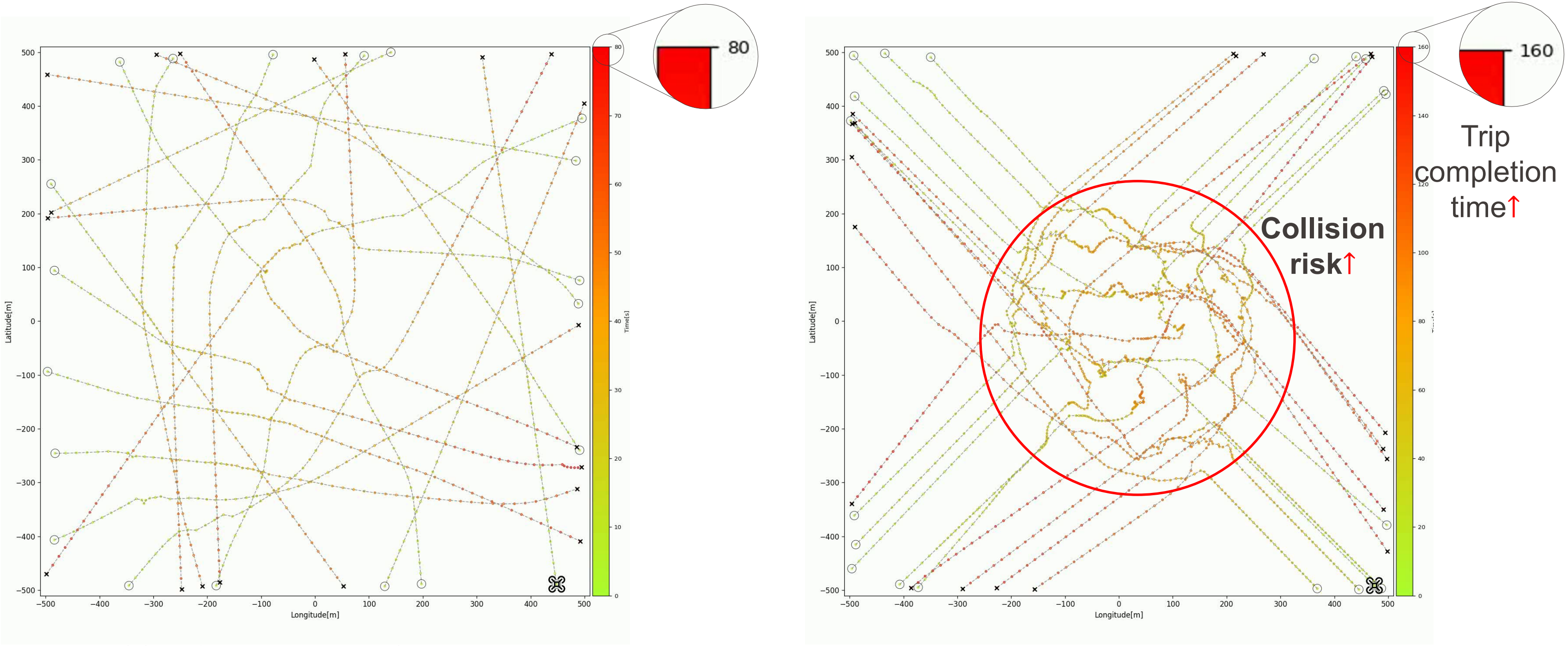


Figure 10. Multi-layer regional airspace network design for large-scale UAM operations

An integrated collision avoidance-path planning framework for UAM microscopic aircraft control

3.2 Microscopic control framework

- Motivation: alleviate local congestion



Trip completion time↑

Collision risk↑

(a) Uniformly distributed OD pattern

(b) Directionally distributed OD pattern

Figure 11. Simulation of collision-free aircraft trajectories in the 2D space with a deployment scale of 20 aircraft

3.2 Microscopic control framework

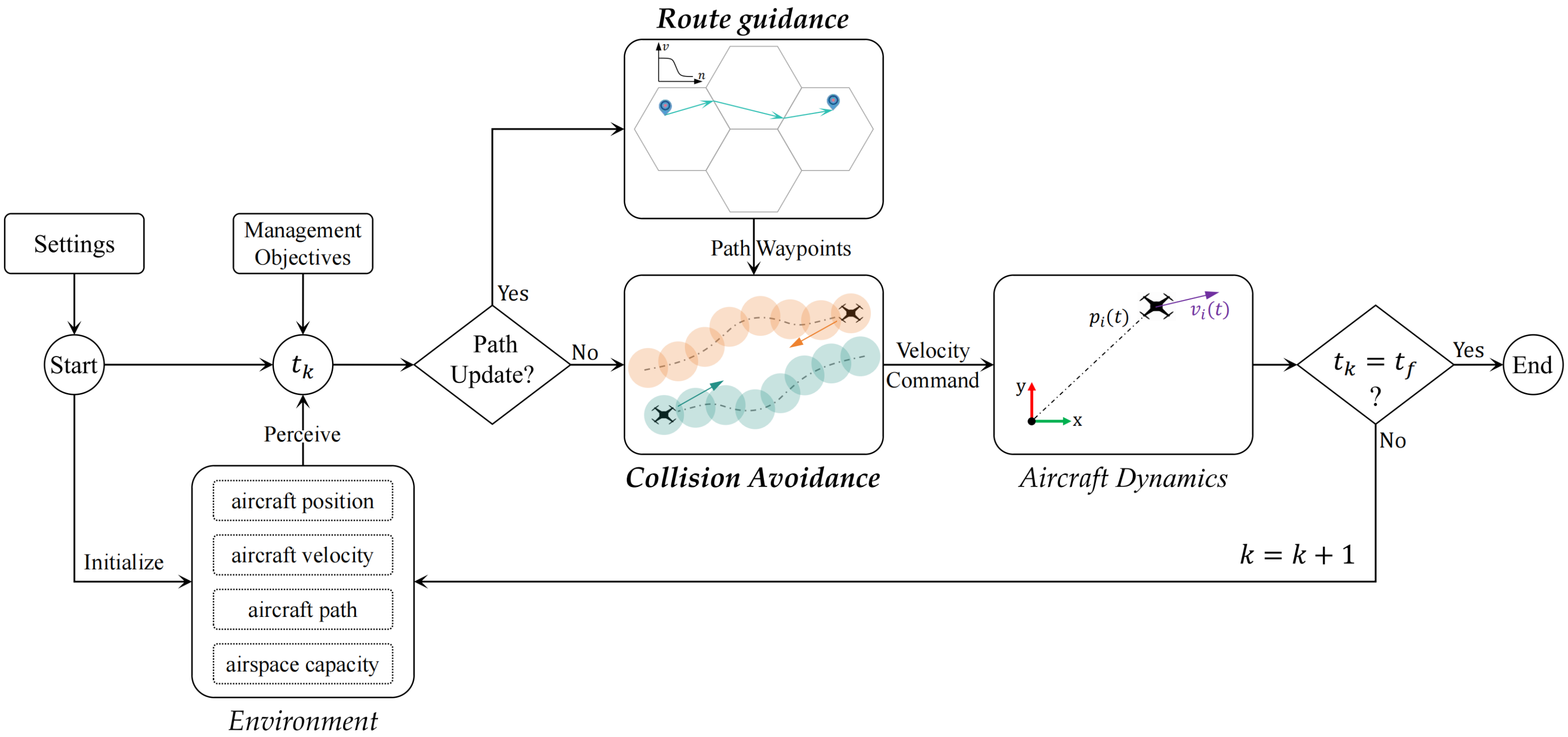


Figure 12. Air traffic management framework integrating route guidance and collision avoidance

3.3 Path planning

- Problem formulation

Combination optimization

$$\boldsymbol{P}^* = \arg\min_{\boxed{\boldsymbol{P}}\in\boxed{\boldsymbol{\Omega}}} \mathcal{J}(\boldsymbol{P}) = \sum_{i=1}^{N} \boxed{\mathcal{C}_i(\boldsymbol{P})}$$

Travel cost of path P_i chosen by aircraft A_i

Joint path decision of N aircraft

Cartesian product of all candidate path

$$\boldsymbol{P} \triangleq (P_1, P_2, \ldots, \boxed{P_i}, \ldots, P_N)$$

Path of aircraft A_i

$$\boldsymbol{\Omega} \triangleq \Omega_1 \times \Omega_2 \times \ldots \boxed{\Omega_i} \times \ldots \times \Omega_N$$

Candidate path set of aircraft A_i

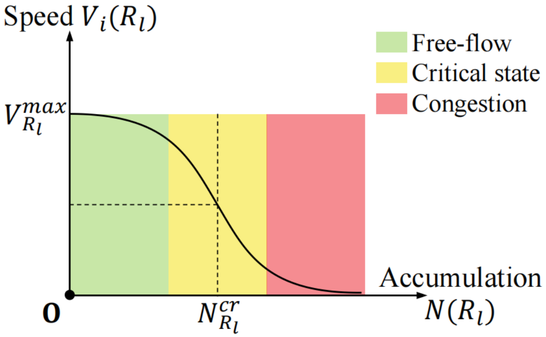
3.3 Path planning

- Path cost

$$P_i \triangleq \langle \underset{\text{origin}}{\boxed{\boldsymbol{p}^w_{i,o}}} \overset{\Delta t_1}{,} \boldsymbol{p}^w_{i,1} \overset{\Delta t_2}{,} \boldsymbol{p}^w_{i,2} \overset{\Delta t_*}{,} \cdots , \boldsymbol{p}^w_{i,m_i} , \underset{\text{destination}}{\boxed{\boldsymbol{p}^w_{i,d}}} \rangle$$

Route choice can be influenced by other aircraft

- Velocity adjustment



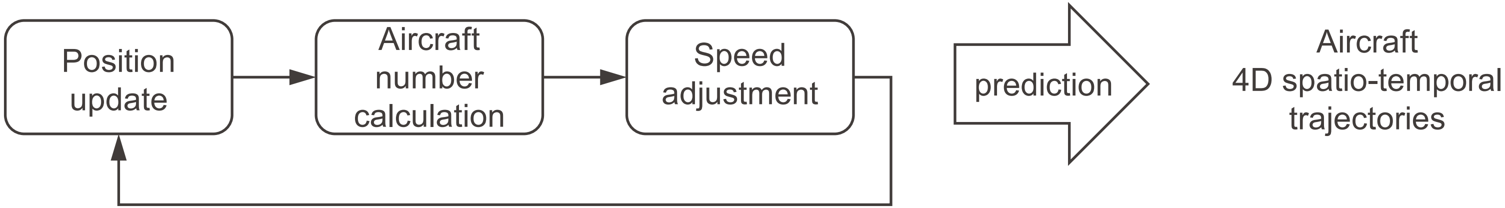
$$\boxed{V_i(R_l)} = \frac{\exp\left(N^{cr}_{R_l} - N_{R_l}\right)}{1 + \exp\left(N^{cr}_{R_l} - \boxed{N_{R_l}}\right)} V^{max}_{R_l}$$

Velocity of aircraft A_i in region R_l

Number of aircraft in region R_l

3.3 Path planning

- Path cost calculation



- Challenge

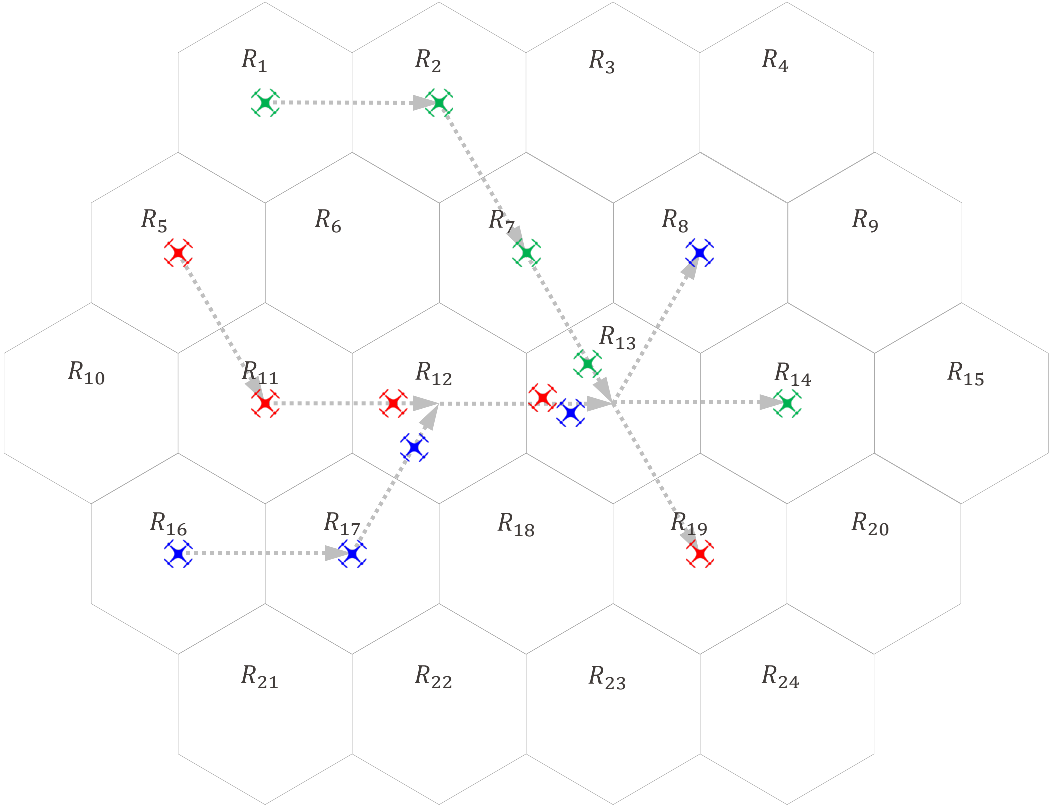
$$\boldsymbol{P}^* = \arg\min_{\boxed{\boldsymbol{P}\in\boldsymbol{\Omega}}} \mathcal{J}(\boldsymbol{P}) = \sum_{i=1}^{N} \boxed{\mathcal{C}_i(\boldsymbol{P})}$$

Curse of dimensionality

Complex calculation of path cost

3.3 Path planning

- Estimating the aircraft path cost



	ΔT_1		ΔT_2		ΔT_3		ΔT_4		ΔT_5
$\boldsymbol{P_1}$:	$\boldsymbol{R_5}$	$\rightarrow$	$\boldsymbol{R_{11}}$	$\rightarrow$	$\boldsymbol{R_{12}}$	$\rightarrow$	$\boldsymbol{R_{13}}$	$\rightarrow$	$\boldsymbol{R_{19}}$
$\boldsymbol{P_2}$:	$\boldsymbol{R_{16}}$	$\rightarrow$	$\boldsymbol{R_{17}}$	$\rightarrow$	$\boldsymbol{R_{12}}$	$\rightarrow$	$\boldsymbol{R_{13}}$	$\rightarrow$	$\boldsymbol{R_8}$
$\boldsymbol{P_3}$:	$\boldsymbol{R_1}$	$\rightarrow$	$\boldsymbol{R_2}$	$\rightarrow$	$\boldsymbol{R_7}$	$\rightarrow$	$\boldsymbol{R_{13}}$	$\rightarrow$	$\boldsymbol{R_{14}}$

$$\Delta T_1 = \frac{L(R_5)}{V(R_5)|_{N(R_5)=1}} + \frac{L(R_{16})}{V(R_{16})|_{N(R_{16})=1}} + \frac{L(R_1)}{V(R_1)|_{N(R_1)=1}}$$

$$\Delta T_2 = \frac{L(R_{11})}{V(R_{11})|_{N(R_{11})=1}} + \frac{L(R_{17})}{V(R_{17})|_{N(R_{17})=1}} + \frac{L(R_2)}{V(R_2)|_{N(R_2)=1}}$$

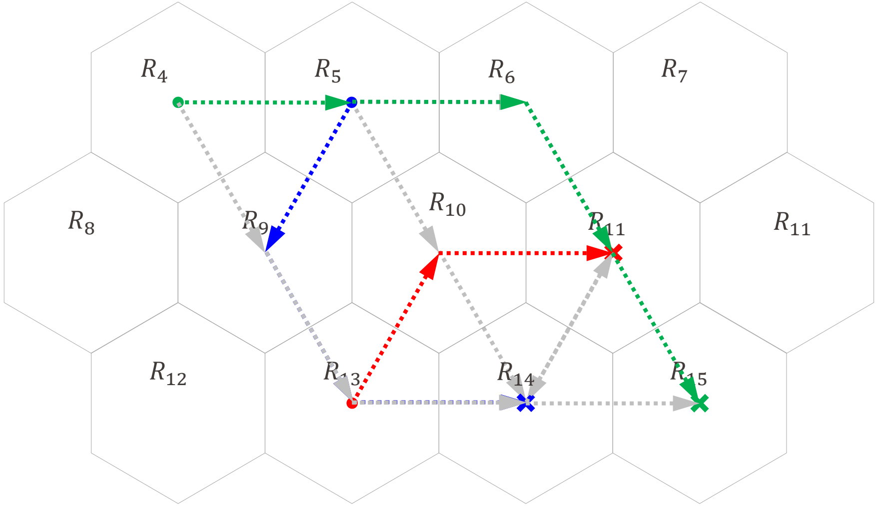
$$\Delta T_3 = \frac{L(R_{12})}{V(R_{12})|_{N(R_{12})=2}} + \frac{L(R_{12})}{V(R_{12})|_{N(R_{12})=2}} + \frac{L(R_7)}{V(R_7)|_{N(R_7)=1}}$$

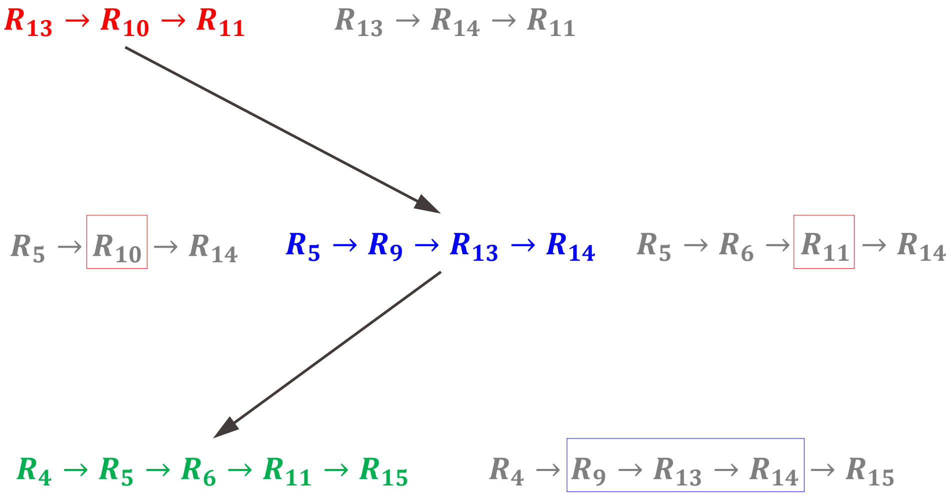
$$\Delta T_4 = \frac{L(R_{13})}{V(R_{13})|_{N(R_{13})=3}} + \frac{L(R_{13})}{V(R_{13})|_{N(R_{13})=3}} + \frac{L(R_{13})}{V(R_{13})|_{N(R_{13})=3}}$$

$$\Delta T_5 = \frac{L(R_{19})}{V(R_{19})|_{N(R_{19})=1}} + \frac{L(R_3)}{V(R_3)|_{N(R_3)=1}} + \frac{L(R_{14})}{V(R_{14})|_{N(R_{14})=1}}$$

3.3 Path planning

- Approximate optimal path search





$R_{13} \rightarrow R_{10} \rightarrow R_{11}$ $\quad$ $R_{13} \rightarrow R_{14} \rightarrow R_{11}$

$R_5 \rightarrow \boxed{R_{10}} \rightarrow R_{14}$ $\quad$ $R_5 \rightarrow R_9 \rightarrow R_{13} \rightarrow R_{14}$ $\quad$ $R_5 \rightarrow R_6 \rightarrow \boxed{R_{11}} \rightarrow R_{14}$

$R_4 \rightarrow R_5 \rightarrow R_6 \rightarrow R_{11} \rightarrow R_{15}$ $\quad$ $R_4 \rightarrow \boxed{R_9 \rightarrow R_{13} \rightarrow R_{14}} \rightarrow R_{15}$

$$\prod_{i=1}^{N} ||\Omega_i|| \xrightarrow{\text{Search space}} \sum_{i=1}^{N} ||\Omega_i||$$

3.4 Collision avoidance

- Velocity obstacle method

Discrete-time dynamics

$$\boldsymbol{p}_i(t_k) = \boldsymbol{p}_i(t_{k-1}) + \boldsymbol{v}_i(t_{k-1})\Delta t$$

$$\boldsymbol{v}_i(t_k) = \boxed{\boldsymbol{v}_i^c(t_k)}$$

Quadratic programming

$$\boldsymbol{v}_i^c = \underset{\boldsymbol{v}\in \boxed{ORCA^{\tau}_{A_i}}}{\arg\min} ||\boldsymbol{v} - \boxed{\boldsymbol{v}_i^p}||$$

Desired speed

Current position

Current targeted position

$$\boldsymbol{v}_i^p = \frac{\boxed{\boldsymbol{p}_i} - \boxed{\boldsymbol{p}_i^w}}{||\boldsymbol{p}_i - \boldsymbol{p}_i^w||} v_i^{max}$$

Safe speed set of aircraft A_i

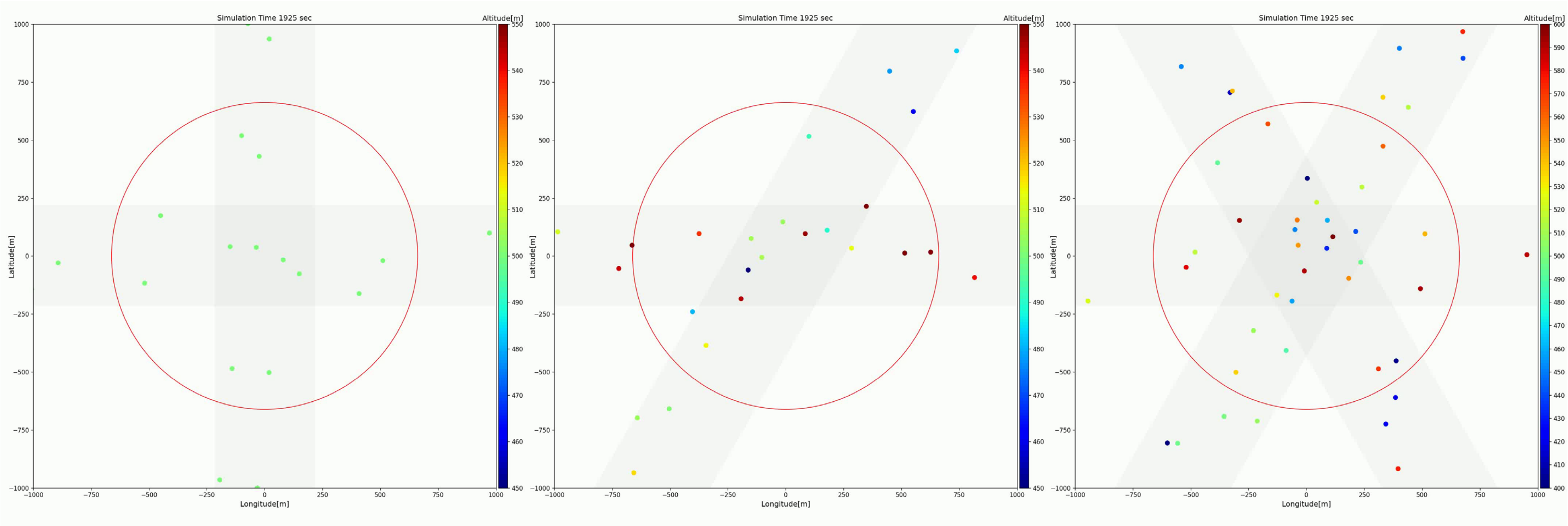
$$ORCA^{\tau}_{A_i} = \bigcap_{A_j\in\mathcal{N}_i} \boxed{ORCA^{\tau}_{A_i|A_j}}$$

Velocity obstacle model[13]

the set of safe velocities for aircraft A_i induced by A_j

3.5 Microscopic simulations

- ➢ Scenarios

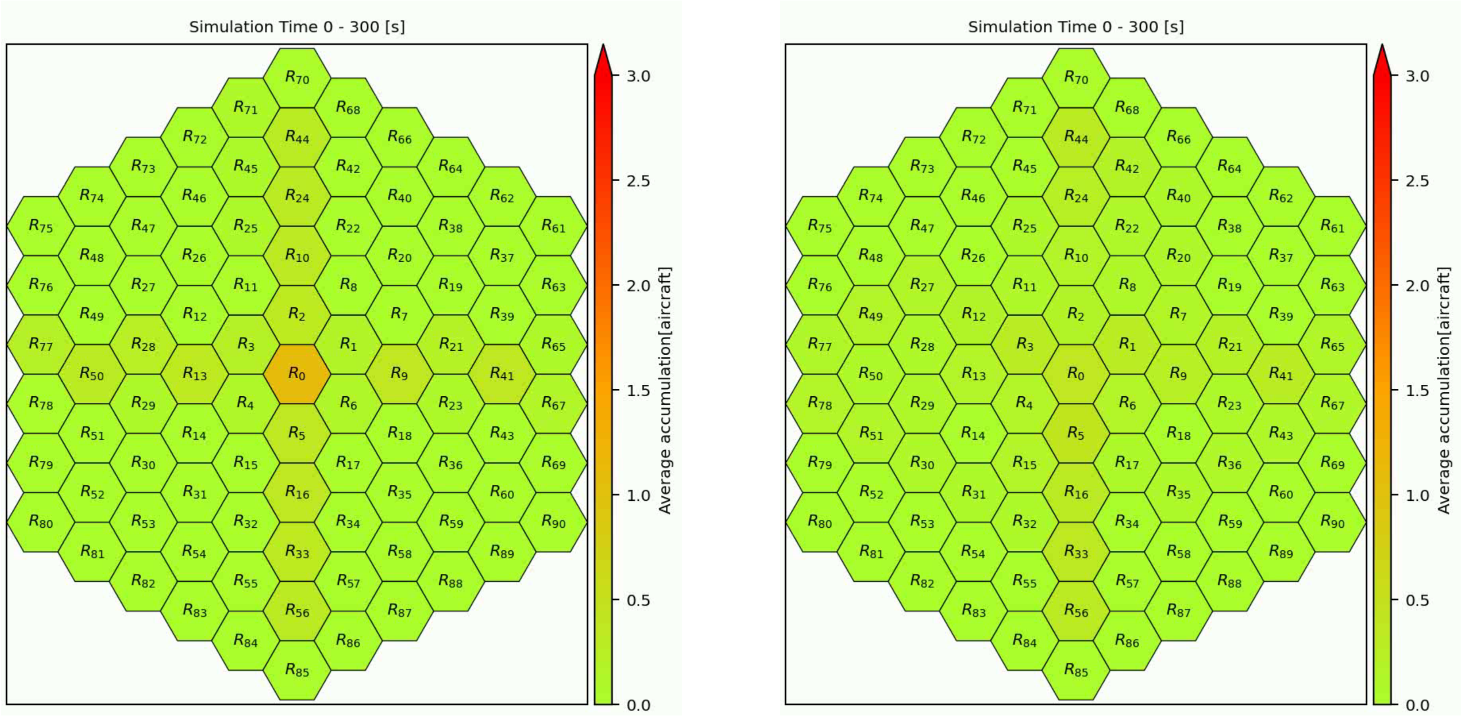


(a) The "+" type scenario (z = 500 m) (b) The "#" type scenario (z ∈ [450, 550] m) (c) "∗" type scenario (z ∈ [400, 600] m)

Figure 12. Testing scenarios: (a) intersection of two orthogonal corridors; (b) intersection of two oblique corridors; (c) intersection of three corridors.

3.5 Microscopic simulations

- ➢ Results (2D scenario)



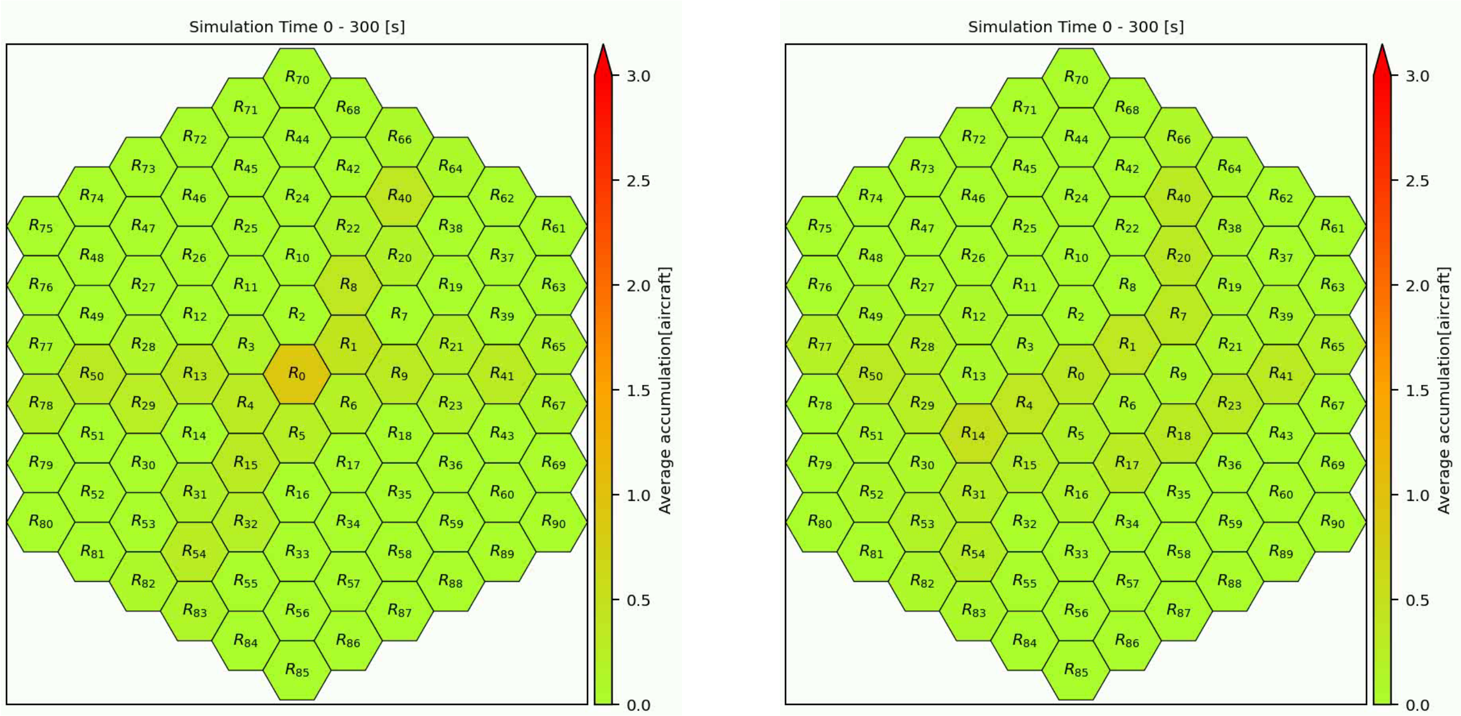
(a) baseline

(b) proposed

Figure 13. The "+" type scenario (z = 500 m)

3.5 Microscopic simulations

- Results (2D scenario)

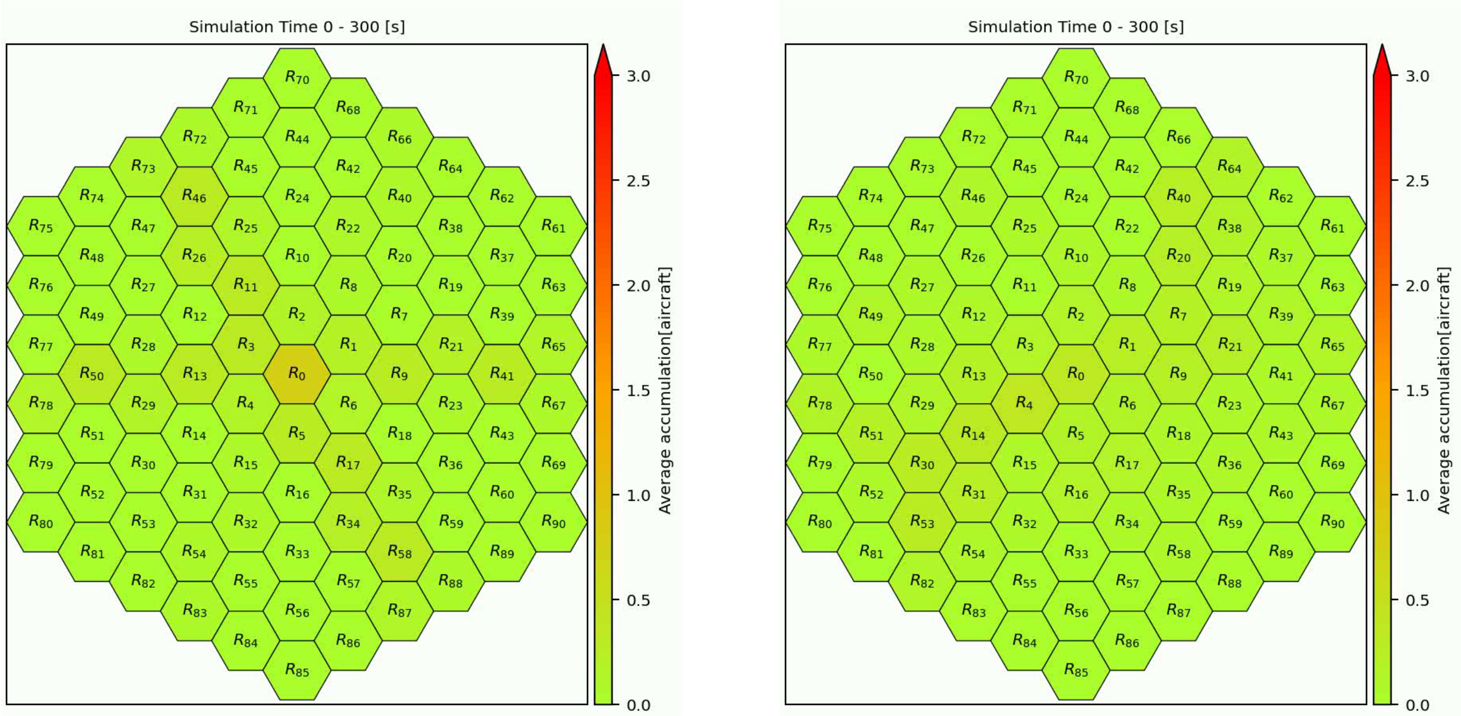


(a) baseline (b) proposed

Figure 14. The “#” type scenario (z ∈ [450, 550] m)

3.5 Microscopic simulations

- Results (2D scenario)



(a) baseline

(b) proposed

Figure 15. The “∗” type scenario (z ∈ [400, 600] m)

Urban low-altitude air transport management:
Bridging dynamic traffic control and static network equilibrium

3.6 Macroscopic urban air traffic flow characteristics

- The 3D flow, speed, and density

Travel distance

Travel time

$$Q = \frac{\sum_{i\in A} \boxed{d_i}}{\boxed{|A|} \cdot |T|}, \quad K = \frac{\sum_{i\in A} \boxed{\tau_i}}{|A| \cdot \boxed{|T|}}, \quad V = \frac{Q}{K} = \frac{\sum_{i\in A} d_i}{\sum_{i\in A} \tau_i}$$

Observed Airspace

Observed Time horizon

$$A = \left\{ (x, y, z) \middle| x \in [x_s, x_e], y \in [y_s, y_e], z \in [z_s, z_e] \right\}$$

$$T = [t_s, t_e]$$

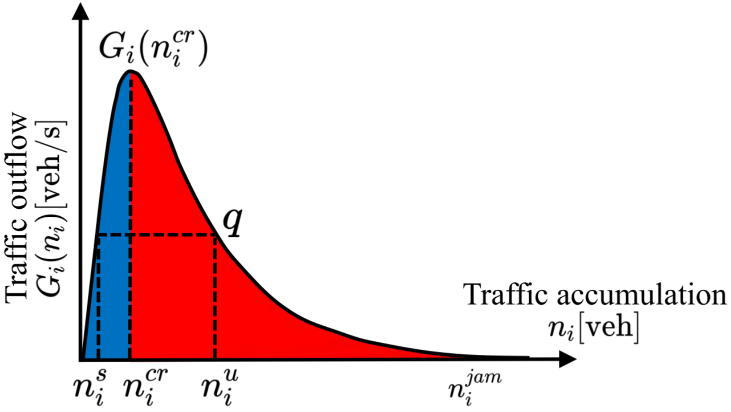
3.7 MFD calibration

- MFD function

$$G(n) = \boxed{\alpha} \cdot n \cdot \exp\left(-\frac{1}{\boxed{\beta}} \left(\frac{n}{\boxed{n^{cr}}} \right)^{\beta} \right), \quad 0 \le n \le n^{jam}$$

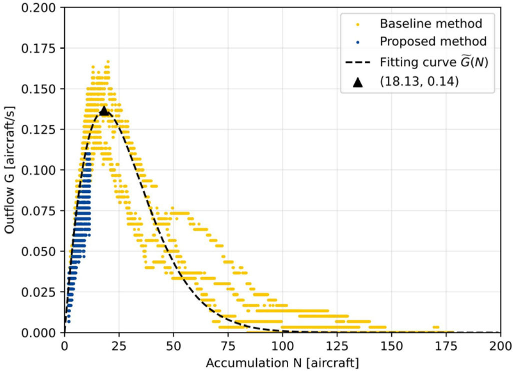
- Least-square method

$$\gamma^{*} = \arg_{\gamma} \sum_{(\tilde{n},\tilde{G}) \in \Phi} \left|\left| \overset{\text{Model}}{\boxed{G(\tilde{n})}} - \underset{\text{Measurement}}{\boxed{\tilde{G}}} \right|\right|$$

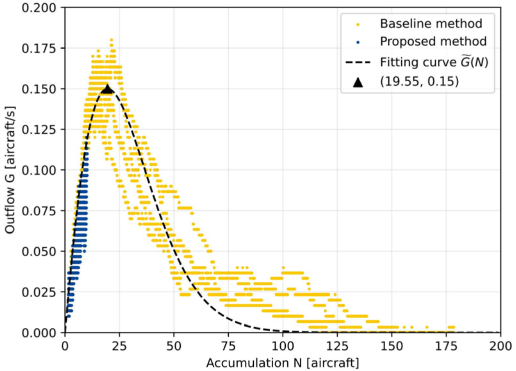


3.7 MFD calibration

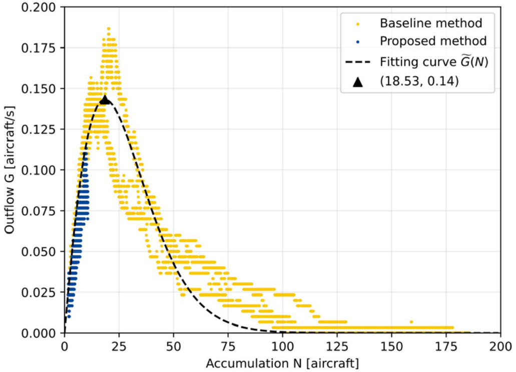
- ➢ 2D scenario



(a) Flow-Accumulation ("+" type scenario)



(b) Flow-Accumulation ("#" type scenario)



(c) Flow-Accumulation ("*" type scenario)

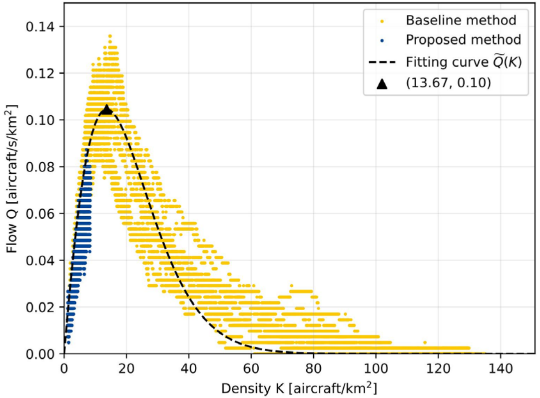


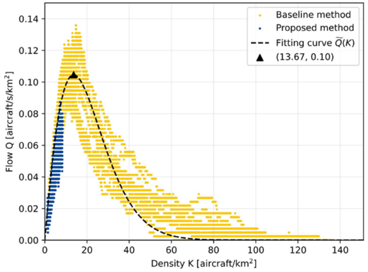
Figure 16. The Flow-Density relationship

3.7 MFD calibration

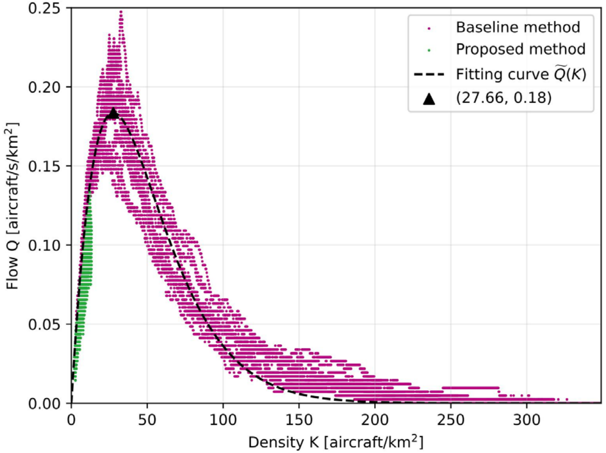
- ➢ 2D → 3D

Critical point

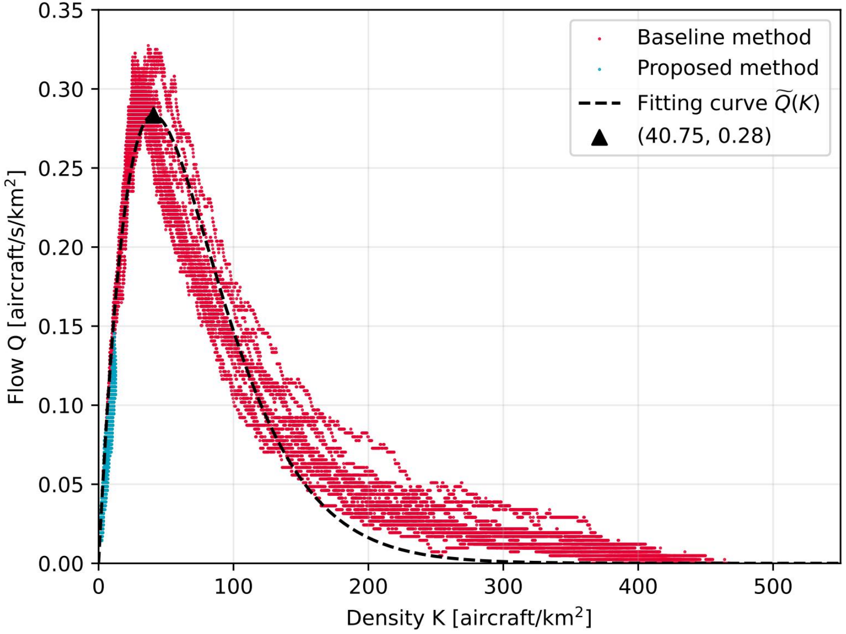
Capacity



2D $z = 500m$



3D $z \in [450, 550]$m



3D $z \in [400, 600]$m

3.8 UAM traffic flow management

- Flow-based UAM traffic management

Traditional management

- × Individual aircraft flight control (low traffic volume)
- × Computationally inefficient as volume increases (pre-solved schemes)

Flow-based management

- ✓ Higher traffic volume and density
- ✓ Macroscopic traffic state regulation (e.g., Q, K, V)
- ✓ Efficient model resolution (real-time solution)

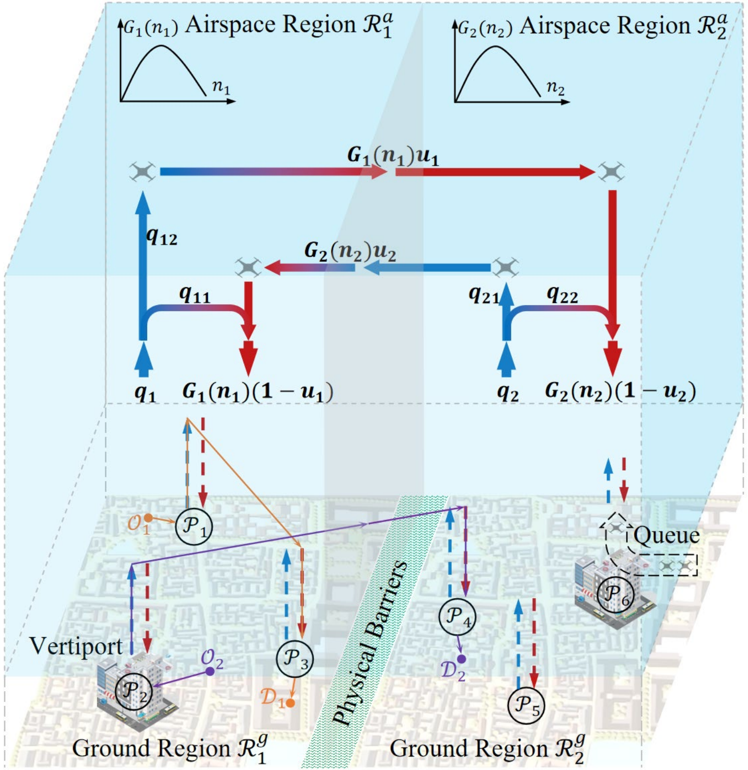
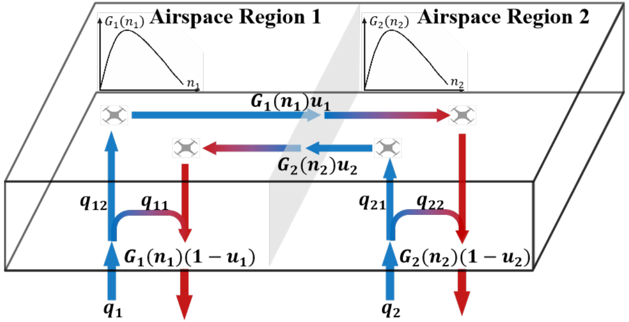


Figure 17. Schematic of air traffic flow management.

3.8 UAM traffic flow management

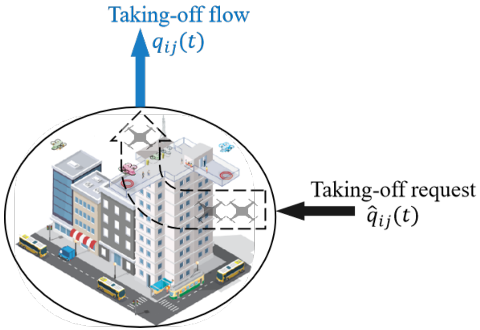
- ➢ Two-region urban air traffic flow management

✓ Airspace traffic flow control



☐ Macroscopic Fundamental Diagram (MFD) model
☐ Regional transfer flow control
☐ Steady-state regulation (preventing airspace traffic congestion)

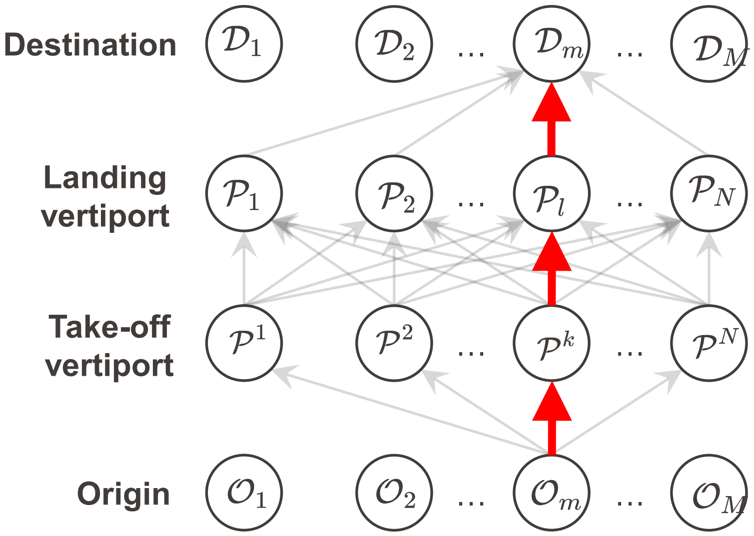
✓ Vertiport traffic flow management

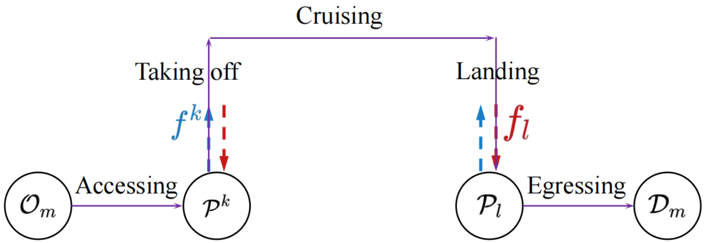


☐ Bottleneck queuing model
☐ Taking-off demand management (aircraft departure control)
☐ Balance traffic demand over time

3.9 Macroscopic urban air traffic flow model

- SO network equilibrium model





Total travel cost

Travel cost

Elastic demand

$$\min_{\boxed{f^k_{l,m}}} \boxed{\mathcal{J}_{elastic}} = \sum_{m=1}^{M}\sum_{k=1}^{N}\sum_{l=1}^{N} f^k_{l,m}\boxed{t^k_{l,m}} - \sum_{m=1}^{M}\int_0^{d_m}\boxed{D_m^{-1}(s)}ds$$

Link flow

Conservation equations

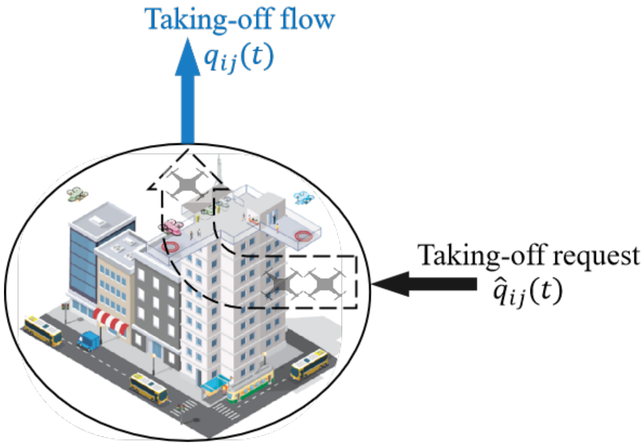
$$\begin{cases} d_m = \sum_{k=1}^{N}\sum_{l=1}^{N} f^k_{l,m}, \ \forall m \in \{1,2,\dots,M\} \\ f^k = \sum_{m=1}^{M}\sum_{l=1}^{N} f^k_{l,m}, \ \forall k \in \{1,2,\dots,N\} \\ f_l = \sum_{m=1}^{M}\sum_{k=1}^{N} f^k_{l,m}, \ \forall l \in \{1,2,\dots,N\} \end{cases}$$

Constraints

$$f^k_{l,m} \geq 0 \qquad , \forall k,l \in \{1,2,\dots,N\}, \forall m \in \{1,2,\dots,M\}$$

3.9 Macroscopic urban air traffic flow model

- Dynamics of demand queue



$R_i \rightarrow R_j$ take-off demand

Queue length

$$\boxed{\dot{Q}_{ij}(t)} = \boxed{g_{ij}(t)} - q_{ij}(t)\ , \forall i, j \in \{1, 2\}$$

$R_i \rightarrow R_j$ take-off flow

$$\boxed{q_{ij}(t)} = s_{ij}\boxed{v_{ij}(t)}\ , \forall i, j \in \{1, 2\}$$

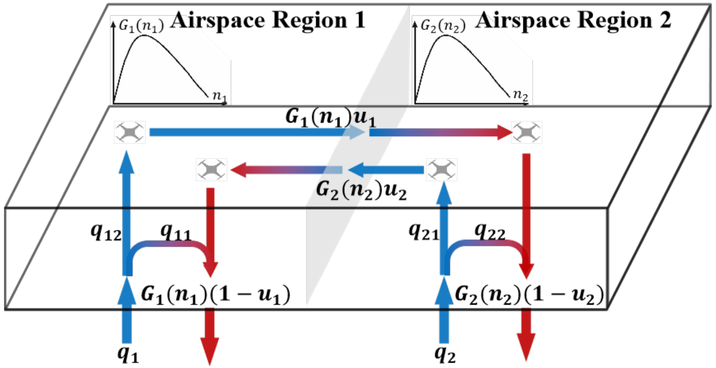
Queue control

$$\max_{v_{ij}(t)}\ \mathcal{J}_{ij}^{Q} = \boxed{\int_0^{t_f} q_{ij}(t)\ \mathrm{d}t},\ \forall i, j \in \{1, 2\}$$

Bottleneck exit flow

3.9 Macroscopic urban air traffic flow model

- Airspace traffic dynamics



Regional accumulation

Cross-boundary transfer flow

$$\begin{aligned}
\dot{n}_{11}(t) &= q_{11}(t) + G_2(n_2(t))u_{21}(t) - G_1(n_1(t))u_{11}(t)\\
\dot{n}_{12}(t) &= q_{12}(t) - G_1(n_1(t))u_{12}(t)\\
\dot{n}_{21}(t) &= q_{21}(t) - G_2(n_2(t))u_{21}(t)\\
\dot{n}_{22}(t) &= q_{22}(t) + G_1(n_1(t))u_{12}(t) - G_2(n_2(t))u_{22}(t)
\end{aligned}$$

Take-off inflow

Landing outflow

Cross-boundary flow control

$$\min_{\boldsymbol{u}(t)} \ \mathcal{J} = \int_0^{t_f} \omega_n(\boldsymbol{n} - \overline{\boldsymbol{n}})^T(\boldsymbol{n} - \overline{\boldsymbol{n}}) + \omega_u(\boldsymbol{u} - \overline{\boldsymbol{u}})^T(\boldsymbol{u} - \overline{\boldsymbol{u}}) \, \mathrm{d}t$$

$$\boldsymbol{n} = [n_1(t), n_2(t)]^T$$

Airspace traffic state

$$\overline{\boldsymbol{n}} = [\overline{n}_1, \overline{n}_2]^T$$

Desired equilibrium

3.10 Derivation of steady-state condition

- Given the steady-state inflow $\bar{q}_{ij}$, derive the steady-state accumulation $\bar{n}_i$ and control input $\bar{u}_{ij}$, $i, j = 1{,}2$.

1. The steady state of the air traffic dynamics implies $\dot{n}_{ij}(t) = 0$, i.e.,

$$0 = \dot{n}_{11}(t) = \bar{q}_{11} + G_2(\bar{n}_2)\bar{u}_{21} - G_1(\bar{n}_1)\bar{u}_{11} \quad \text{(1a)}$$

$$0 = \dot{n}_{12}(t) = \bar{q}_{12} - G_1(\bar{n}_1)\bar{u}_{12} \quad \text{(1b)}$$

$$0 = \dot{n}_{21}(t) = \bar{q}_{21} - G_2(\bar{n}_2)\bar{u}_{21} \quad \text{(1c)}$$

$$0 = \dot{n}_{22}(t) = \bar{q}_{22} + G_1(\bar{n}_1)\bar{u}_{12} - G_2(\bar{n}_2)\bar{u}_{22} \quad \text{(1d)}$$

2. Suppose that the control inputs are coupled, i.e.,

$$u_{ii}(t) + u_{ij}(t)|_{i\neq j} = 1, \forall i, j \in \{1, 2\} \quad \text{(2)}$$

3. We combine (1) and (2) to get the following steady-state condition

$$G_1(\bar{n}_1) = \bar{q}_{11} + \bar{q}_{12} + \bar{q}_{21} \;,\; G_2(\bar{n}_2) = \bar{q}_{22} + \bar{q}_{12} + \bar{q}_{21} \quad \text{(3)}$$

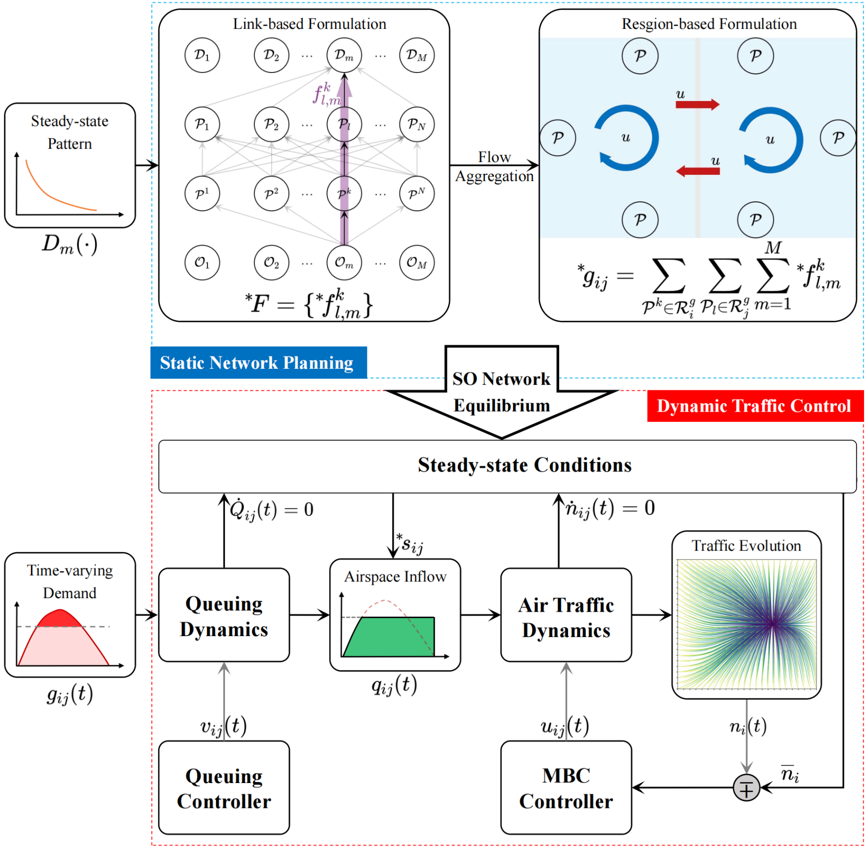
4. The desired steady-state accumulation is

$$\bar{n}_1 = G_{1,s}^{-1}(\bar{q}_{11} + \bar{q}_{12} + \bar{q}_{21}) \;,\; \bar{n}_2 = G_{2,s}^{-1}(\bar{q}_{22} + \bar{q}_{12} + \bar{q}_{21}) \quad \text{(4)}$$

5. Substituting (2), (3), and (4) into (1), the steady-state control inputs are derived as

$$\begin{aligned} \bar{u}_{11} &= \frac{\bar{q}_{11} + \bar{q}_{21}}{\bar{q}_{11} + \bar{q}_{12} + \bar{q}_{21}} \;, & \bar{u}_{22} &= \frac{\bar{q}_{22} + \bar{q}_{12}}{\bar{q}_{22} + \bar{q}_{12} + \bar{q}_{21}} \\ \bar{u}_{12} &= \frac{\bar{q}_{12}}{\bar{q}_{11} + \bar{q}_{12} + \bar{q}_{21}} \;, & \bar{u}_{21} &= \frac{\bar{q}_{21}}{\bar{q}_{22} + \bar{q}_{12} + \bar{q}_{21}} \end{aligned} \quad \text{(5)}$$

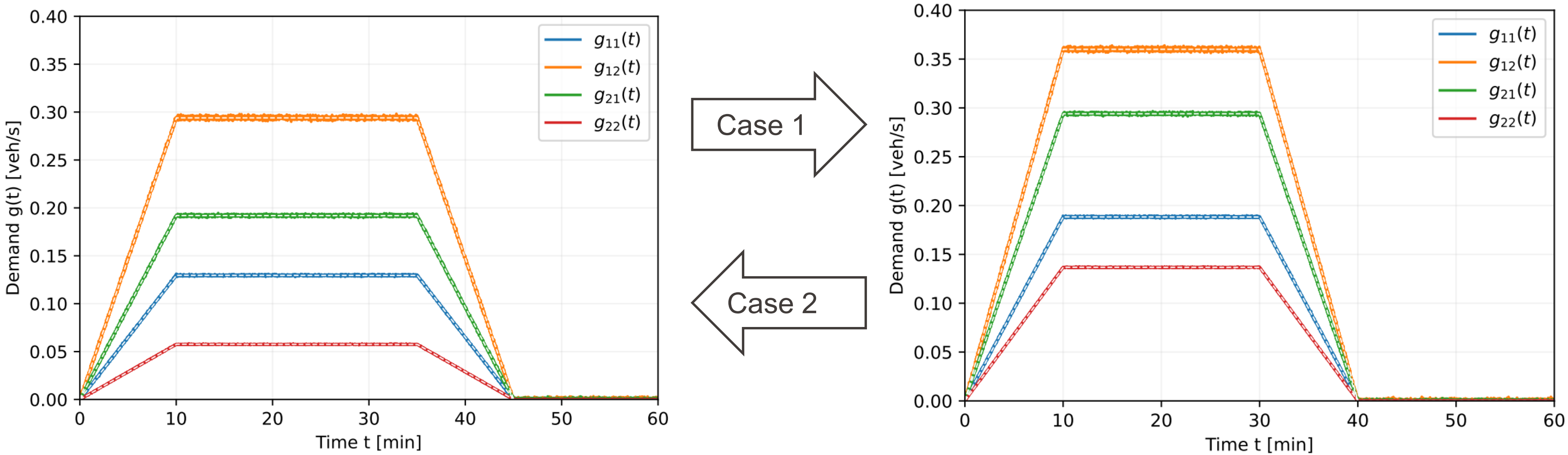
3.11 Bi-level control framework



- ➢ Challenges
  - ☐ Traditional methods: equilibrium selection based on experiences
  - ☹ No guarantee of tractability of MFD set-point control problem
  - ☹ Lack of convincing interpretation, hard to response to the changes in MFD system demand-supply
- ➢ Bi-level control method
  - ☐ Desired equilibrium derived from SO network equilibrium model
  - ☺ Feasibility of equilibrium guaranteed by demand management
  - ☺ The derived equilibrium is ensured to exist as a stable equilibrium and can be adjusted in response to traffic demand and airspace capacity

3.12 Numerical experiments

- Settings

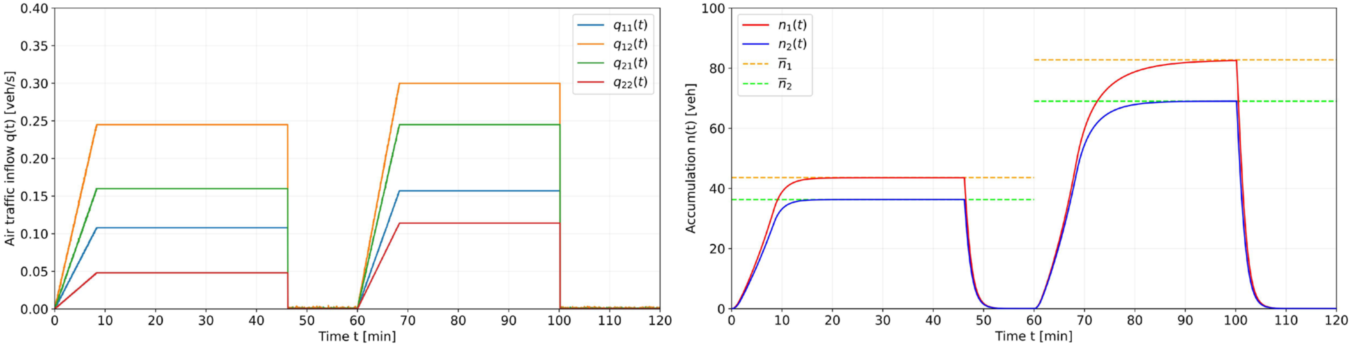


(a) Medium demand level

(b) High demand level

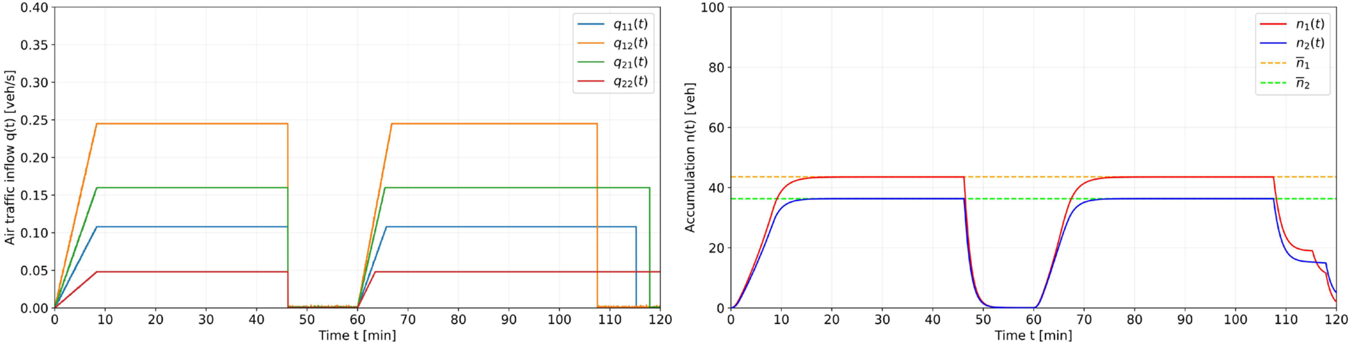
Figure 18. Time-varying demand patterns

3.12 Numerical experiments



(a) Air traffic inflow given by demand management (b) Air traffic accumulation given by air traffic control

Figure 19. Case 1 by the bi-level method



(a) Air traffic inflow given by demand management (b) Air traffic accumulation given by air traffic control

Figure 20. Case 1 by the baseline method

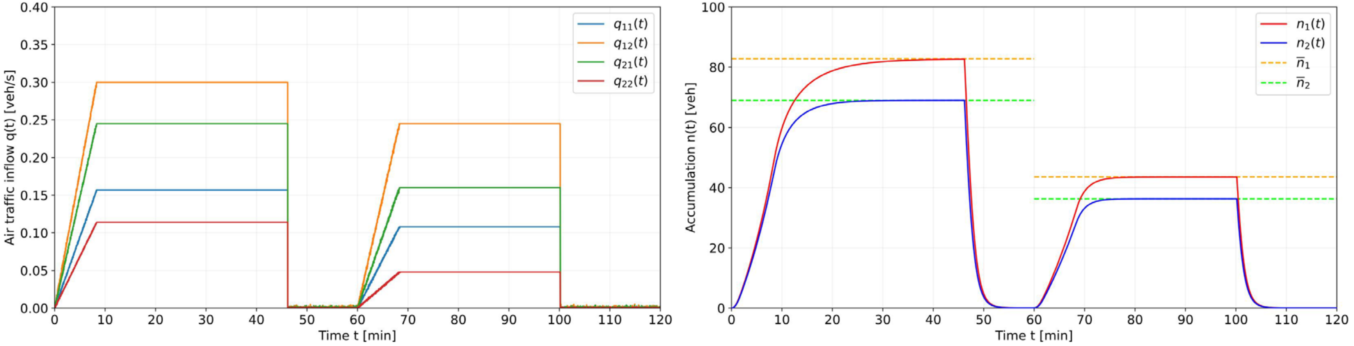
➢ Comparison

☺ Trip completion 26.9%↑

☺ Max queue length 52.6%↓

☺ Avg. queuing time 42.3%↓

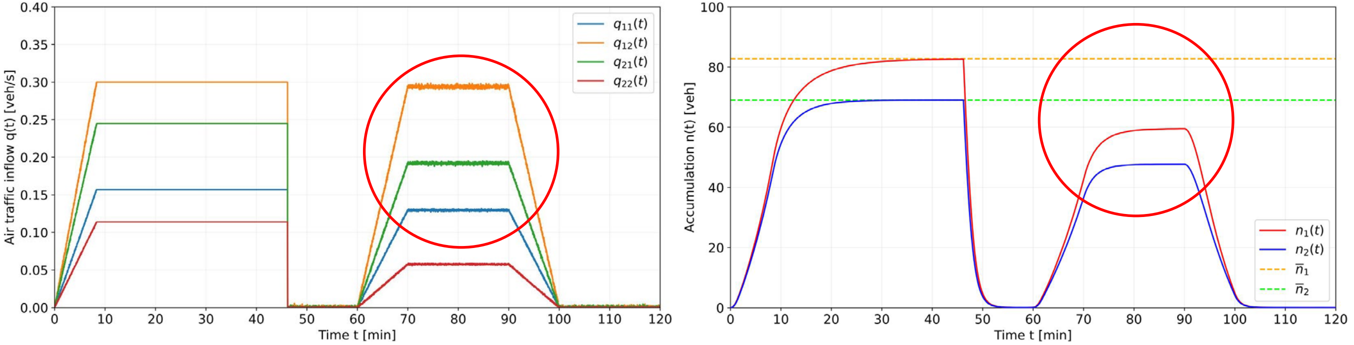
3.12 Numerical experiments



(a) Air traffic inflow given by demand management

(b) Air traffic accumulation given by air traffic control

Figure 21. Case 2 by the bi-level method



(a) Air traffic inflow given by demand management

(b) Air traffic accumulation given by air traffic control

Figure 22. Case 2 by the baseline method

- Comparison

baseline：

- ☹ Failure in demand management
- ☹ Fail to converge to the desired equilibrium

References

[1] https://droneii.com/what-is-aam-uam-ram-air-mobility.

[2] 百度地图2023年中国城市交通报告.

[3] Cohen A P, Shaheen S A, Farrar E M. Urban air mobility: History, ecosystem, market potential, and challenges[J]. IEEE Transactions on Intelligent Transportation Systems, 2021, 22(9): 6074-6087.

[4] https://www.slideshare.net/sanathviswanathan/final-presentation-stl-uampptx.

[5] Liu Y, Lyu C, Bai F, et al. The Role of Intelligent Technology in the Development of Urban Air Mobility Systems: A Technical Perspective[J]. Fundamental Research, 2023.

[6] Bauranov A, Rakas J. Designing airspace for urban air mobility: A review of concepts and approaches[J]. Progress in Aerospace Sciences, 2021, 125: 100726.

[7] Straubinger A, Rothfeld R, Shamiyeh M, et al. An overview of current research and developments in urban air mobility–Setting the scene for UAM introduction[J]. Journal of Air Transport Management, 2020, 87: 101852.

[8] Xiang S, Xie A, Ye M, et al. Autonomous eVTOL: A summary of researches and challenges[J]. Green Energy and Intelligent Transportation, 2023: 100140.

[9] Wisk B. Concept of Operations for Uncrewed Urban Air Mobility[J]. 2022.

[10] FAA engineering brief No.105

[11] Wu Z, Zhang Y. Integrated network design and demand forecast for on-demand urban air mobility[J]. Engineering, 2021, 7(4): 473-487.

[12] Shrestha R, Oh I, Kim S. A survey on operation concept, advancements, and challenging issues of urban air traffic management[J]. Frontiers in Future Transportation, 2021, 2: 1.

[13] Goyal R, Reiche C, Fernando C, et al. Urban air mobility (UAM) market study[R]. 2018.

[14] Oubbati O S, Lakas A, Lorenz P, et al. Leveraging communicating UAVs for emergency vehicle guidance in urban areas[J]. IEEE Transactions on Emerging Topics in Computing, 2019, 9(2): 1070-1082.

EPFL
LUTS

Thank you for being here!

Can Chen (EPFL-LUTS)
can.chen@epfl.ch