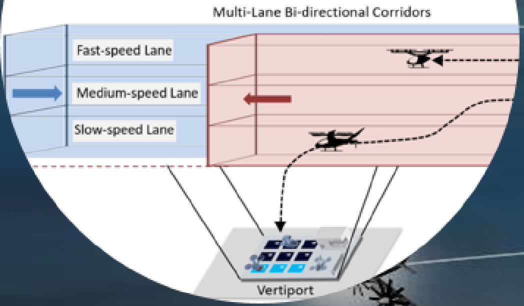
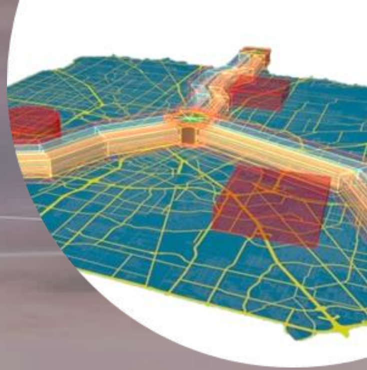
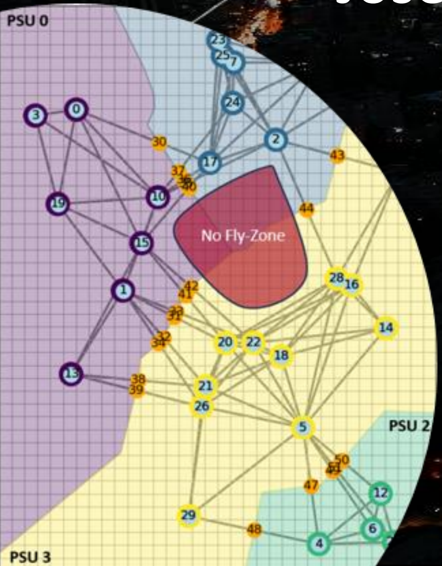
UNIVERSITY OF MICHIGAN





Centralized and Distributed Optimization of AAM Strategic Traffic Management

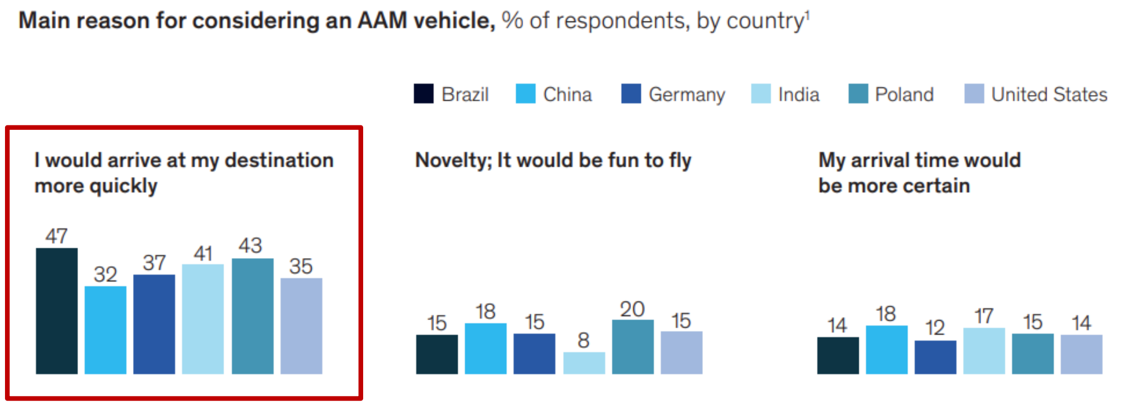
Joseph Kim

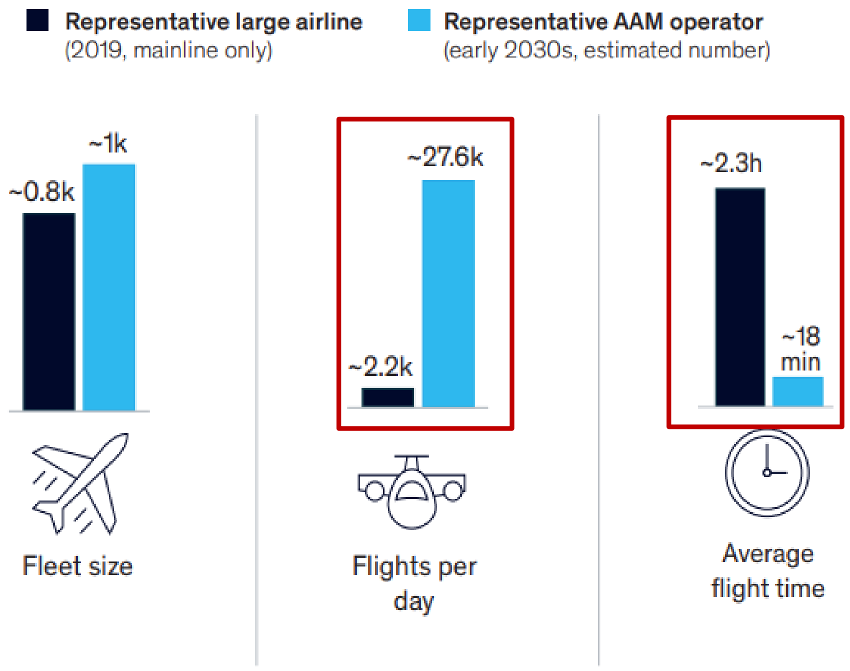


LATTICE

A2 SYS LAB

Future AAM Demand the Quest for Efficient Management





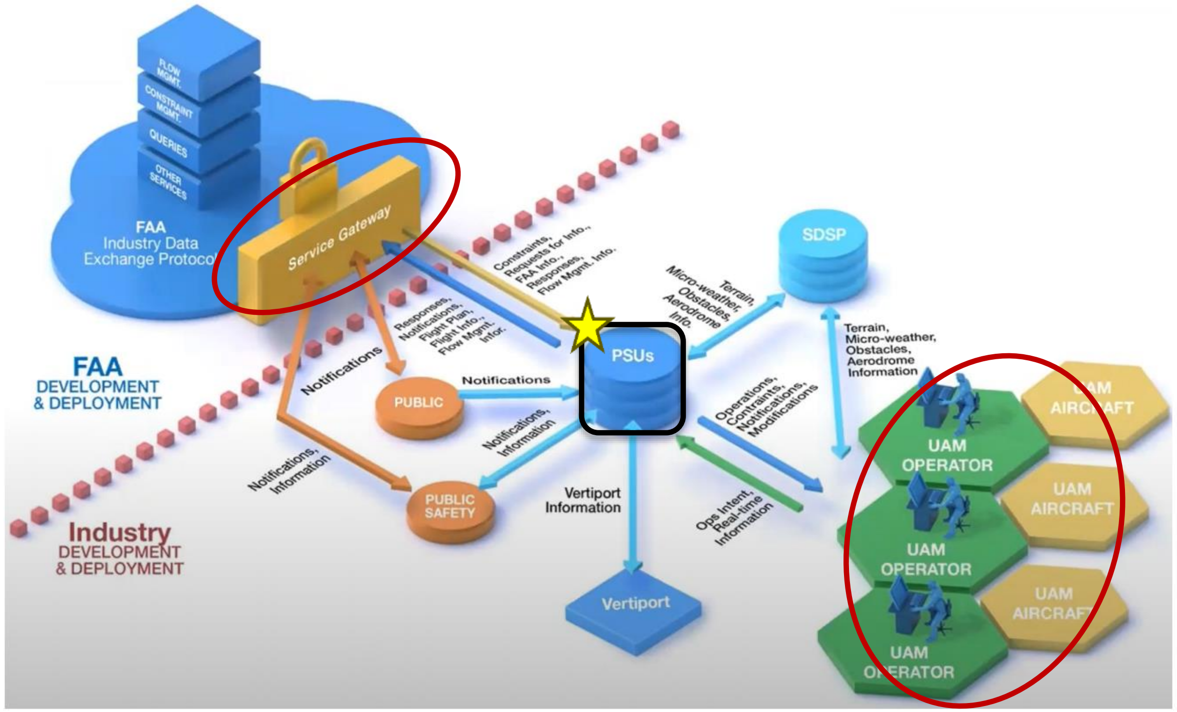
[1] McKinsey & Company. "Perspectives on advanced air mobility." 2022
[2] https://www.jobyaviation.com/

AAM Airspace Design ConOps

	sesar JOINT UNDERTAKING	NASA	Federal Aviation Administration	JAXA	DLR	ONERA THE FRENCH AEROSPACE LAB
Airspace	Corridors	Corridor/ Skylanes	Corridors	Corridors	Cells	Vertical Layer Separations
System	Centralized	Centralized	Centralized	Centralized	Centralized	Centralized
Capacity	High	Medium/ Low	Medium	High	High	Medium
Automation	Piloted & Uncrewed	Uncrewed	Piloted	Uncrewed	Piloted & Uncrewed	Manned & Uncrewed
Static/ Dynamic Geofence	✓	✓	✓	✓	✓	✓

	MITRE	wisk	A^3	amazon	Aurora FLIGHT SCIENCES A Boeing Company	EMBRAER·X
Airspace	VFR Free-flight + Corridors	Corridor	Free-flight / Corridors	Vertical Layer Separations	Sky-tubes (i.e., constant speed)	Vertical layers, Corridors
System	Centralized	Centralized / Decentralized	Centralized	Decentralized	Decentralized	Centralized
Capacity	High	Medium	High/ Medium	Medium	Medium	High
Automation	Piloted & Uncrewed	Uncrewed	Piloted & Uncrewed	Uncrewed	Uncrewed	Uncrewed
Static/ Dynamic Geofence	✓	✓	✓	✓	✓	✓

FAA Envisioned AAM Architecture

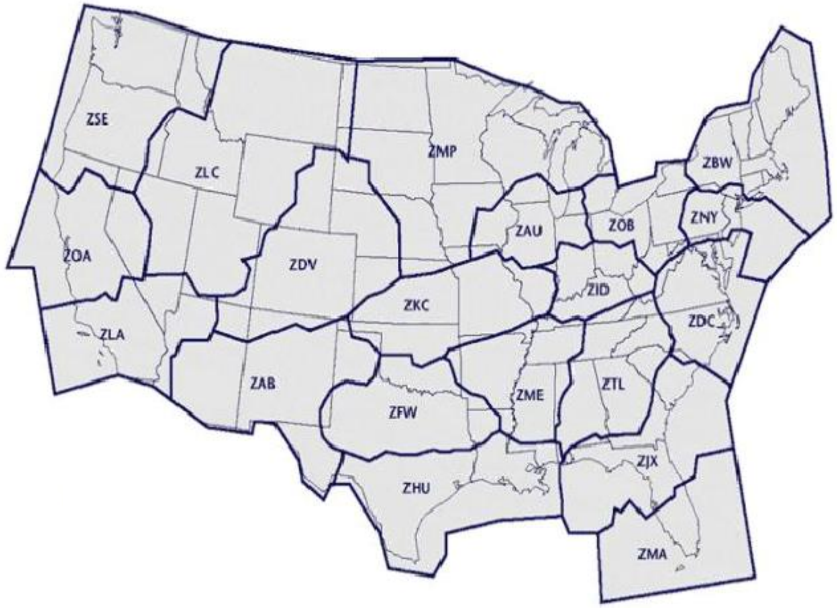


- PSU: Provider of Services for UAM
- SDSP: Supplemental Data Service Providers
- UAM: Urban Air Mobility (i.e., AAM)

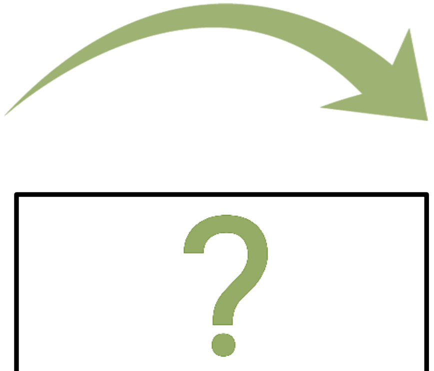
[1] Bauranov, A, and Jasenka R. "Designing airspace for urban air mobility: A review of concepts and approaches." *Progress in Aerospace Sciences* 125 (2021): 100726.
[2] Undertaking, SESAR Joint. "European ATM Master Plan: Roadmap for the safe integration of drones into all classes of airspace." *SESAR Joint Undertaking: Brussels, Belgium* (2018).
[3] NASA, UTM. "Air Traffic Management for Low-altitude Drones, NA a." *SA (NASA), Washington DC, USA* (2015).
[4] Le Tallec, Claude, Patrick Le Blaye, and Moustafa Kasbari. "Low Level RPAS Traffic Management (LLRTM) Concept of Operation." *17th AIAA Aviation Technology, Integration, and Operations Conference*. 2017.
[5] FAA-NextGen, "A New U.S. DOT Volpe Center-FAA Thought Leadership Series. Transformation: Urban Air Mobility Concept of Operations," https://www.volpe.dot.gov/events/transformation-urban-air-mobility-conceptoperations, 2023.

Three Questions in AAM Traffic Management

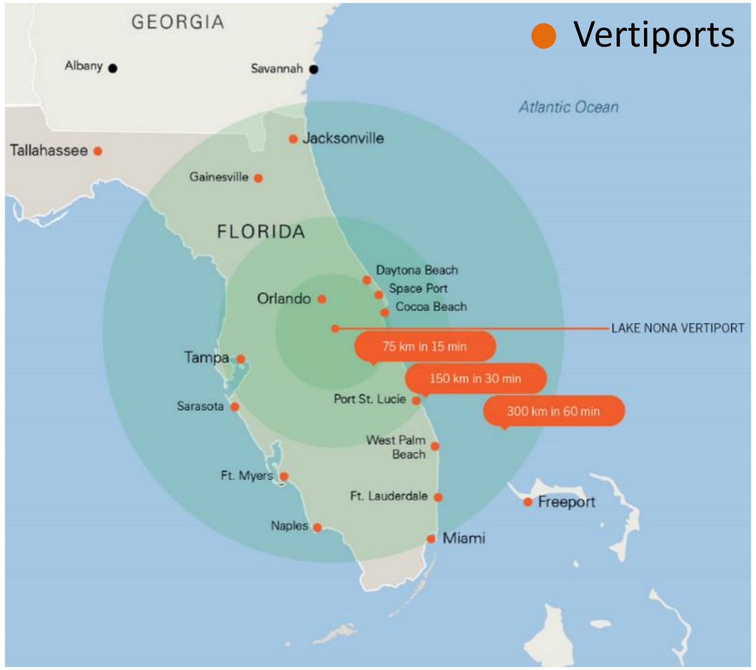
1. **Airspace Sectorization:**
   - Can urban airspace be effectively divided to allow local traffic managers (PSUs/ USSP/ fleet operators) to handle AAM operations?
     → As the number of operation increases, robust & efficient AAM flight management will become essential



US Airspace Sectorization



AAM
Airspace Sectorization



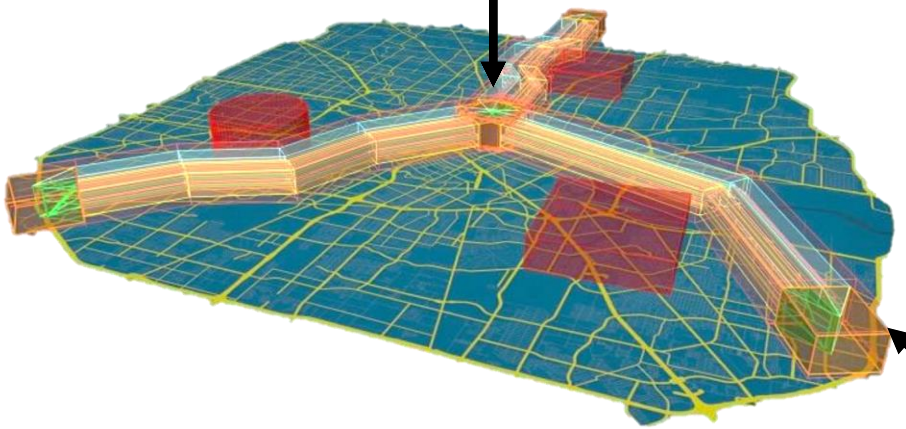
Example: Potential Vertiport Locations in Florida

Three Questions in AAM Traffic Management

2. AAM Route Planning:

- How can we efficiently plan AAM routes considering vehicular, infrastructural & operational constraints?
  → vehicle types (i.e., speed & range), service priorities, corridor & vertiport capacities, equity/fairness

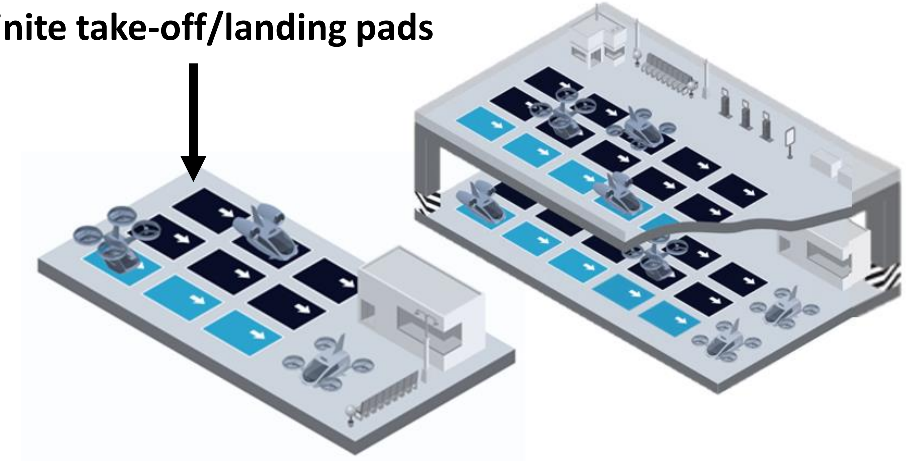
Corridor transition



Fixed corridor volume

Bi-directional Flight Corridors with Fixed-size

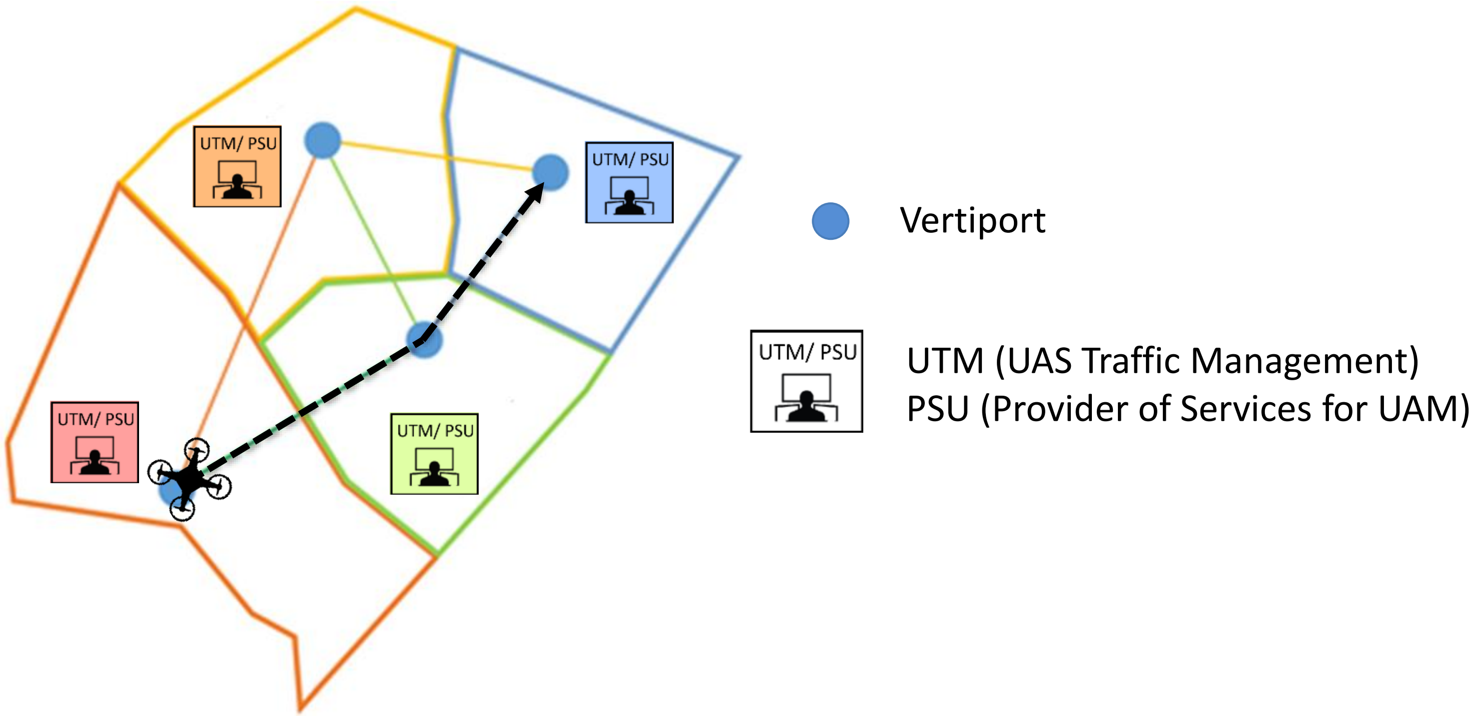
Finite take-off/landing pads



Vertiports with Landing Pads

Three Questions in AAM Traffic Management

3. **Distributed Management:**
   - How to efficiently generate AAM traffic management solution given the specific demands/ traffic of their regions?
   - Can neighboring PSUs/ USSPs coordinate airspace management to ensure smoother AAM operations while maintaining traffic flow capacities?

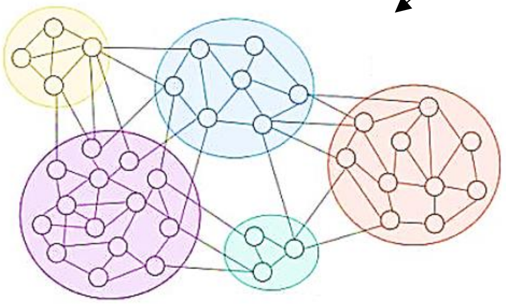


Methods and Algorithms

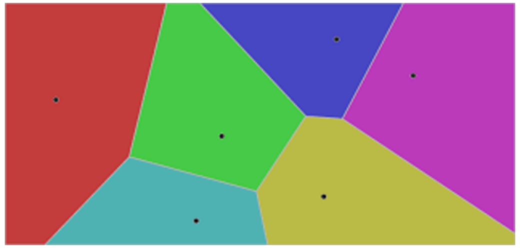
What Our Research Offers:

1. Airspace Sectorization
2. Corridor-based Route Planning
3. AAM Traffic Flow Management in Single (Centralized) Setting
4. AAM Traffic Flow Management in Distributed Settings

Detects groups with similar properties

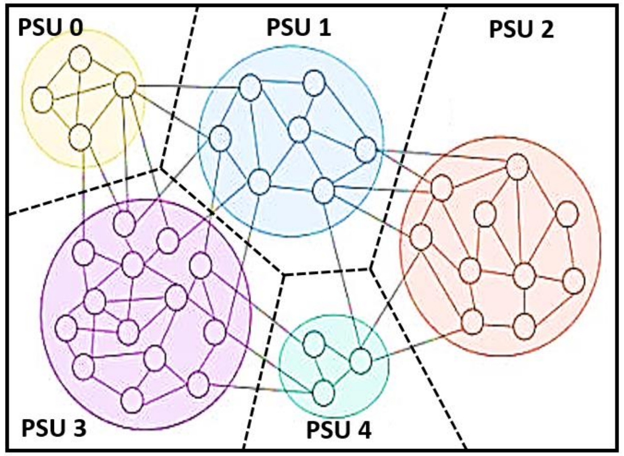


Louvain Community Detection



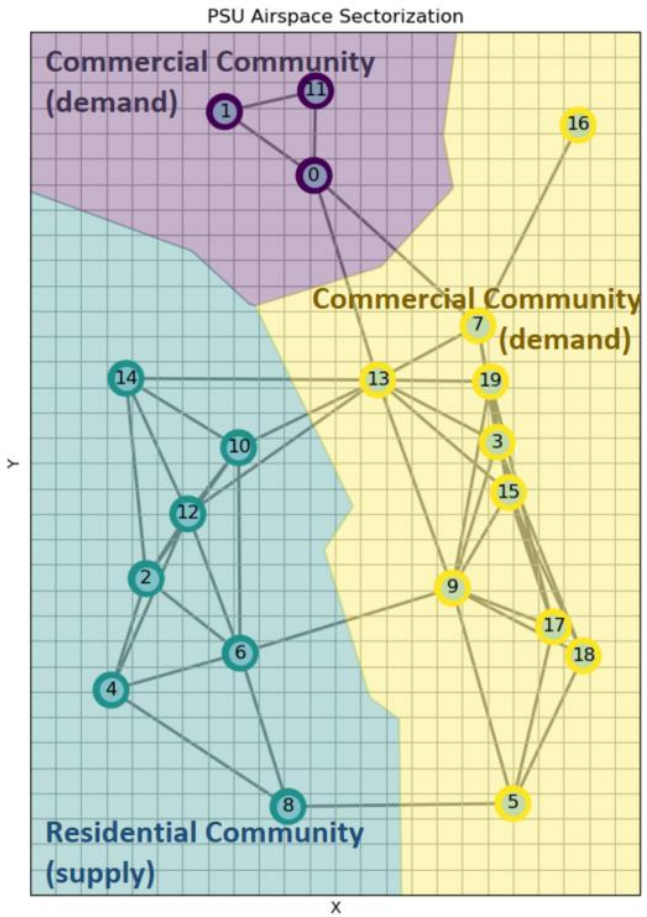
Voronoi Diagram

Generate geographic partitioning



Airspace Sectorization

Airspace Sectorization



PSU Airspace Sectorization Example
(Grid size: 5 km)

Edge weight: $w_i = \alpha_1 \cdot \mathcal{G}_i + \alpha_2 \cdot \mathcal{N}_i + \alpha_3 \cdot \mathcal{H}_i + \alpha_4 \cdot \mathcal{Q}_i$

Normalized distance between vertiport: $\mathcal{G}_i = \frac{max(d_{corridor}) - d_{u,v}}{max(d_{corridor})}$

Connectivity: number of corridors connected to a vertiport

$$\mathcal{N}_i = \frac{m_u + m_v}{2 * max(m_{vertiport})}$$

Population similarity factor: $\mathcal{H}_i = \exp\left(-\frac{|p_u - p_v|}{\max(p_u, p_v)}\right)$

Vertiport capacity similarity factor: $\mathcal{Q}_i = \exp\left(-\frac{|c_u - c_v|}{\max(c_u, c_v)}\right)$

Weight Factors: $\sum_{i=1}^{4} \alpha_i = 1, \quad 0 < \alpha_i < 1$

i.e., [0.55, 0.25, 0.1, 0.1]

Methods and Algorithms

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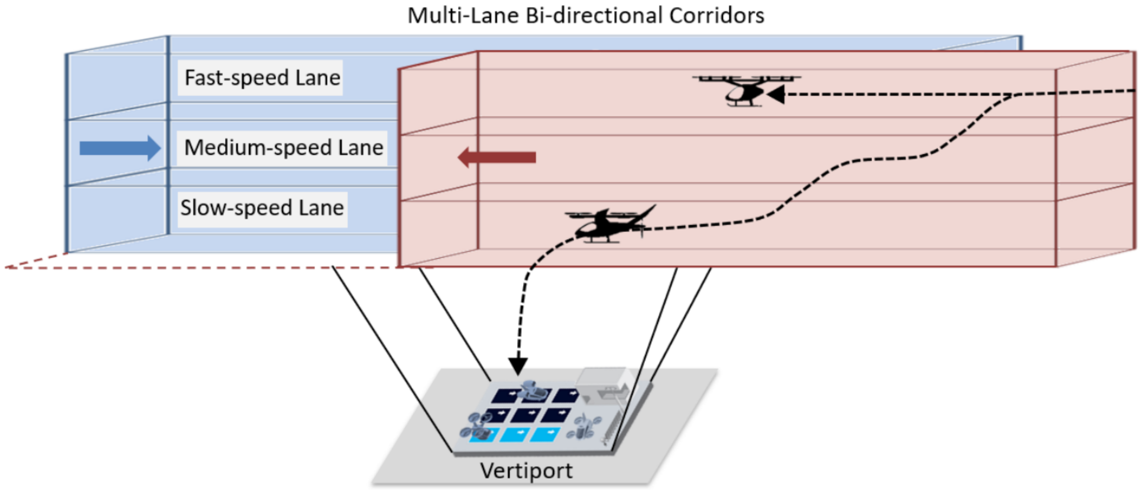
Corridor Design:

- Multiple lanes to accommodate diverse speed for AAM traffic
  - Fast/ Medium/ Slow Speed Lane
- Maximum throughput capacity:

$$\overrightarrow{k_i} = \frac{dist(i)}{d_s} \cdot h_i$$

- Vertical layering
  - Smooth transition of speeds and altitudes



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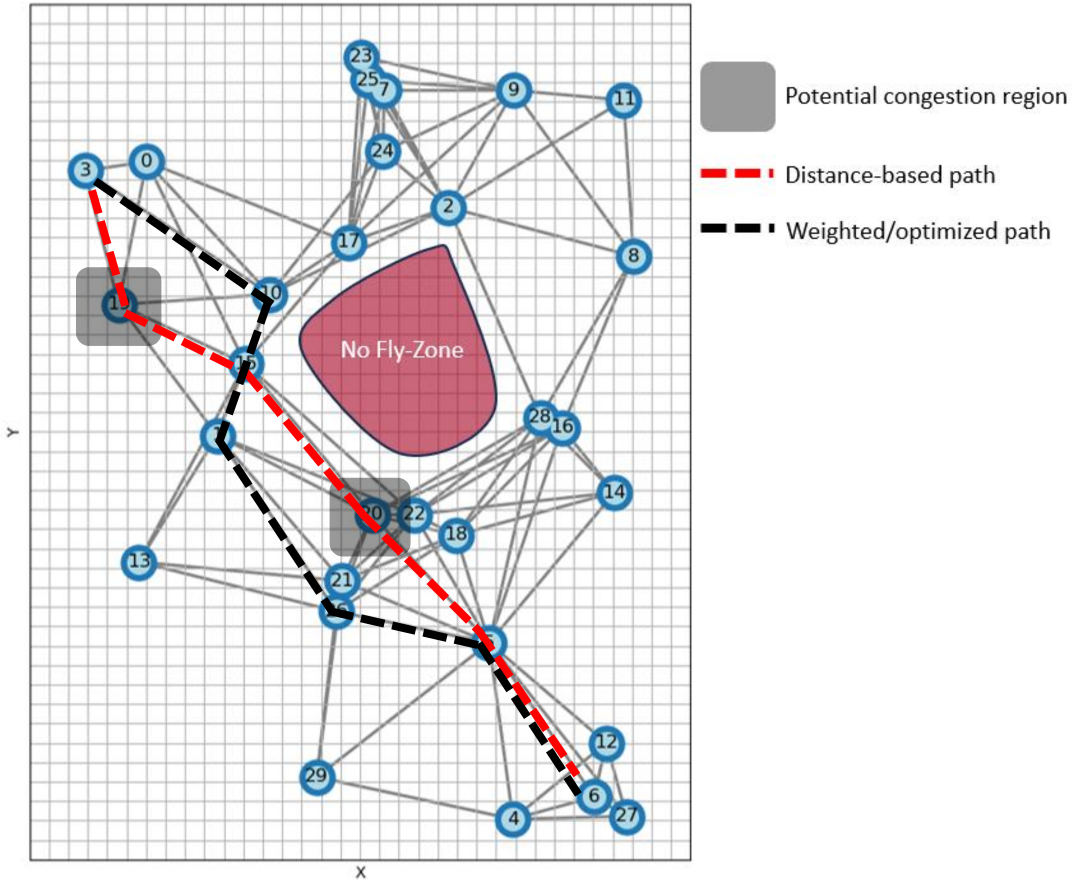
Distance-based vs. Weighted/optimized Path Construction

- Dijkstra's Algorithm[1]
- Explores route planning approaches



[1] Prim, R. C., "Shortest connection networks and some generalizations," The Bell System Technical Journal, Vol. 36, No. 6, 1957, pp. 1389–1401

Methods and Algorithms

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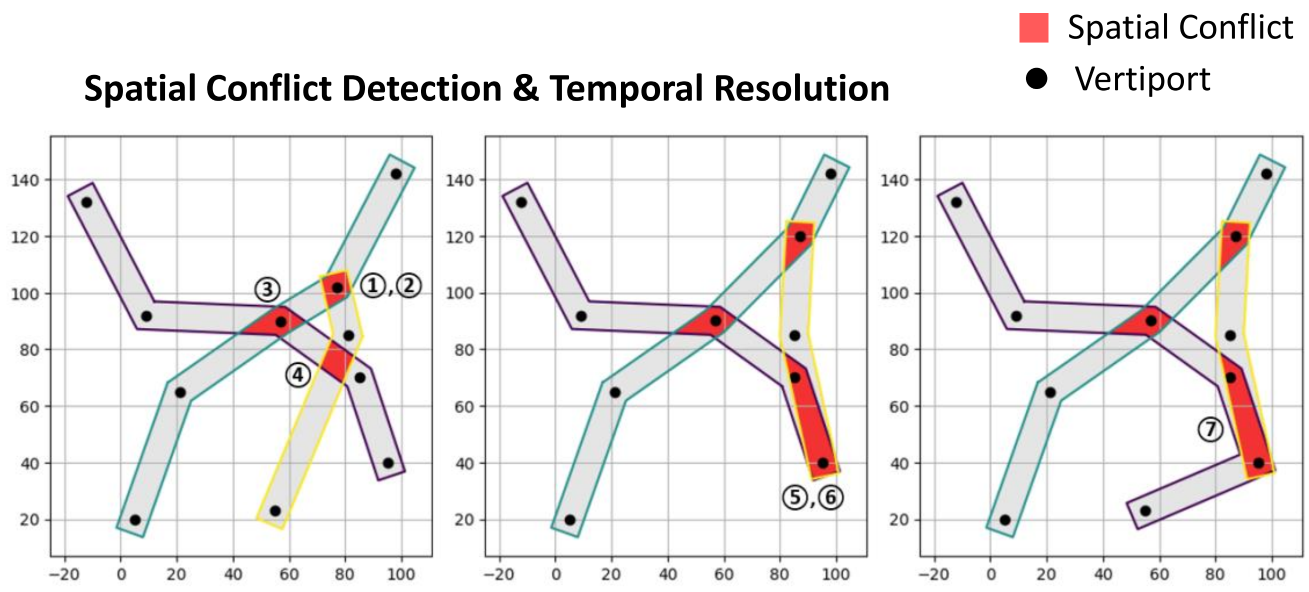
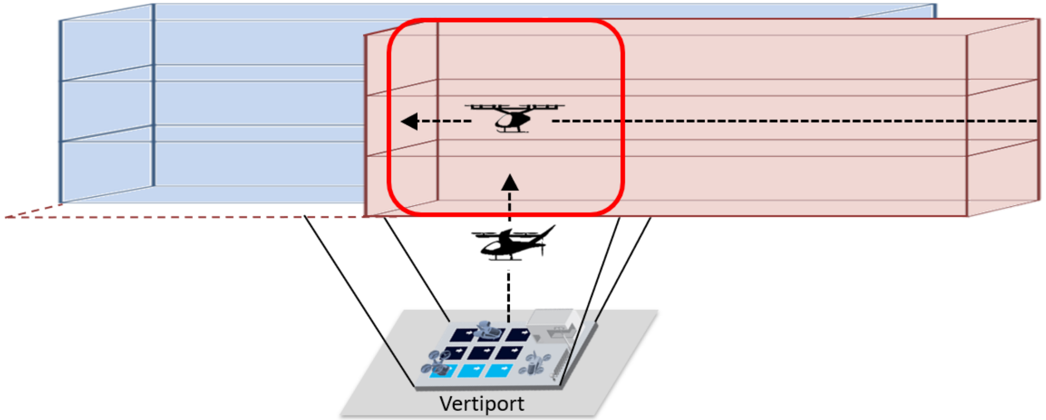
Spatial Conflict Detection & Temporal Resolution



Spatial Conflict Type ① and ②



Methods and Algorithms

What Our Research Offers:

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3. AAM Traffic Flow Management in Single (Centralized) Setting
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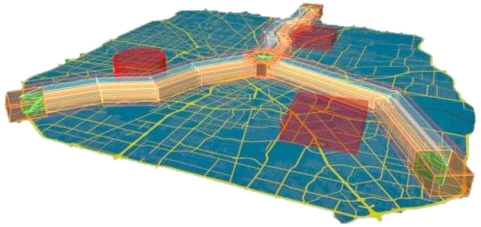
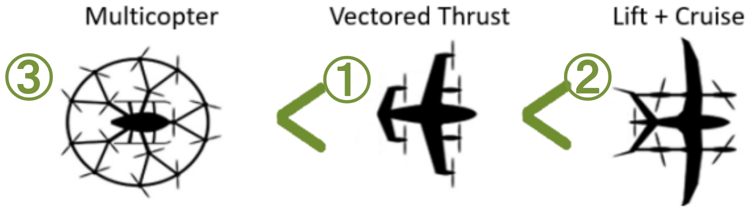
Considerations

<u>Take-off/ Landing Vertiport Capacities:</u>

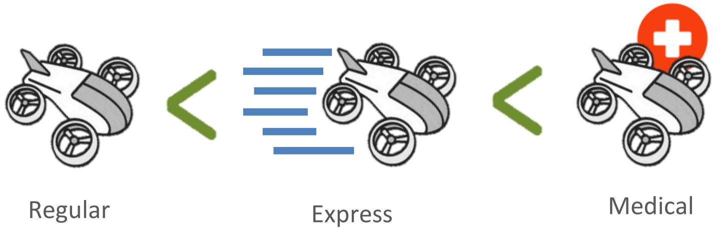
<u>Multi-Lane Bi-directional Corridors:</u>



<u>Vehicle Types:</u>



<u>Service Priority Types:</u>



Methods and Algorithms

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Objective Function	Consideration
Minimize [departure delay & airborne delay]	Equity of Assigning Departure Time

Parameters	Constraints
Min & Max Speed per Vehicle Type	Departure Takeoff & Arrival Landing Capacity Constraint
Departure, Arrival Vertiport Max Capacities	Corridor Capacity Constraints During Operation Time
Each Corridor's Max Capacity	Min & Max Speed Constraints per Vehicle
Scheduled Departure & Arrival Time per Vehicle	Temporal Conflict Resolution Constraints
Cost of Departure Delay & Airborne Delay per Vehicle Type	(# of MIP constraints: 13)

Methods and Algorithms

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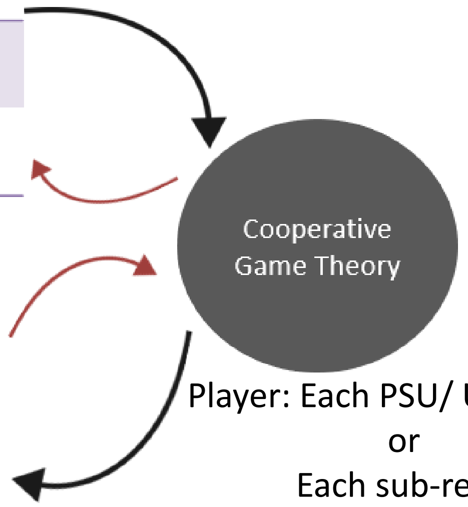
Distributed AAM Traffic Management:

- Offers scalability, ensuring the safe and efficient operation of numerous AAM vehicles
- Locally optimizes traffic solutions and coordinates /resolves conflicts for vehicles transitioning through multiple PSUs
- 1.4 to 30 times faster than centralized AAM traffic management

Methods and Algorithms

AAM traffic density,
number of transition corridors,
number of spatial conflicts

High-Level Optimization (Game Theory)	
Decision Variables	Bargaining Power of PSU during operation time
Objective Function	Fair and coordinated Negotiation among Conflicted PSUs

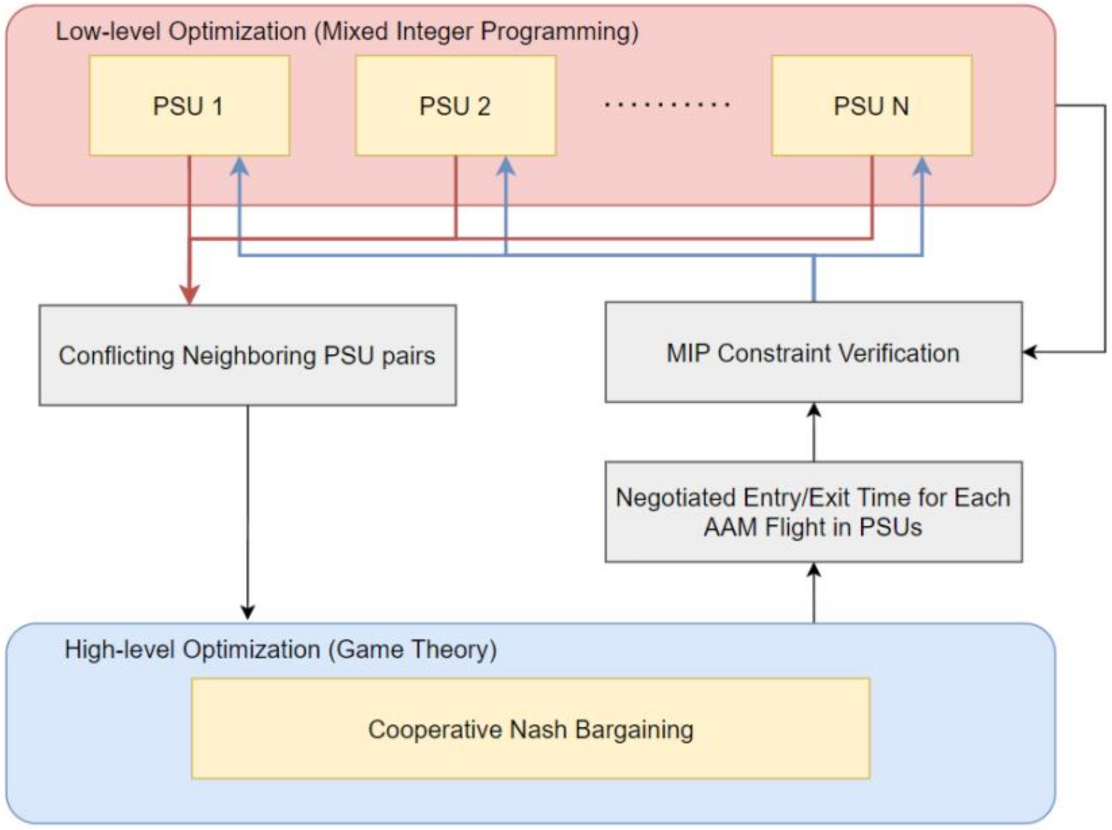


Player: Each PSU/ USSP
or
Each sub-regions owned by PSU

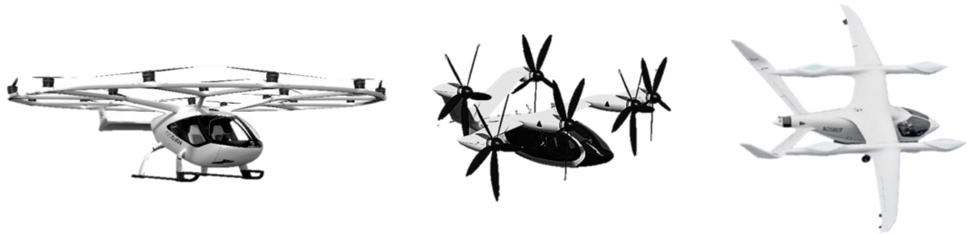
Low-Level Optimization (MIP)	
Decision Variables	Departure time for each AAM within each PSU airspace
Objective Function	Minimize overall departure and airborne delay within each PSU airspace
Constraints	Speed, capacity and temporal conflict resolution

Negotiable bargaining power of PSUs varies with each operational time window

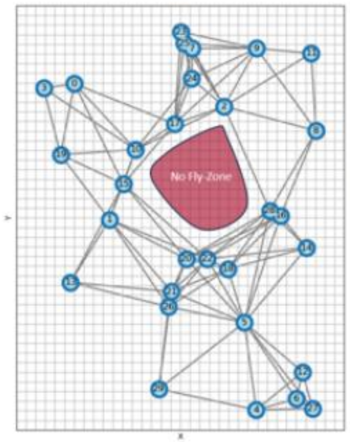
Bi-Level Optimization
Distributed AAM Traffic Management

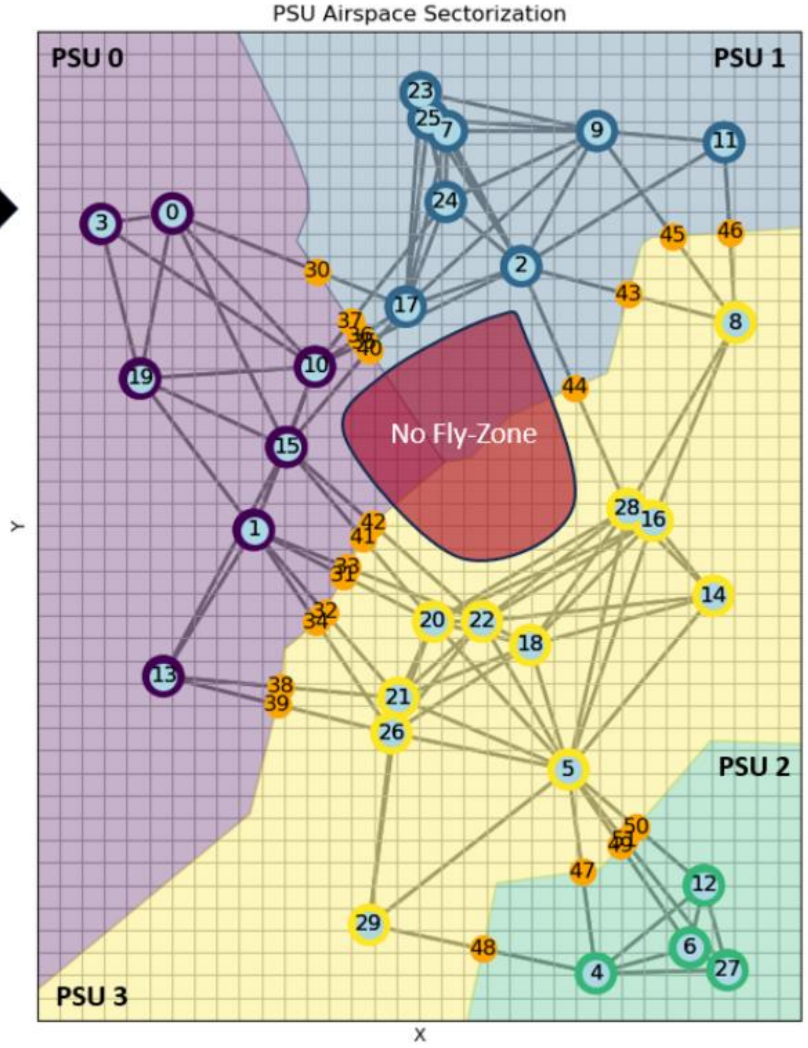


Monte Carlo Simulation Setup



	Volocity	Joby Aviation	Beta Technologies
Range [km]	35 ~ 65	240	500
Min. Cruise Speed* [km/hr]	30	100	100
Ideal Cruise Speed [km/hr]	90	320	270
Seating Capacity	2	4	4





Artificial Map Construction Parameters	
Min/ Max Town Population	26/ 967
Concurrent TLOF Capacity	5 ~ 15
Directional Corridor Max Length	60 km
Directional Corridor Geofence Width	50 m
PSU Sectorization Weights $\alpha_1, \alpha_2, \alpha_3, \alpha_4$	[0.55, 0.25, 0.1, 0.1]

AAM Flight Operation Parameters	
Operation Time Window	4 hr
Scheduled Departure Time Interval	5 min
t_s	30 sec
Vehicle Type Distribution Ratio	Type 1, 2, 3: [1/3, 1/3, 1/3]
Service Priority Percentage per Vehicle Type	Type 1, 2, 3: [50%, 40%, 10%]
PSU Bargain Power Weight $\beta_1, \beta_2, \beta_3$	[0.3, 0.45, 0.25]

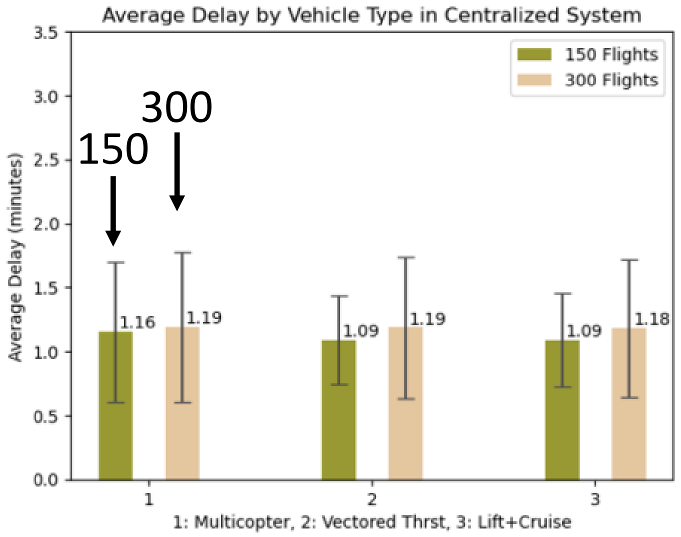
Vehicle Types:

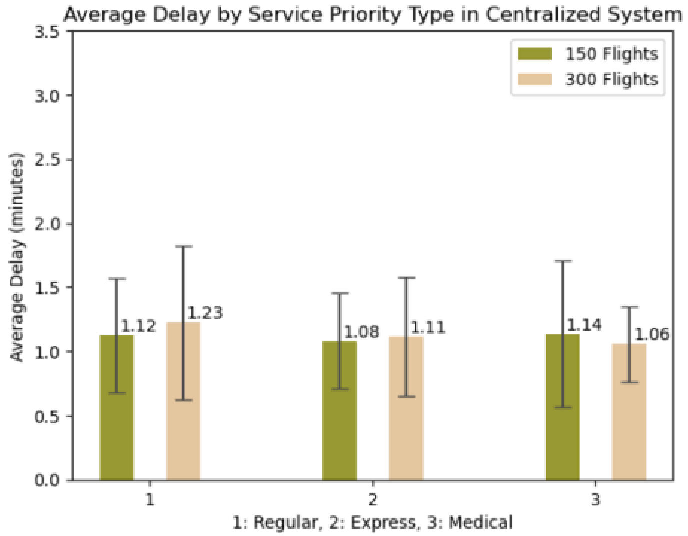
Multicopter | Vectored Thrust | Lift + Cruise

Service Priority Types:

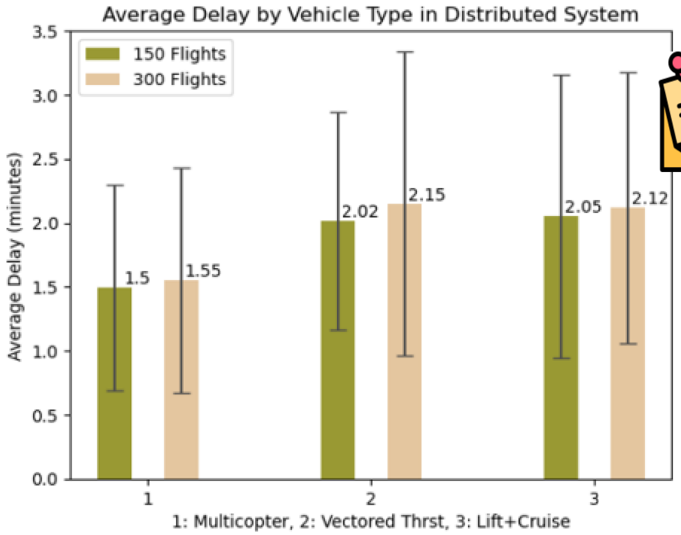
Regular | Express | Medical

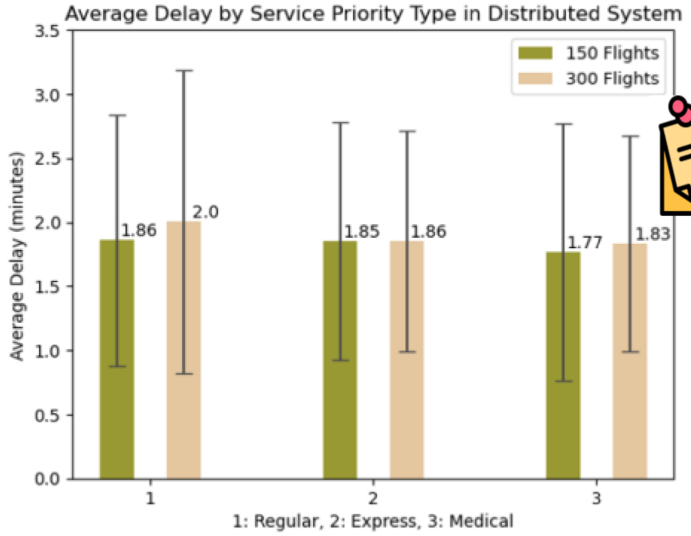
Centralized





Distributed





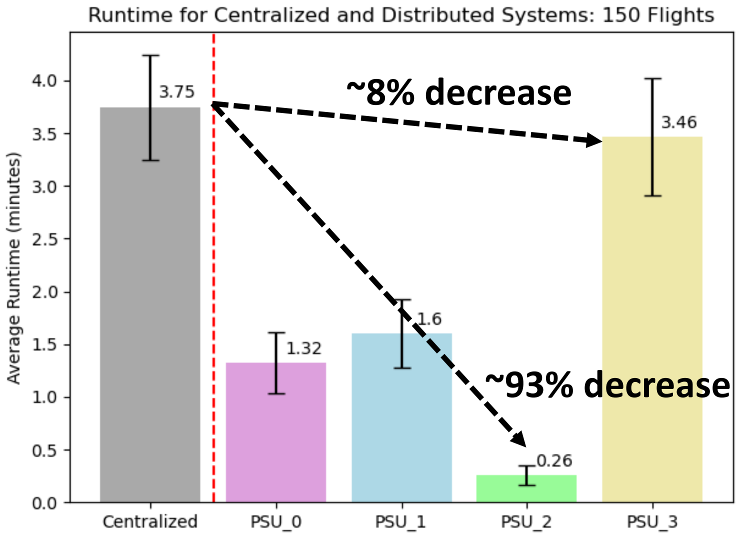
- 300 flights experienced more delays than 150 flights (both C & D)

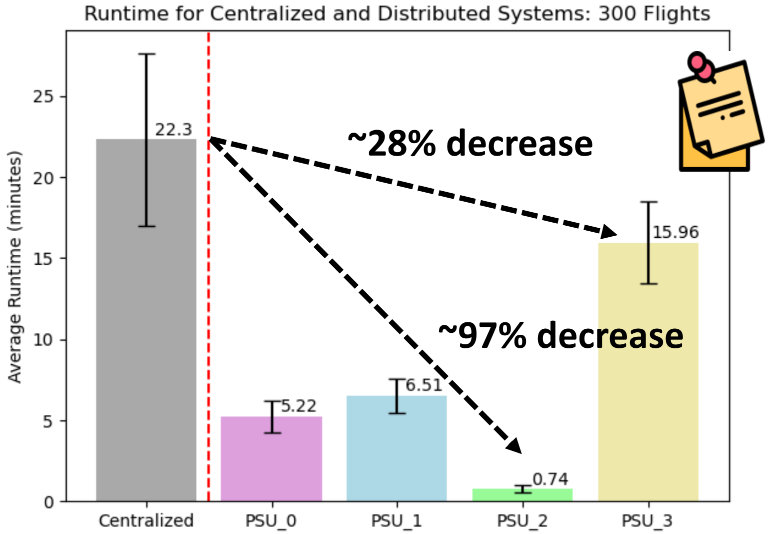
- Distributed PSU: multicopter has the least ground & airborne delay

- Medical operation has the least ground & airborne delay

150 Flights | 300 Flights

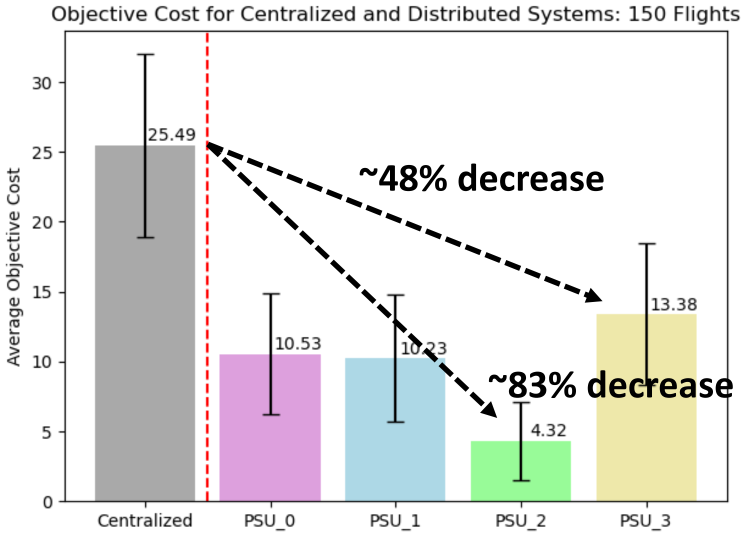

Runtime

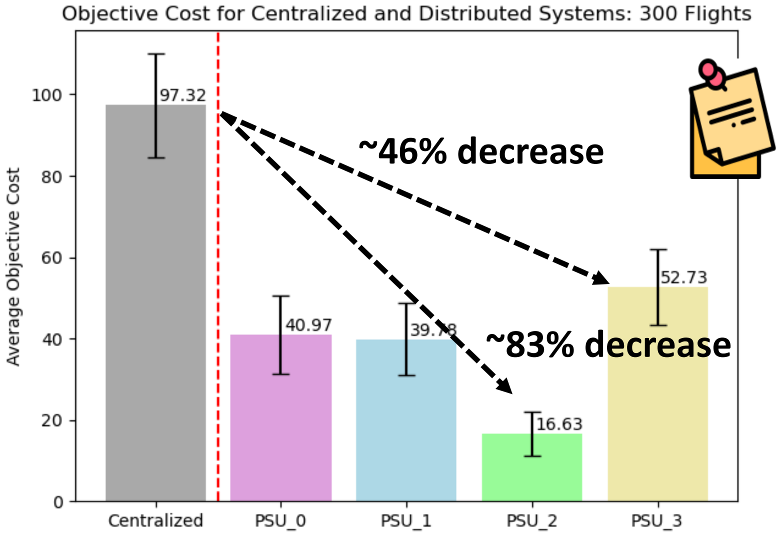




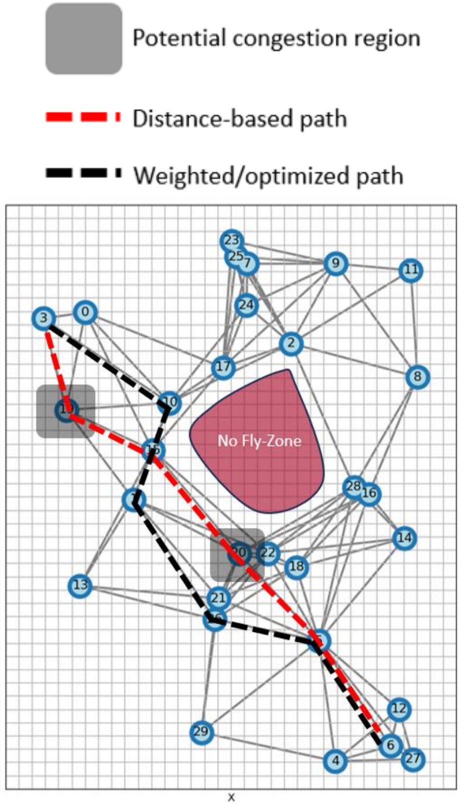
As the number of flights increases, distributed system performs better than centralized system in terms of runtime!


Cost

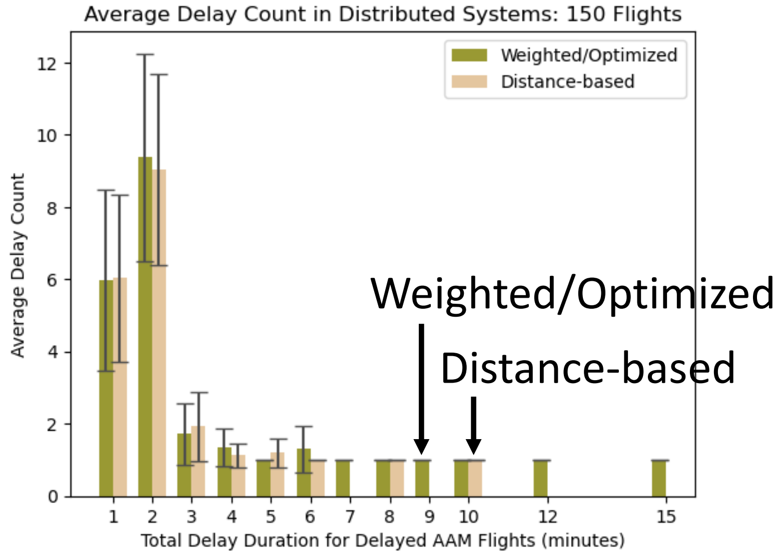


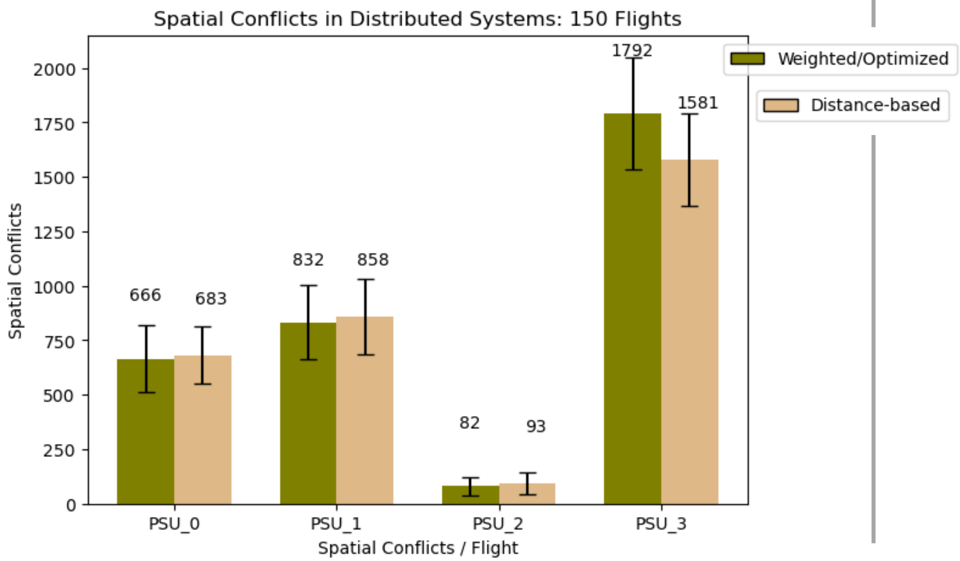


As the number of flights increases, objective cost remained almost the same!

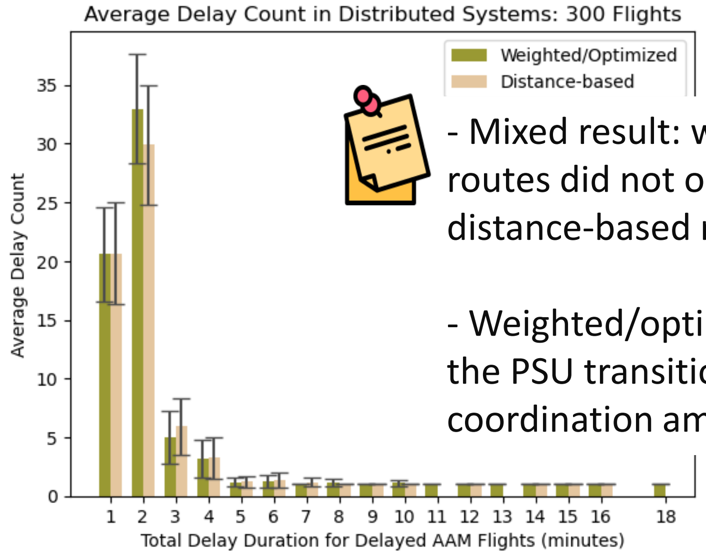


150 Flights



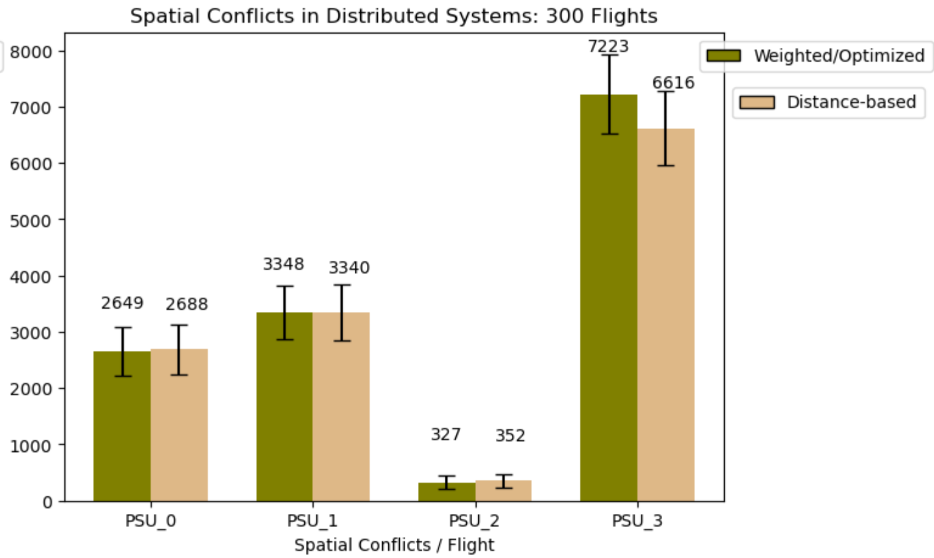


300 Flights



- Mixed result: weighted/optimized routes did not outperform the distance-based routes

- Weighted/optimized routes minimize the PSU transitions, reducing # of coordination among PSUs



Why AAM Matters to Me

The University of Texas at Austin
Aerospace Engineering and Engineering Mechanics
Cockrell School of Engineering

대한민국공군
REPUBLIC OF KOREA AIR FORCE

A2 SYS LAB

LATTICE

ENGINEERING AERO

ROBOTICS

Collins Aerospace
An RTX Business

NASA

Acknowledgement

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UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

COLLEGE OF ENGINEERING
KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH™

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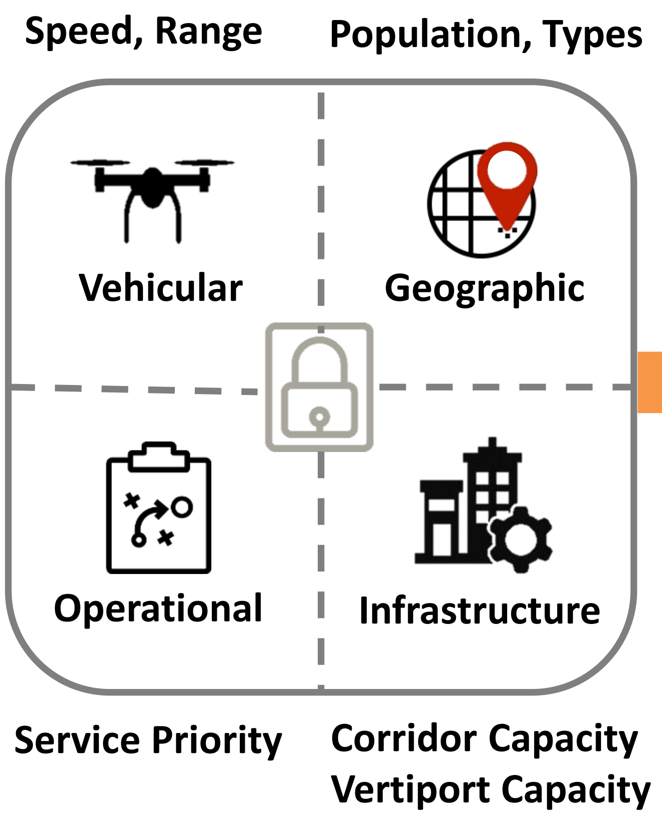
An RTX Business

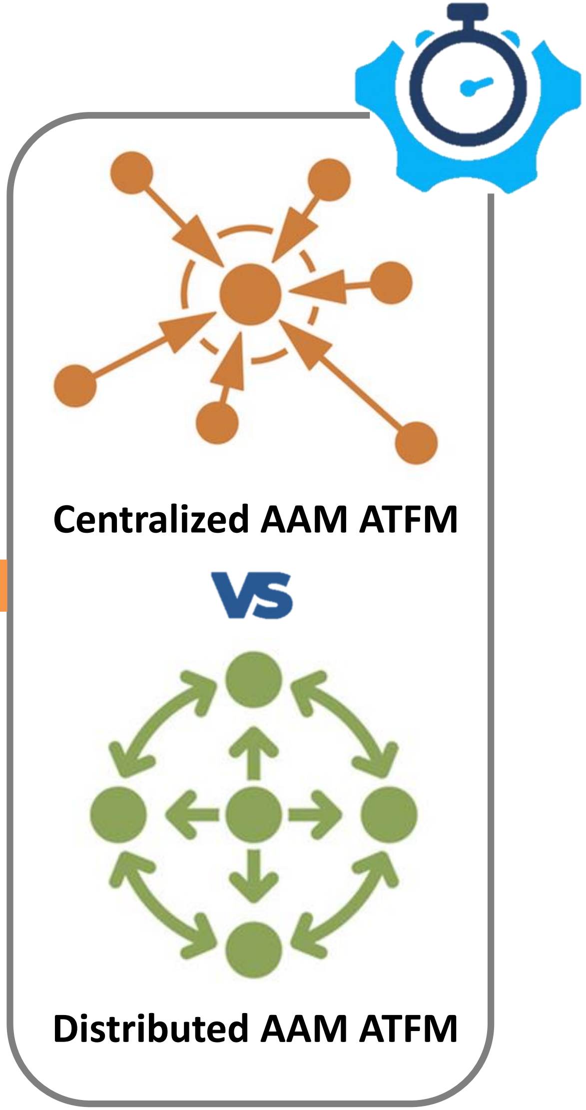
This work was funded by **Collins Aerospace**

Thank you, everyone

Backup Slides

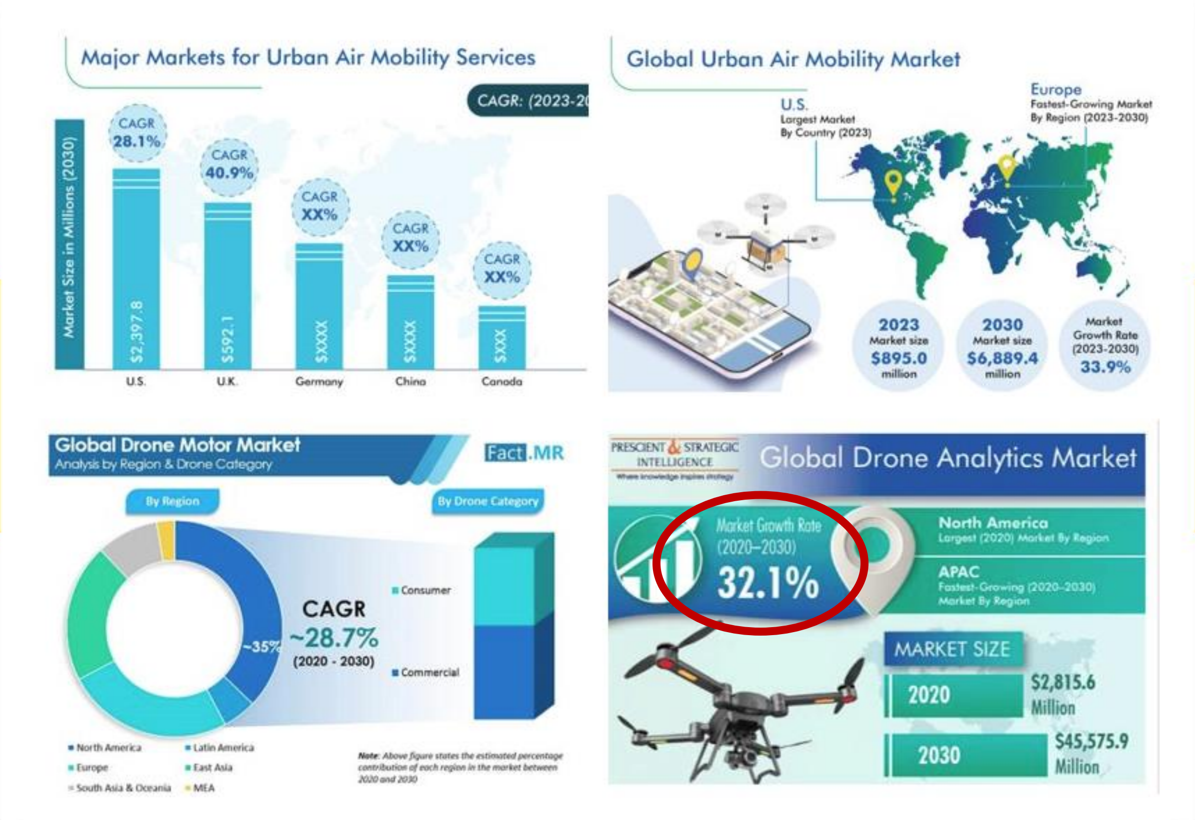
What Our Research Offers

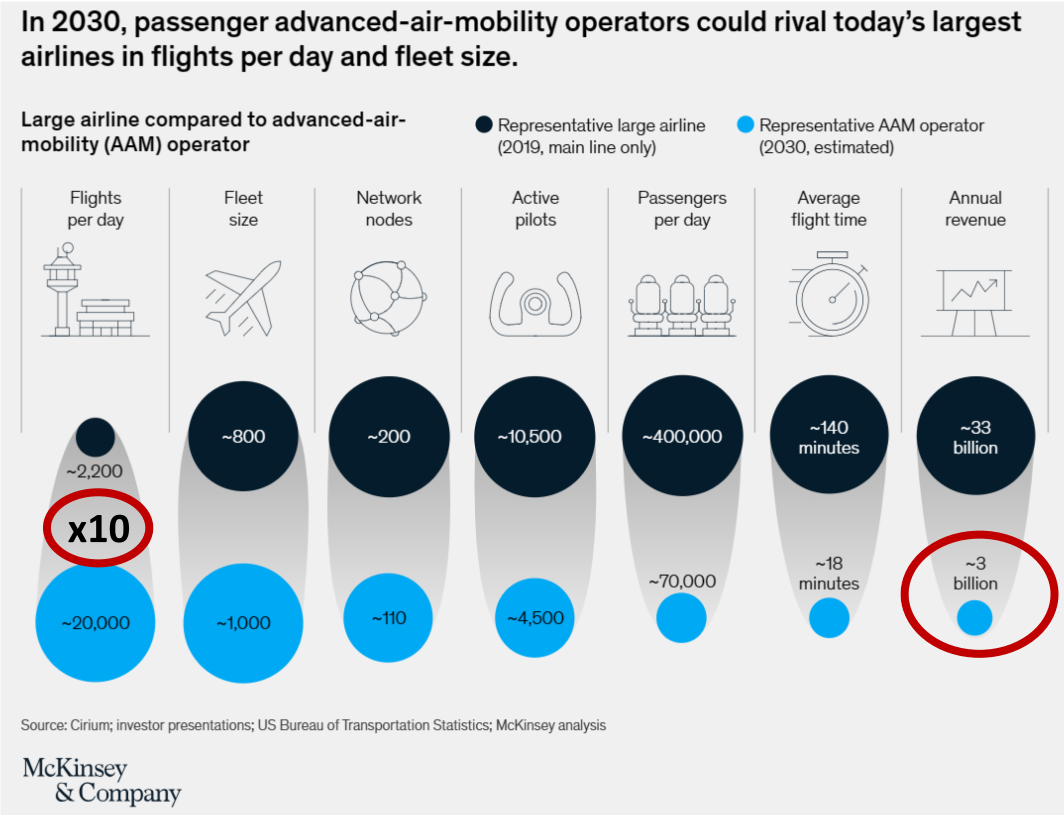




[1] NASA

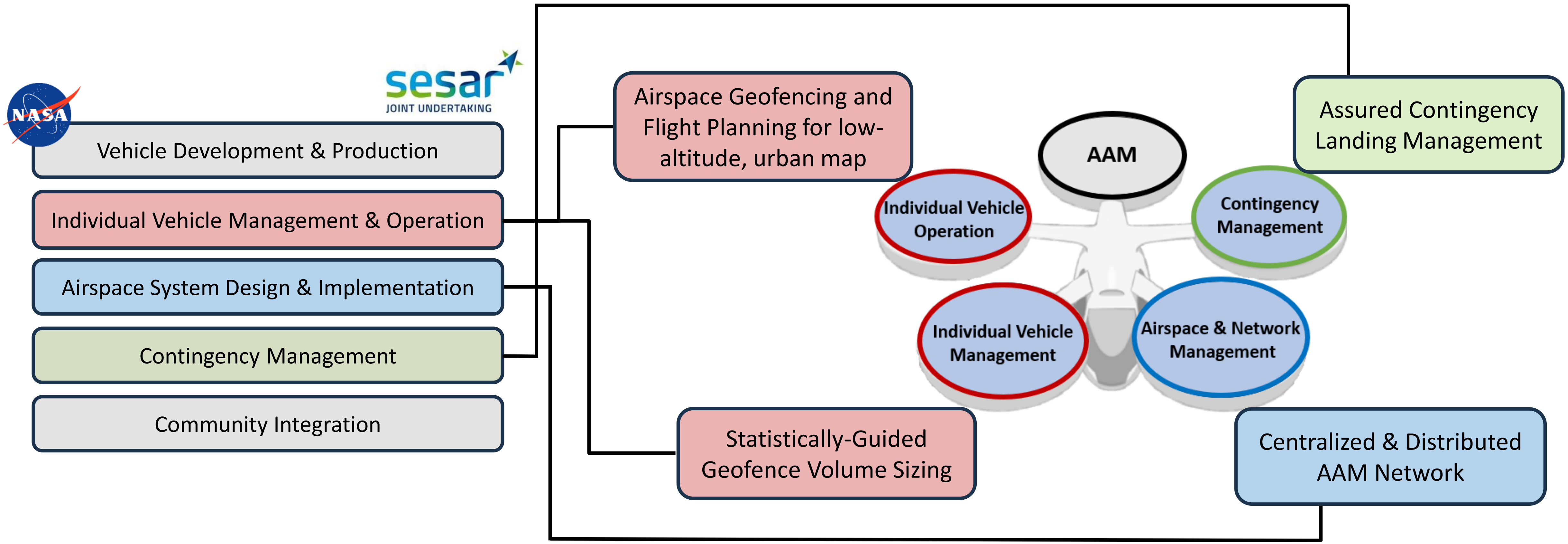
The Near-Future of AAM and Challenges





[1] Urban Air Mobility (UAM) Market Research Report: By Aircraft Type, Range, Operation Type - Global Industry Analysis and Growth Forecast to 2030, P&S Intelligence, 2020
[2] Drone Analytics Market Research Report, P&S Intelligence, 2021
[3] McKinsey & Company. "Perspectives on advanced air mobility." 2022.

Research Focus



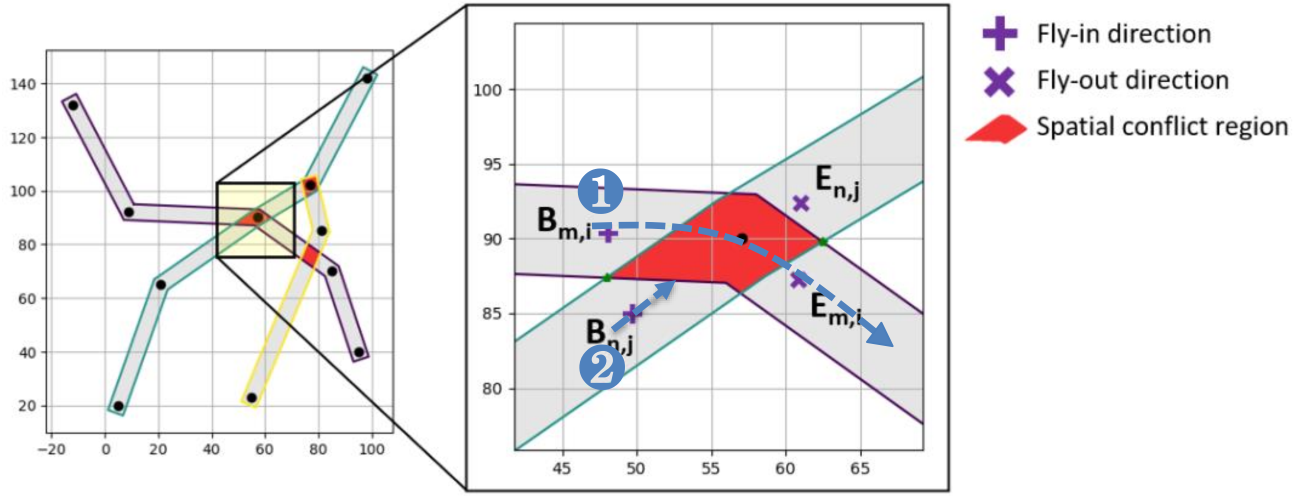
[1] Price, George, et al. "Urban air mobility operational concept (OpsCon) passenger-carrying operations." (2020).
[2] Goodrich, Kenneth H., and Colin R. Theodore. "Description of the NASA urban air mobility maturity level (UML) scale." *AIAA Scitech 2021 forum*. 2021.

Methods and Algorithms

What Our Research Offers:

1. Airspace Sectorization
2. Corridor-based Route Planning
3. AAM Traffic Flow Management in Single (Centralized) PSU Setting
4. AAM Traffic Flow Management in Distributed PSU Settings

Spatial Conflict Detection & Temporal Conflict Detection



$$B_{m,i} > E_{n,j} + t_s \quad or \quad B_{n,j} > E_{m,i} + t_s$$

Centralized AAM Traffic Management

Set	
$\mathcal{F}$	Set of flights
$\mathcal{V}$	Set of vertiports
$\mathcal{D}$	Set of departure vertiports
$\mathcal{A}$	Set of arrival vertiports
$\mathcal{C}$	Set of corridors
$\mathcal{O}$	Set of flight operation time
$\mathcal{S}$	Set of spatially conflicted flight corridors

Decision Variables	
$w_{f,t}^{departure}$	1: if AAM flight f leaves at departure vertiport by time t. 0: otherwise.
$w_{f,t}^{arrival}$	1: if AAM flight f arrives at destination vertiport by time t. 0: otherwise.
$w_{f,t}^{k}$	1: if AAM flight f arrives at corridor k by time t. 0: otherwise.
$\mathcal{X}_c$	Binary variable, where c = (m,n,i,j) ∈ $\mathcal{S}$. $\mathcal{X}_c = 1$ if AAM flight m exits conflicted corridor i before AAM flight n enters conflicted corridor j. Otherwise, 0.
x_c	Binary variable, where c = (m,n,i,j) ∈ $\mathcal{S}$. $x_c = 1$ if AAM flight n exits conflicted corridor j before AAM flight m enters conflicted corridor i. Otherwise, 0.

Parameters	
a_f	scheduled arrival time of AAM flight f
d_f	scheduled departure time of AAM flight f
$l_{f,k}$	minimum time that AAM flight f takes to travel through corridor k
$u_{f,k}$	maximum time that AAM flight f takes to travel through corridor k
a_f	scheduled arrival time of AAM flight f
s_f	service priority of AAM flight f
t_s	safety separation time of spatially conflicted flight pairs
ϵ	delay equity weight
γ	cost ratio of airborne delay to departure delay
$\mathcal{T}_{v,t}$	take-off capacity at vertiport v at time t
$\mathcal{L}_{v,t}$	landing capacity at vertiport v at time t
$\mathcal{M}_k$	throughput capacity at corridor k
$B_{f,i}$	ratio of the conflict region's start point within corridor i relative to its full length, for flight f
$E_{f,i}$	ratio of the conflict region's end point within corridor i relative to its full length, for flight f

Centralized AAM Traffic Management Formulation

Cost Ratio of Airborne to Departure Delay

Equity of Assigning Departure Time

$$\text{Minimize} \sum_{f\in\mathcal{F}} \left\{ \sum_{t\in O} \left(\boxed{\gamma} \cdot \boxed{s_f} \cdot \boxed{(t-a_f)}^{\boxed{1+\epsilon}} \cdot \left(w^{arrival}_{f,t} - w^{arrival}_{f,t-1}\right)\right) - \sum_{t\in O} \left((\boxed{\gamma} - 1) \cdot \boxed{s_f} \cdot \boxed{(t-d_f)}^{\boxed{1+\epsilon}} \cdot \left(w^{departure}_{f,t} - w^{departure}_{f,t-1}\right)\right) \right\}$$

Actual Departure

Service Priority Actual Arrival

subject to

$$\sum_{t\in O}\left(w^{departure}_{f,t} - w^{departure}_{f,t-1}\right) \le \mathcal{T}_{v,t} \quad \forall f\in\mathcal{F}, \quad \forall v\in\mathcal{V}$$

$$\sum_{t\in O}\left(w^{arrival}_{f,t} - w^{arrival}_{f,t-1}\right) \le \mathcal{L}_{v,t}$$

$$\sum_{t\in O}\left(w^{k}_{f,t} - w^{k+1}_{f,t}\right) \le M_k \quad \forall f\in\mathcal{F}, \quad \forall k\in\mathcal{C}\cup\mathcal{D}\cup\mathcal{A}$$

$$\sum_{t\in O} t\cdot\left(w^{k'}_{f,t} - w^{k'}_{f,t-1}\right) - \sum_{t\in O} t\cdot\left(w^{k}_{f,t} - w^{k}_{f,t-1}\right) \ge l_{f,k} \quad \forall f\in\mathcal{F}, \quad \forall k,\ k'\in\mathcal{C}\cup\mathcal{D}\cup\mathcal{A}$$

$$\sum_{t\in O} t\cdot\left(w^{k'}_{f,t} - w^{k'}_{f,t-1}\right) - \sum_{t\in O} t\cdot\left(w^{k}_{f,t} - w^{k}_{f,t-1}\right) \le u_{f,k}$$

$$w^{k}_{f,t-1} - w^{k}_{f,t} \le 0 \quad \forall f\in\mathcal{F}, \quad \forall k\in\mathcal{C}\cup\mathcal{D}\cup\mathcal{A}, \quad \forall t\in O$$

$$\sum_{t\in O} w^{k}_{f,t} \ge 1 \quad \forall f\in\mathcal{F}, \quad \forall k\in\mathcal{C}\cup\mathcal{D}\cup\mathcal{A}$$

$$t\cdot w^{departure}_{f,t} \ge d_f \quad \forall f\in\mathcal{F}, \quad departure\in\mathcal{D}, \quad \forall t\in O$$

$$\sum_{t\in O} t\cdot\left(w^{i}_{m,t} - w^{i}_{m,t-1}\right) + \left(\sum_{t\in O} t\cdot\left(w^{i+1}_{m,t} - w^{i+1}_{m,t-1}\right) - \sum_{t\in O} t\cdot\left(w^{i}_{m,t} - w^{i}_{m,t-1}\right)\right)\cdot E_{m,i} + t_s$$
$$\le M\cdot(1-X_c) + \sum_{t\in O} t\cdot\left(w^{j}_{n,t} - w^{j}_{n,t-1}\right) + \left(\sum_{t\in O} t\cdot\left(w^{j+1}_{n,t} - w^{j+1}_{n,t-1}\right) - \sum_{t\in O} t\cdot\left(w^{j}_{n,t} - w^{j}_{n,t-1}\right)\right)\cdot B_{n,j}$$
$$\forall (m,n,i,j) = c_i \in \mathscr{C}$$

$$\sum_{t\in O} t\cdot\left(w^{j}_{n,t} - w^{j}_{n,t-1}\right) + \left(\sum_{t\in O} t\cdot\left(w^{j+1}_{n,t} - w^{j+1}_{n,t-1}\right) - \sum_{t\in O} t\cdot\left(w^{j}_{n,t} - w^{j}_{n,t-1}\right)\right)\cdot E_{n,j} + t_s$$
$$\le M\cdot(1-x_c) + \sum_{t\in O} t\cdot\left(w^{i}_{m,t} - w^{i}_{m,t-1}\right) + \left(\sum_{t\in O} t\cdot\left(w^{i+1}_{m,t} - w^{i+1}_{m,t-1}\right) - \sum_{t\in O} t\cdot\left(w^{i}_{m,t} - w^{i}_{m,t-1}\right)\right)\cdot B_{m,i}$$
$$\forall (m,n,i,j) = c_i \in \mathscr{C}$$

$$X_c + x_c = 1$$

Centralized AAM Traffic Management Formulation

$$\text{Minimize} \quad \sum_{f \in \mathcal{F}} \left\{ \sum_{t \in O} \left(\gamma \cdot s_f \cdot (t - a_f)^{1+\epsilon} \cdot (w_{f,t}^{arrival} - w_{f,t-1}^{arrival}) \right) - \sum_{t \in O} \left((\gamma - 1) \cdot s_f \cdot (t - d_f)^{1+\epsilon} \cdot (w_{f,t}^{departure} - w_{f,t-1}^{departure}) \right) \right\}$$

subject to

Time-dependent TLOF Capacity Constraints

$$\sum_{t \in O} (w_{f,t}^{departure} - w_{f,t-1}^{departure}) \le \mathcal{T}_{v,t} \quad \forall f \in \mathcal{F}, \quad \forall v \in \mathcal{V}$$

$$\sum_{t \in O} (w_{f,t}^{arrival} - w_{f,t-1}^{arrival}) \le \mathcal{L}_{v,t}$$

Corridor Throughput Capacity Constraint

$$\sum_{t \in O} (w_{f,t}^{k} - w_{f,t}^{k+1}) \le \mathcal{M}_k \quad \forall f \in \mathcal{F}, \quad \forall k \in \mathcal{C} \cup \mathcal{D} \cup \mathcal{A}$$

AAM Vehicle-type Speed Constraints

$$\sum_{t \in O} t \cdot (w_{f,t}^{k'} - w_{f,t-1}^{k'}) - \sum_{t \in O} t \cdot (w_{f,t}^{k} - w_{f,t-1}^{k}) \ge l_{f,k} \quad \forall f \in \mathcal{F}, \quad \forall k,\ k' \in \mathcal{C} \cup \mathcal{D} \cup \mathcal{A}$$

$$\sum_{t \in O} t \cdot (w_{f,t}^{k'} - w_{f,t-1}^{k'}) - \sum_{t \in O} t \cdot (w_{f,t}^{k} - w_{f,t-1}^{k}) \le u_{f,k}$$

Corridor Confinement Constraints

$$w_{f,t-1}^{k} - w_{f,t}^{k} \le 0 \quad \forall f \in \mathcal{F}, \quad \forall k \in \mathcal{C} \cup \mathcal{D} \cup \mathcal{A}, \quad \forall t \in O$$

$$\sum_{t \in O} w_{f,t}^{k} \ge 1 \quad \forall f \in \mathcal{F}, \quad \forall k \in \mathcal{C} \cup \mathcal{D} \cup \mathcal{A}$$

Assigned Departure Time constraint

$$t \cdot w_{f,t}^{departure} \ge d_f \quad \forall f \in \mathcal{F}, \quad departure \in \mathcal{D}, \quad \forall t \in O$$

Temporal Conflict Resolution Constraints

$$\sum_{t \in O} t \cdot (w_{m,t}^{i} - w_{m,t-1}^{i}) + \left(\sum_{t \in O} t \cdot (w_{m,t}^{i+1} - w_{m,t-1}^{i+1}) - \sum_{t \in O} t \cdot (w_{m,t}^{i} - w_{m,t-1}^{i}) \right) \cdot E_{m,i} + t_s$$
$$\le M \cdot (1 - X_c) + \sum_{t \in O} t \cdot (w_{n,t}^{j} - w_{n,t-1}^{j}) + \left(\sum_{t \in O} t \cdot (w_{n,t}^{j+1} - w_{n,t-1}^{j+1}) - \sum_{t \in O} t \cdot (w_{n,t}^{j} - w_{n,t-1}^{j}) \right) \cdot B_{n,j}$$

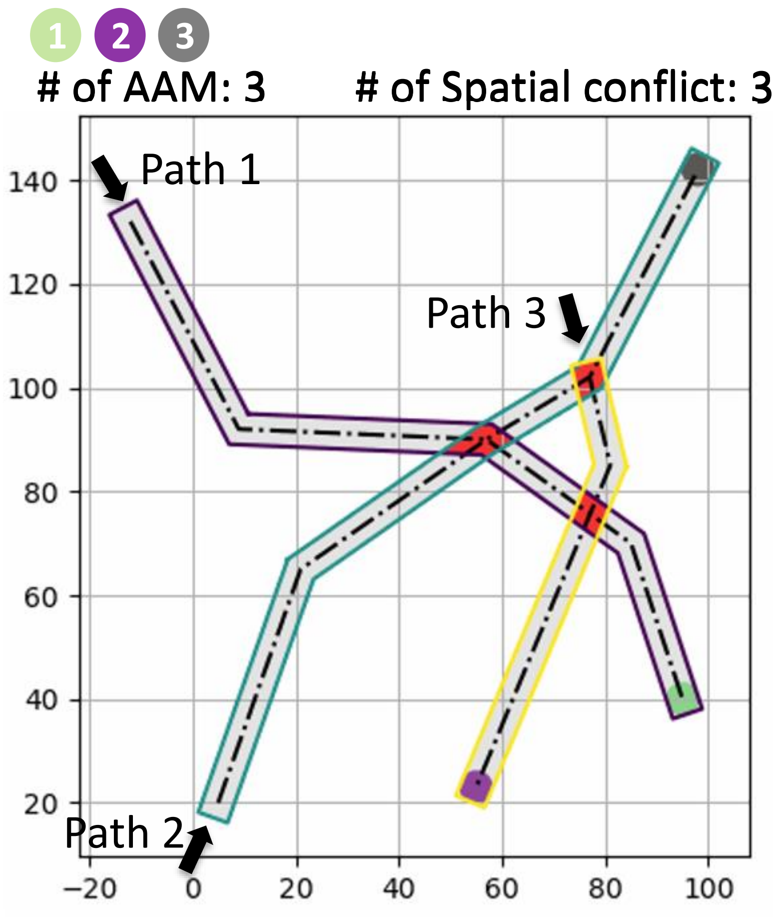
$$\forall (m, n, i, j) = c_i \in \mathscr{C}$$

$$\sum_{t \in O} t \cdot (w_{n,t}^{j} - w_{n,t-1}^{j}) + \left(\sum_{t \in O} t \cdot (w_{n,t}^{j+1} - w_{n,t-1}^{j+1}) - \sum_{t \in O} t \cdot (w_{n,t}^{j} - w_{n,t-1}^{j}) \right) \cdot E_{n,j} + t_s$$
$$\le M \cdot (1 - x_c) + \sum_{t \in O} t \cdot (w_{m,t}^{i} - w_{m,t-1}^{i}) + \left(\sum_{t \in O} t \cdot (w_{m,t}^{i+1} - w_{m,t-1}^{i+1}) - \sum_{t \in O} t \cdot (w_{m,t}^{i} - w_{m,t-1}^{i}) \right) \cdot B_{m,i}$$

$$\forall (m, n, i, j) = c_i \in \mathscr{C}$$

$$X_c + x_c = 1$$

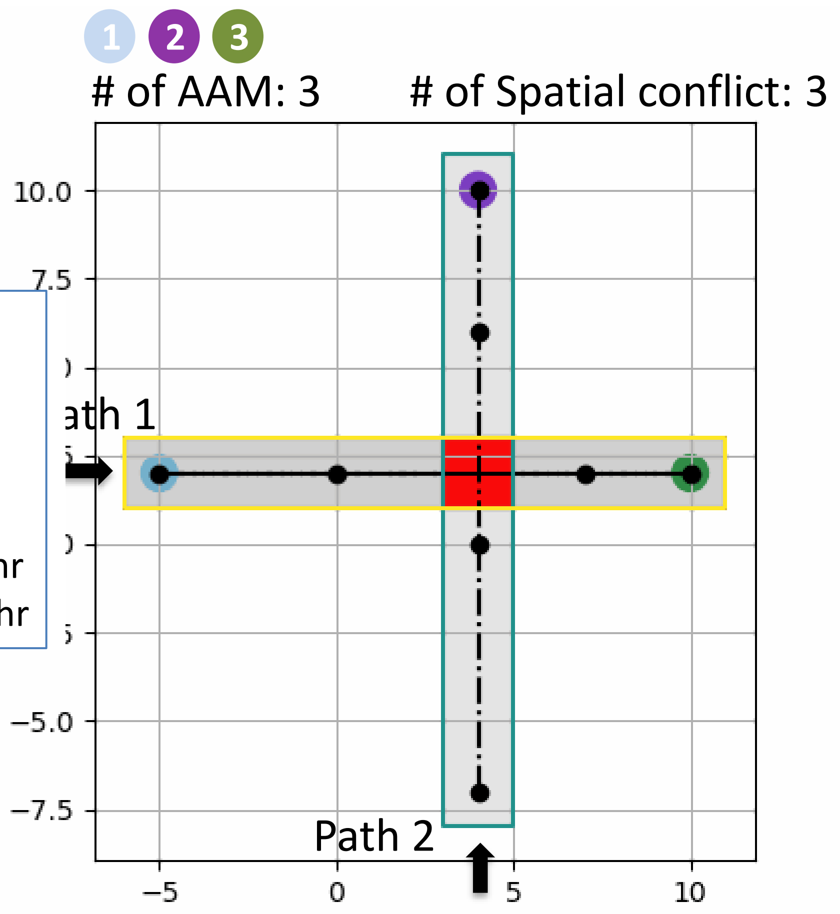
Centralized AAM Traffic Management Solutions



Multiple Corridor structure

Path 1: 159.3 km
Path 2: 160.1 km
Path 3: 84.7 km

Same Vehicle Type
Min. speed: 230 km/hr
Max. speed: 300 km/hr



Bi-Directional Multiple Corridor structure
(Vertical multi-lane corridor with capacity 1)

Distributed AAM Traffic Management

Decision Variables	
$b_{f,i}$	bargained entry/ exit transition time of AAM flight f in PSU i
$y_{i,j}^{f}$	payoff $\in [0, 1]$ of AAM flight f traveling through conflicted PSUs i and j
p_{i}^{f}	payoff $\in [0, 1]$ of AAM flight f entering/ exiting PSU i

Parameters	
n_i	negotiable bargain power of PSU i during flight operation time window O
$t_{f,i}$	optimal entry/ exit time of AAM flight f in PSU i from low-level MIP
$\delta_{i,j}^{f}$	time difference between an AAM flight f's optimal departure from PSU i and its optimal arrival at adjacent PSU j, where PSUs i and j are in conflict
$\mathcal{P}_f$	transition pseudo-vertiport(s) for flight f
$\mathscr{C}_{f,i}$	total number of corridors AAM flight f travels through inside PSU i
$\mathscr{T}_i$	total number of transition corridors in PSU i
$\mathscr{S}_i$	total number of spatially conflicted flight paths inside PSU i
β_{1-3}	bargain parameter weight factors for $\mathscr{C}_{f,i}$, $\mathscr{T}_i$, $\mathscr{S}_i$

Methods and Algorithms

Key Objectives:

1. PSU Airspace Sectorization
2. Corridor-based Route Planning
3. AAM Traffic Flow Management in Single (Centralized) PSU Setting
4. AAM Traffic Flow Management in Distributed PSU Settings

Game Theoretic Approach

Game Type	Objective	Decision-Making Approach	Example
Cooperative	Maximize total system throughput Minimize overall air delay	Collaborative decisions to optimize corridor usage and airspace efficiency	PSUs forming a coalition for joint optimization
Non-Cooperative	Maximize individual PSU's throughput Minimize its own airspace delay	Independent decisions by each PSU, optimizing for individual goals	PSUs optimizing airspace without coordination

Distributed AAM Traffic Management Formulation

Cooperative Nash Bargain

Negotiable bargain power of PSU i

$$n_i = \beta_1 \cdot \sum_{f=1}^{N} \frac{1}{\mathscr{C}_{f,i}} + \beta_2 \cdot \mathscr{T}_i + \beta_3 \cdot \mathscr{S}_i$$

AAM traffic density,
# of transition corridors,
# of spatial conflicts

$$\sum_{i=1}^{3} \beta_i = 1, \quad 0 < \beta_i < 1$$

Weight factors

Transition time equity function (i.e., "utility function")

$$\text{Maximize} \quad U_i \cdot U_j$$
$$\text{subject to} \quad n_j \geq n_i \quad \forall f \in \mathcal{F}, \quad \forall \text{ [conflicted PSU pair (i,j)]}$$
$$U_i(y^f_{i,i}) = 1 - y^f_{i,i}$$
$$U_j(y^f_{i,j}) = \left(y^f_{i,j}\right)^{\frac{n_i}{n_j}}$$

Modified Objective Function

$$\text{Minimize} \quad \sum_{f \in \mathcal{F}} \left\{ \sum_{t \in O} \left(\gamma \cdot s_f \cdot (t - a_f)^{1+\epsilon} \cdot (w^{arrival}_{f,t} - w^{arrival}_{f,t-1}) \right) - \sum_{t \in O} \left((\gamma - 1) \cdot s_f \cdot (t - d_f) \cdot (w^{departure}_{f,t} - w^{departure}_{f,t-1}) \right) \right\}$$

Additional Constraint

$$w^{\mathcal{P}_f}_{f,b_{f,i}} + w^{\mathcal{P}_f}_{f,b_{f,i}-1} == 1$$

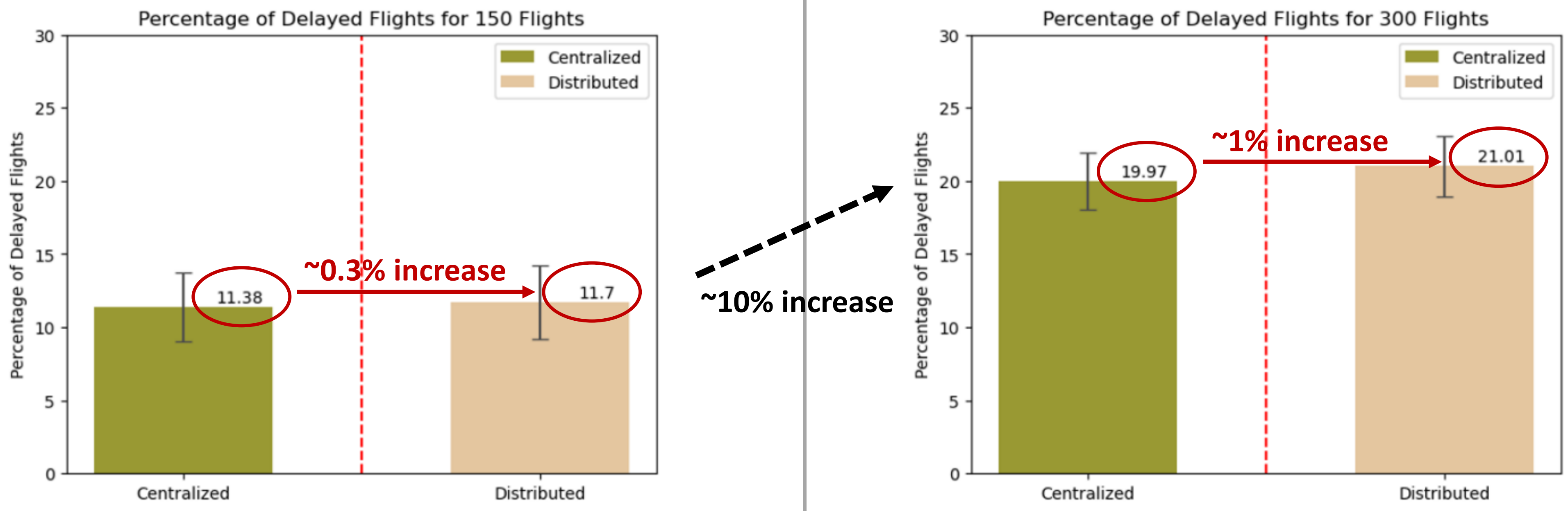
Relaxed Constraint

$$t \cdot w^{departure}_{f,t} \geq d_f \quad \forall f \in \mathcal{F}, \quad departure \in \mathcal{D}, \quad \forall t \in O$$

Negotiable bargaining power of PSUs varies with each operational time window

Simulation Analysis

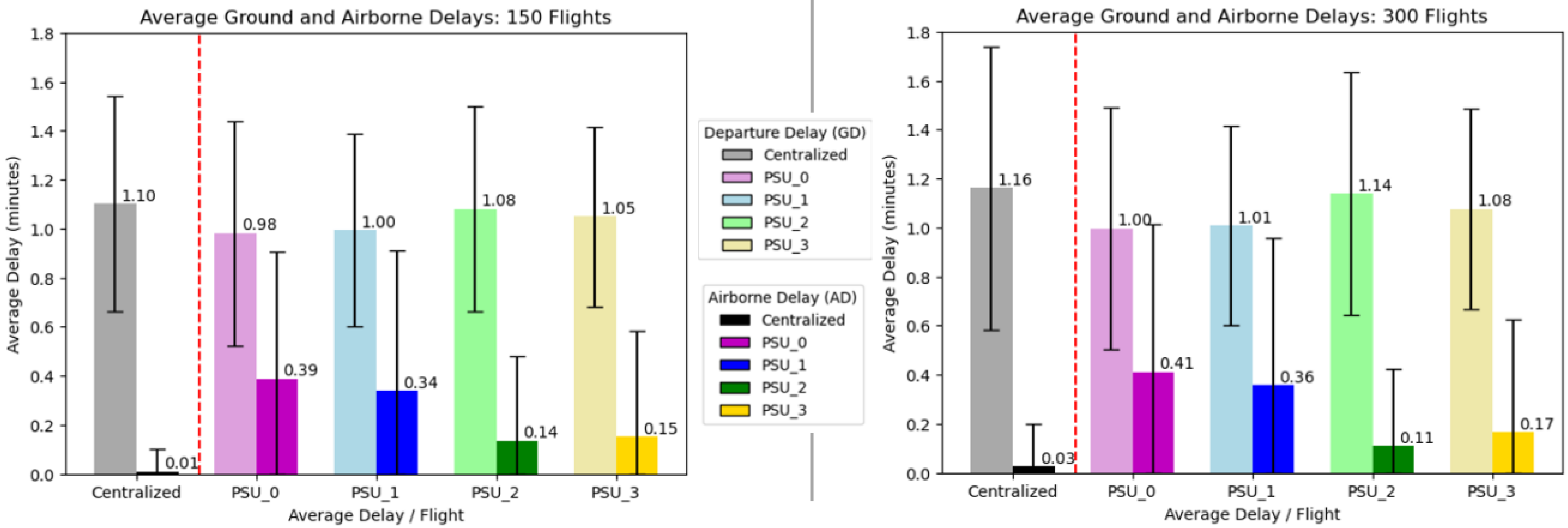
150 Flights | 300 Flights



Distributed AAM traffic management solution remains largely unaffected by its sub-optimality after cooperative negotiation among conflicting PSUs

150 Flights

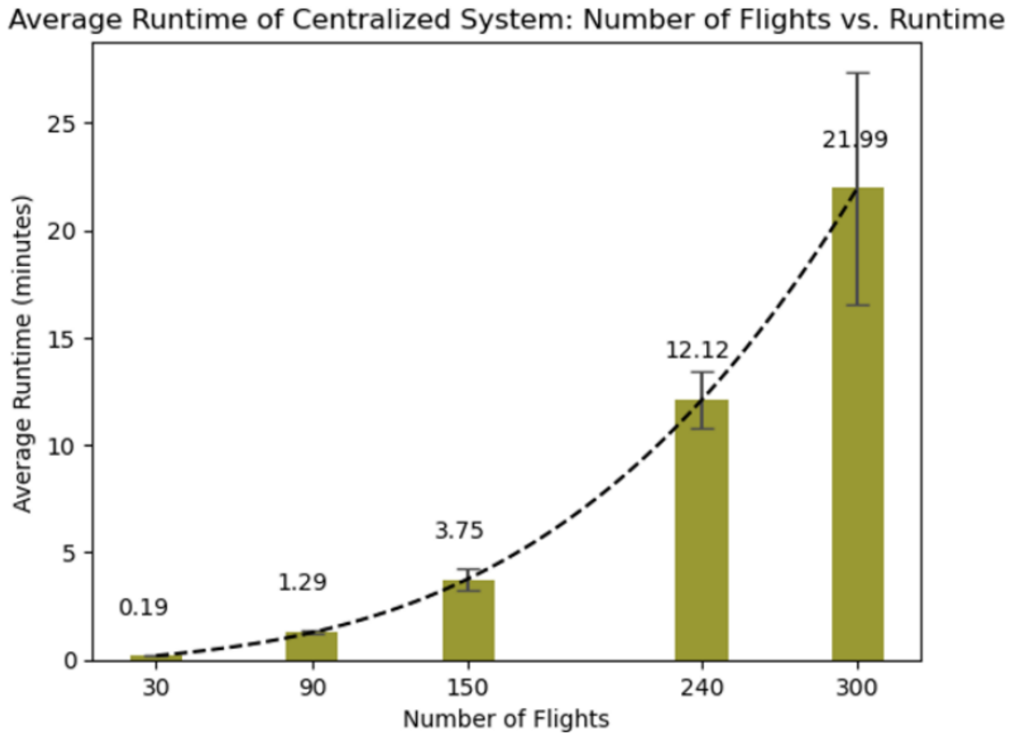
300 Flights



- As the number of AAM flight increases, more ground & airborne delays are observed

- Distributed system did not incur significantly greater delay than the centralized system

Simulation Analysis



Scalability: computation time has cubic increase for centralized system