

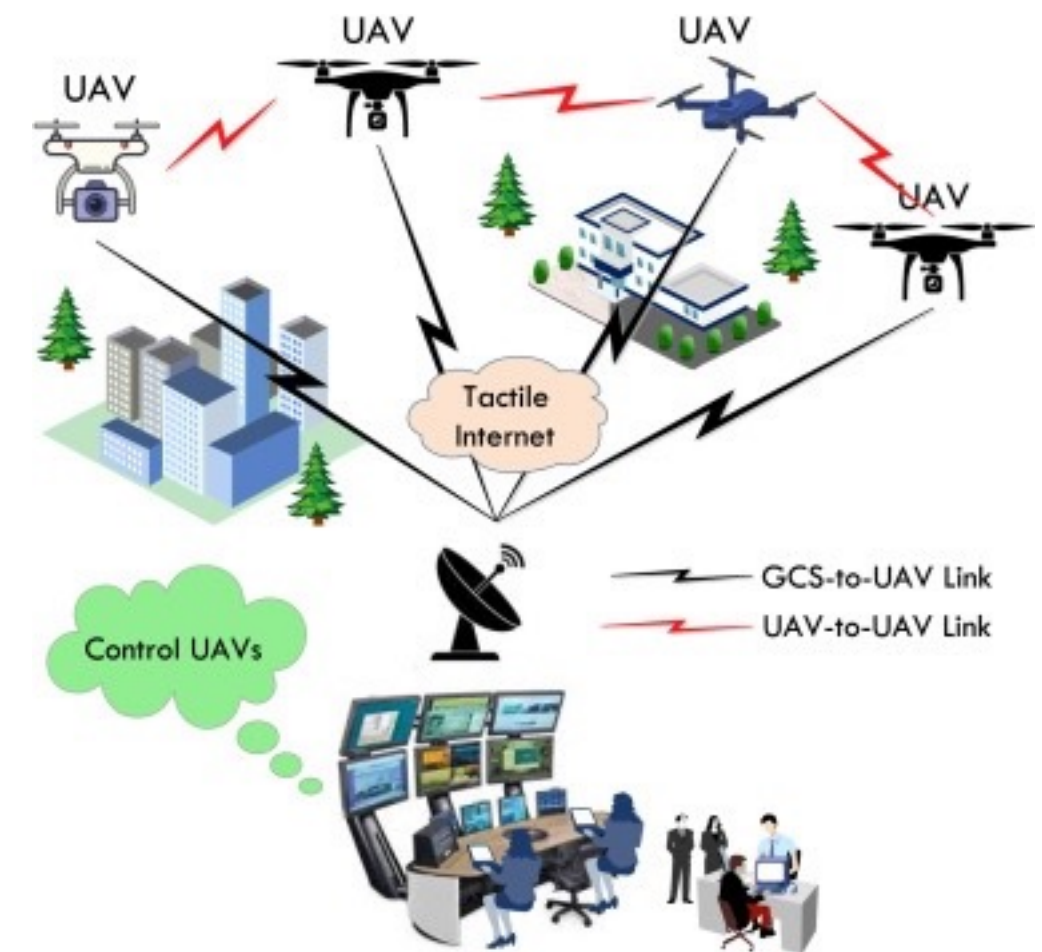
A Risk-aware Spatio-temporal Scheduler for Large-scale UAV Operations

Speaker: Wenxuan Wang

Authors: Wenxuan Wang, Prof Arnab Majumdar, Prof Washington Ochieng, Dr Jose Escribano

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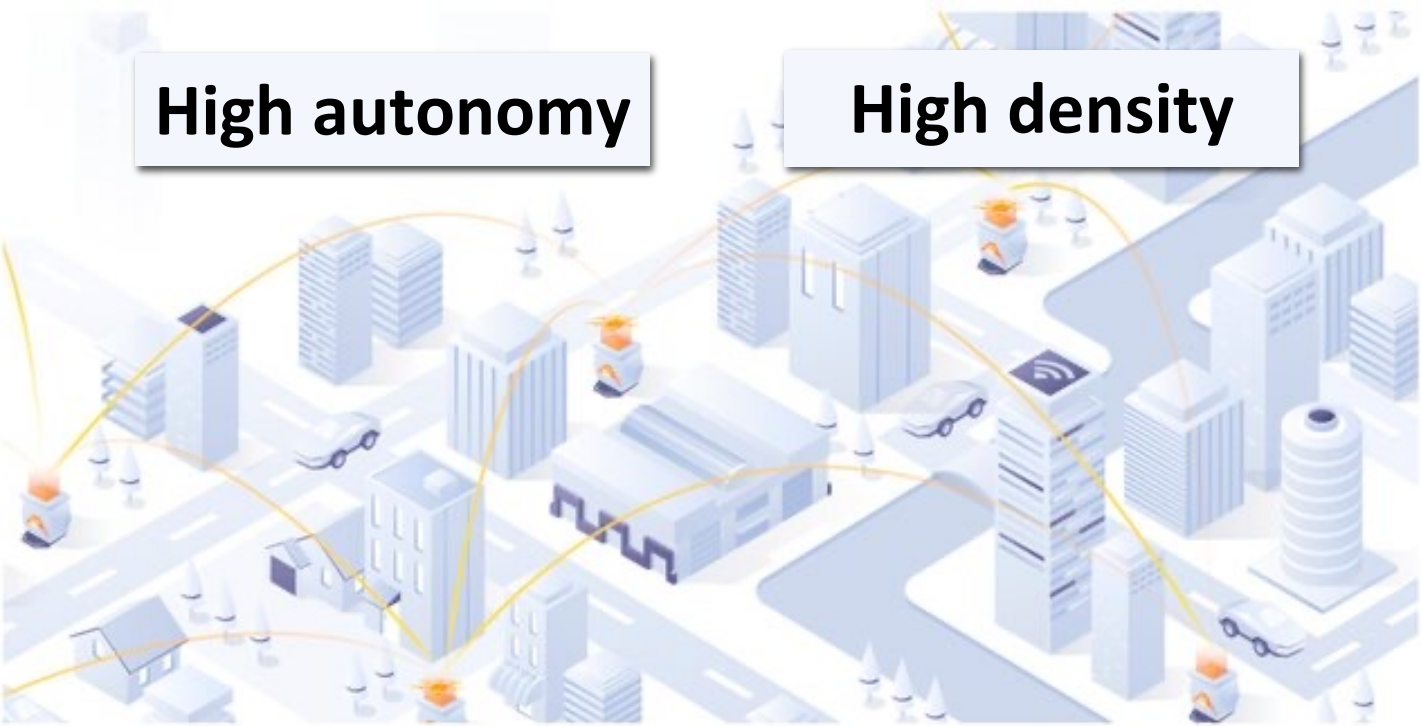
Background

U-SPACE CONOPS AND ARCHITECTURE
(EDITION 4)

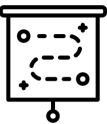


the operators to plan and declare their operations. When required, airspace structures are defined, temporarily or permanently, to allow drone operations (e.g., corridors for point-to-point goods or passenger carriage).

- U-space airspaces are defined:
 - In controlled airspace, crewed aviation is not allowed to enter U-space airspace hence ensuring separation from all UAS operations. Using the concept of Dynamic Airspace Reconfiguration (DAR), Air Traffic Control can temporarily change the boundaries of U-space by deactivating parts of the U-space airspace to allow for exceptional passage of crewed aircraft. The U-space Service Providers (USSPs) are informed by ATC if and when DAR is being used so they can adapt their flight authorisations in order for the drone operators to no longer use these temporarily deactivated parts of the U-space airspace.
 - In uncontrolled airspace, crewed aviation is allowed to freely enter U-space airspace provided that it is electronically conspicuous.
- In U-space airspace conflict resolution is strategic, that is, the plans are free of conflicts.
- Within U-space airspace, BVLOS operations are significantly easier to organise than has been possible before.
- Traffic densities are expected to be relatively low. In the initial period flights are expected to be widely spaced.



Conflict Resolution:



Strategic resolution – occurring in planning

Tactical avoidance – shortly before departure



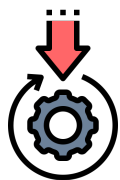
Escape maneuvers – seconds before conflicts

“...In U-space airspace, conflict resolution is strategic, that is the plans are free of conflicts...”

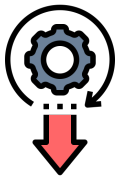
Gaps We Aim to Solve

Scheduling process

Flight requests



UAV scheduler



Spatial paths & temporal slots

Existing schedulers

Objectives

- Minimum delays
- Maximum event coverage
- Minimum conflict

Constraints

- Energy limits
- Conflict avoidance
- Completion time
- Payload capacity

Is Safety sufficiently considered?

- ✓ Conflict-related risk
- ✗ Other UAV operational risks

Objective:

To build a risk-aware scheduler that is scalable for large-scale urban UAV operations.

Recap of the UAV Operational Risk Model

Ground/Aerial Risk: Quantified by the Expected Number of Lethal Injuries

Likelihood

- Definition: the number of people on the ground potentially affected by a spontaneous UAV failure.

$$L(g, f) = p_g \rho_g \lambda_f$$

- p_g : probability that a UAV failure will hit grid g .
- ρ_g : population density (varies by grid type) in grid g .
- λ_f : Failure probability of UAV Flight f .

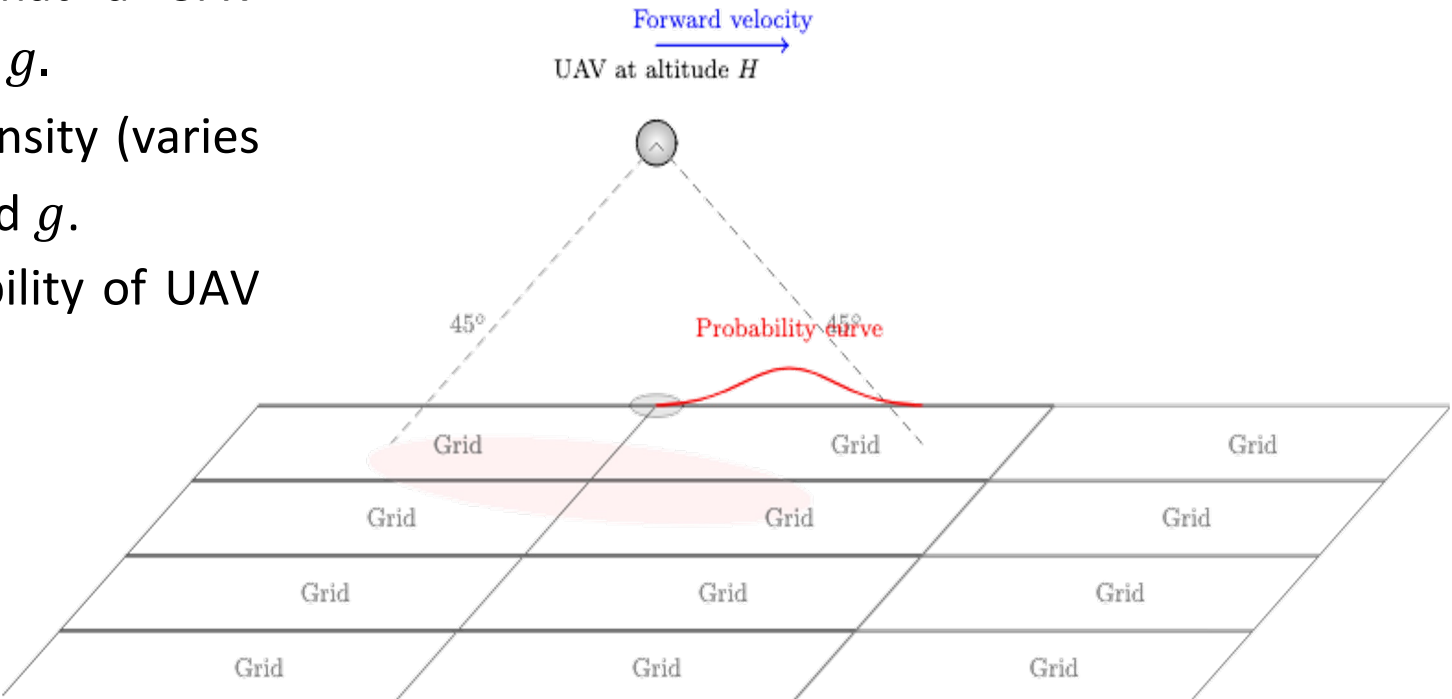
Severity

- Definition: the probability that a UAV failure will cause lethal injuries to those affected.
- The modelling of $S_{(g,f)}$ varies a lot for different grid types.

$$R_g = \sum_{f=1}^F L(g, f) S(g, f)$$

Airspace Segmentation

- Pavements x_p (for pedestrians).
- Roads x_r (for vehicles).
- Buildings x_b .



Severity Modelling - Pedestrians

Impact Energy

Defined as the sum of the kinetic energy, E_k , and the change in gravitational potential energy, ΔG , incurred from the loss of control unit impact.

$$E_{imp} = E_k + \Delta G = mg\Delta h + \frac{1}{2}mv^2$$

where:

 g denotes gravitational acceleration;
 m represents UAV mass;
 Δh is the UAV falling height;
 v is the UAV velocity.

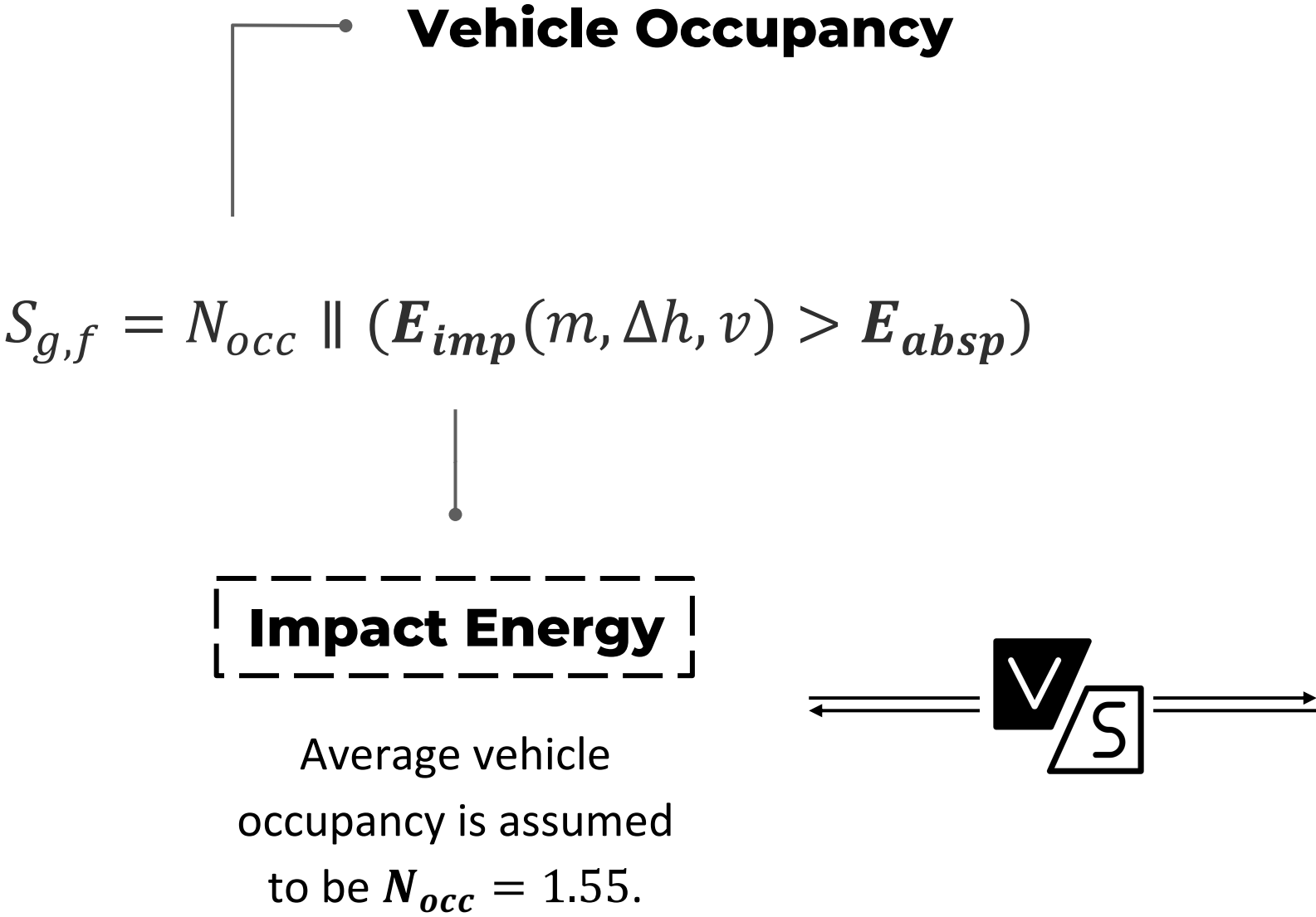
Minimal UAV Modelling



DJI MAVIC 3 ENTERPRISE
0.916kg | Maximal speed: 21 m/s

Minimal Mass m	4 kg
Minimal velocy v	4.24 m/s
Minimal falling height Δh	9.17 m
Impact energy E_{imp}	$R_g = 4 \times 9.8 \times 9.17 + \frac{1}{2} \times 4 \times 4.24^2 = 395.42$
Lethal threshold	79 joules (from North Atlantic Treaty)

Severity Modelling - Vehicles



Vehicle Absorption Capacity

A maximum energy absorption capacity E_{absp} of 2.8 kilojoules is assumed for an average vehicle to limit deformation to less than 127 millimeters when subjected to a force of 1.5 times its unloaded weight.

Lethal Threshold for Vehicle Occupants: 2.8 kilojoules

Severity Modelling - Buildings

Crash Area: Building roof

Loading values of crash to building roof

Loading Mode	Loading Value
Point loading	$M_P = 2.25\text{ kN}$
Distributed loading	$M_D = 3D^2$
Helipad loading	$M_H = 3000\sqrt{m}$

- Severity $S(g, f) = \rho_g D^2 (E_{imp}(M) // E_{res})$
- In all cases, total structural collapse is impossible.
- E_{res} : Building floor energy resistance.
- D : characteristic dimension – determined by population density and gravitational acceleration.

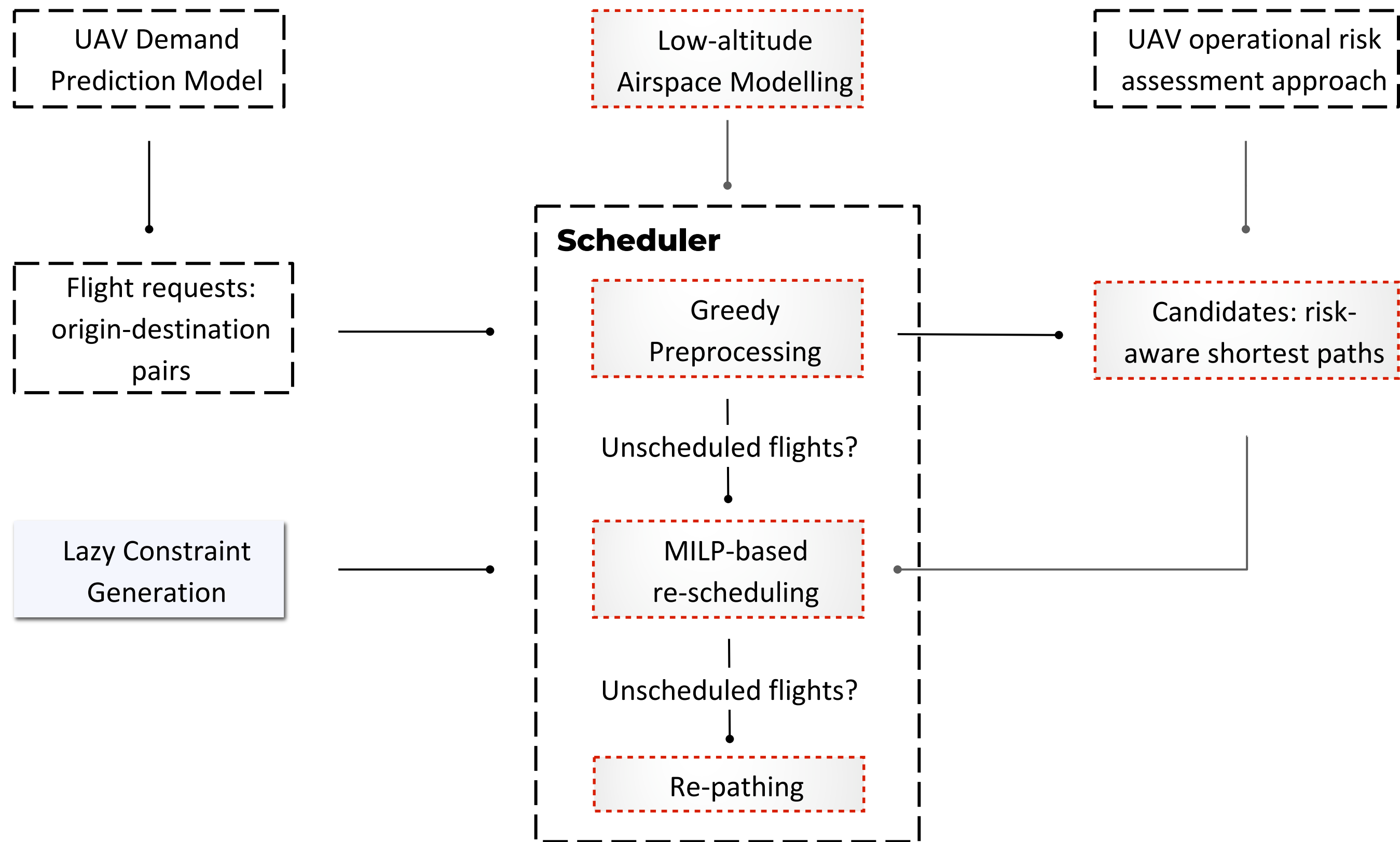
Crash Area: Building wall with standard coating

- Wall structural failure occurs only at a penetration distance of 220 millimetres, according to European standards.
- The Eurocode standard specifies a flat resistance of 250kN of force for a collision perpendicular to the direction of travel.

Crash Area: Building wall with Glass Panels

- For building wall structures constructed with glass panels, the severity is determined by the probability of glass fracture, $P(fracture)$, primarily depending on Blunt Criterion (BC), which is influenced by the UAV mass (m), velocity (v), and the dimensions of the glass pane - its width (w), height (h), and thickness (t).
- Blunt Criterion: $BC = \ln\left(\frac{mv^2}{2wht}\right)$
- $P(fracture) = 1 - \frac{1}{1 + e^{4.5854BC - 11.1656}}$

Scheduler Architecture



Methodology – Heuristics Preprocessing

To find risk-acceptable shortest paths for as many flights as possible with minimal computational overhead.

Objective: Maximize $\sum_{f \in F} w_f x_f$ ————— x_f : a binary variable indicating if flight f is scheduled or not
 w_f : weight of flight f

Subjective to:

$$\sum_{g \in P_f} L(g, f) S(g, f) \leq R_{max}, \quad \forall f \in F$$

Risk constraint

$R_{max} = 0.1$: maximum acceptable risk

$$\sum_{g \in P_f} h_{f,g} \leq T_f^{max}, \quad \forall f \in F$$

Endurance constraint

$h_{f,g}$: Operation time of f in grid g

$$I_{f_1,k} \cap I_{f_2,k} = \emptyset, \quad \forall f_1 \neq f_2, \forall k \in P_{f_1} \cap P_{f_2}$$

Conflict avoidance

$I_{f,k} = [t_f + kh_f, t_f + (k+1)h_f]$:
occupancy interval of f in grid k

$$0 \leq d_f \leq \Delta_{max}, \quad \forall f \in F$$

Launch flexibility

d_f : Non-negative launch delay

Methodology – MILP-based Core Scheduler

To improve the pre-scheduling outcomes and accommodate the remaining flights.

Objective: Minimize $\alpha \cdot \text{makespan} + \beta \sum_f (1 - u_f)$ ————— $u_f = 1$ if flight f is scheduled, otherwise 0;
This is to minimize unscheduled flights.

Subjective to: ————— The completion time of the last scheduled flight

Constraints in the pre-processor:

$$\sum_{g \in P_f} L(g, f) S(g, f) \leq R_{max}, \quad \forall f \in F$$

Risk constraint
 $R_{max} = 0.1$: maximum acceptable risk

$$\sum_{g \in P_f} h_{f,g} \leq T_f^{max}, \quad \forall f \in F$$

Endurance constraint
 $h_{f,g}$: Operation time of f in grid g

$$I_{f_1,k} \cap I_{f_2,k} = \emptyset, \quad \forall f_1 \neq f_2, \forall k \in P_{f_1} \cap P_{f_2}$$

Conflict avoidance
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Launch flexibility
 d_f : Non-negative launch delay

Why MILP: MILP can directly handle binary and integer decision variables; it's able to find the global optimum.

All pairwise conflict constraints lead to large and often intractable MILP formulations

Methodology – MILP-based Core Scheduler

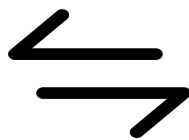
To improve the pre-scheduling outcomes and accommodate the remaining flights.

MILP limitation

All pairwise conflict constraints lead to large and often intractable MILP formulations.



Lazy Constraint: The scheduler begins with only the core temporal constraints. After solving the reduced model, it detects conflicts in provisional schedules, and only their corresponding separation constraints are added.

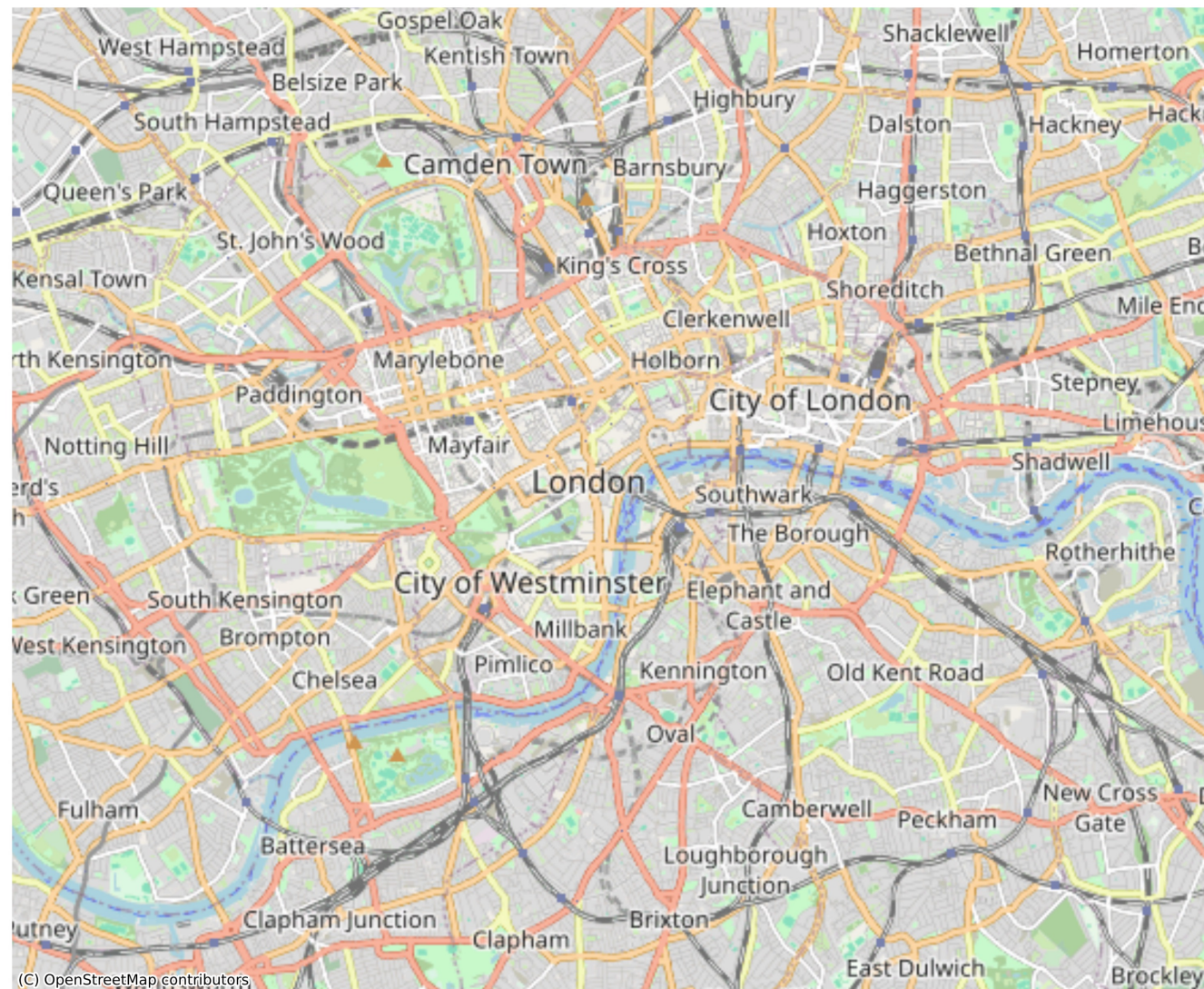


Algorithm 2 MILP-based Core UAV Scheduler with Iterative Constraint Generation

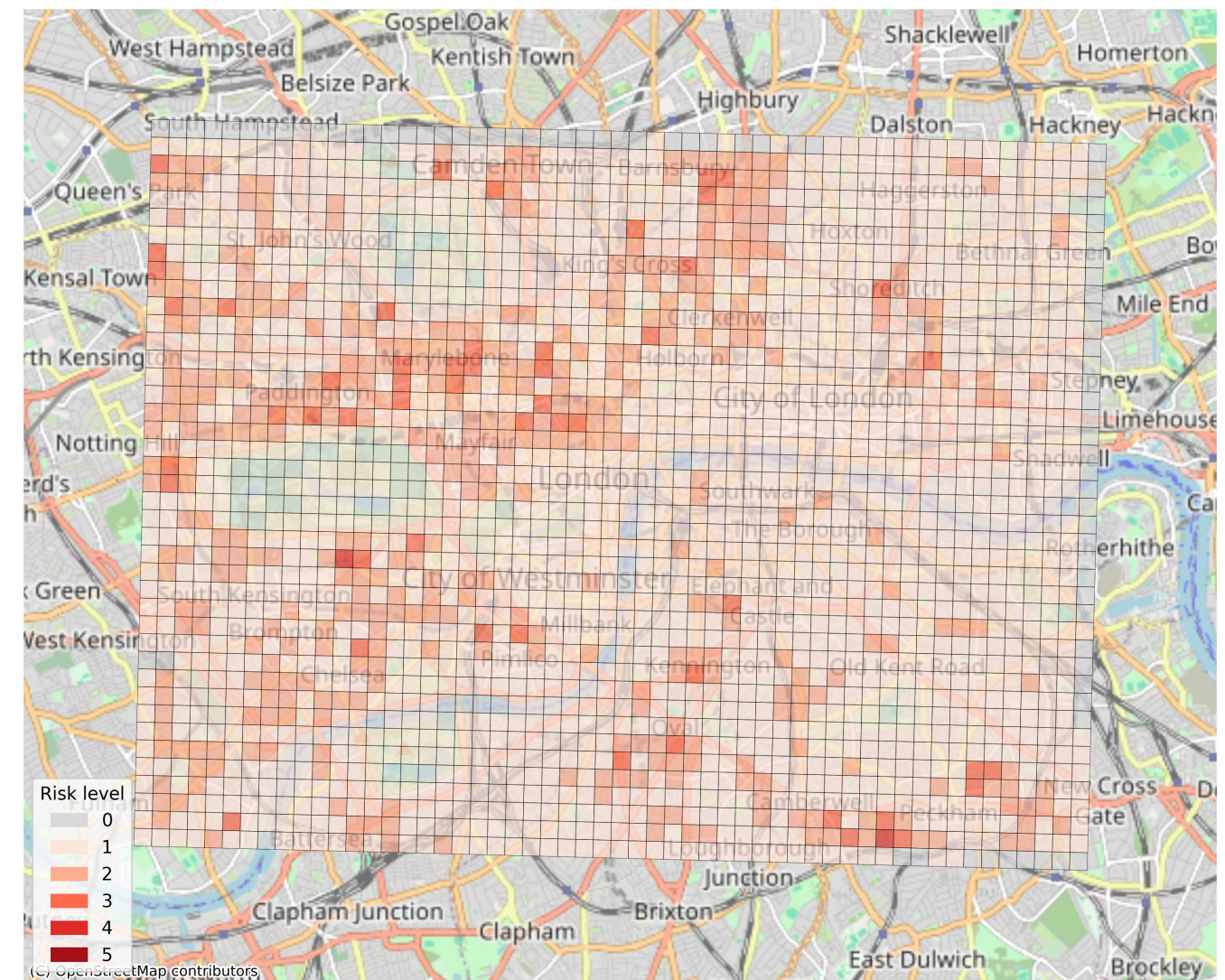
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MILPSCHEDULE( $\mathcal{S}, \mathcal{P}, \mathcal{U}$ )
  Input:  $\mathcal{S}, \mathcal{P}, \mathcal{U}$ 
  Output: Scheduled flights  $\mathcal{S}'$  with paths  $\mathcal{P}'$ , unsched-
    uled flights  $\mathcal{U}'$ 
   $\mathcal{S} \leftarrow \emptyset, \mathcal{U} \leftarrow \emptyset$ 
  Initialize  $\mathcal{M}$  with variables  $t_f, e_f, u_f, b_{ijck}$ 
   $\mathcal{M}.$ ADDCONSTRAINTS
   $\mathcal{M}.$ SETOBJECTIVE
  repeat
    Solve  $\mathcal{M} \rightarrow \{t_f, e_f, p_f \in \mathcal{P}\}$ 
     $\mathcal{C} \leftarrow \text{DETECTCONFLICTS}(\mathcal{F}, \mathcal{P}, \mathcal{S})$ 
    for each  $(i, j, c, k_i, k_j) \in \mathcal{C}$  do
       $\mathcal{M}.$ ADDITERATIVECONSTRAINTS
    end for
  until  $\mathcal{C} = \emptyset$  or objective stabilizes
   $\mathcal{P}' \leftarrow \mathcal{M}$ 
   $\mathcal{S}' \leftarrow \{f \in \mathcal{F} : u_f = 1\}$ 
   $\mathcal{U}' \leftarrow \{f \in \mathcal{F} : u_f = 0\}$ 
  return  $\mathcal{S}', \mathcal{P}', \mathcal{U}'$ 
```

Simulation – Study Area

Map of central London



Risk Map of the study area



- **Study space:** $51.47^{\circ} - 51.54^{\circ}N, 0.20^{\circ} - 0.50^{\circ}S$
- Between **Westminster** and the **city of London**
- Discretized into a **grid of $0.2km \times 0.2km$ cells**

- **Area:** $80 km^2$
- Leading to 2,754 cells
- Data gathered from **OpenStreetMap**

Simulation – Origin-Destination Pairs Generation

Flight categories

Emergency response

o is sampled around a corner c_{corner} , while d is sampled near the opposite diagonal corner c_{diag} .

Police activity

o is drawn from k Gaussian clusters centered at c_i ; d is sampled from the remaining part of the grid relative to o .

Delivery

Hubs h are sampled uniformly across the grid; spokes s_j are sampled around spoke centers c_j .

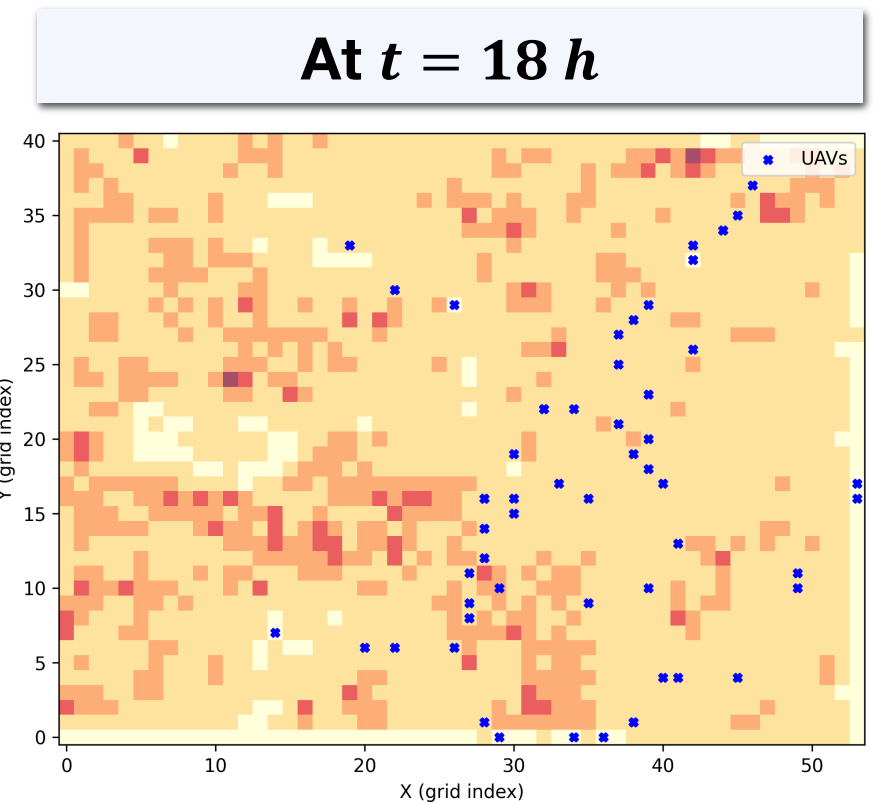
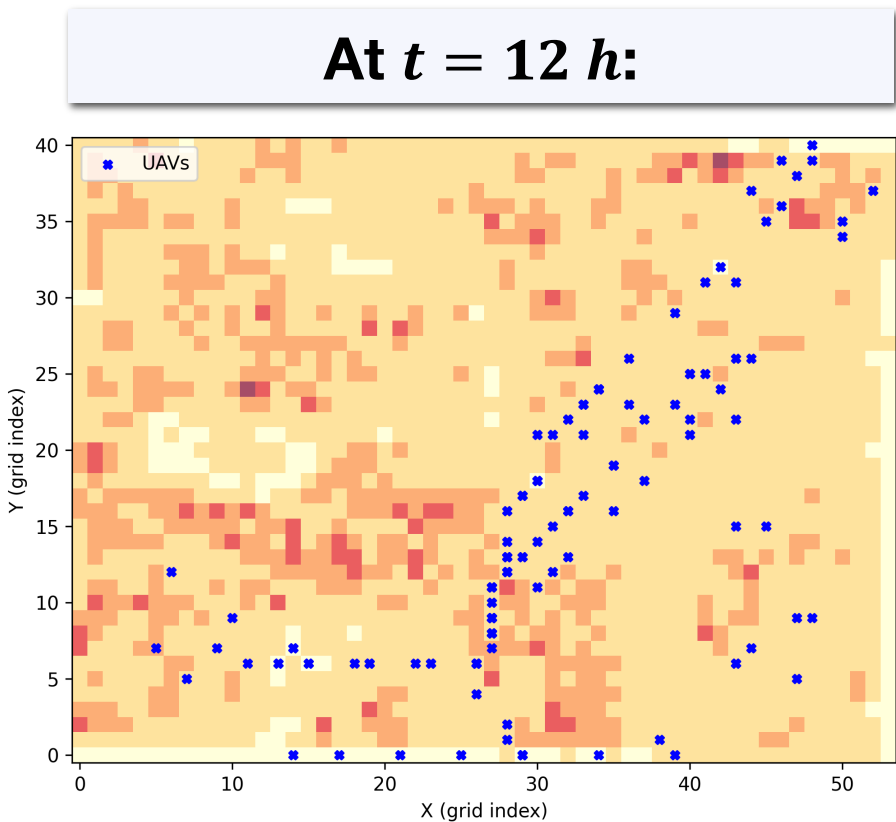
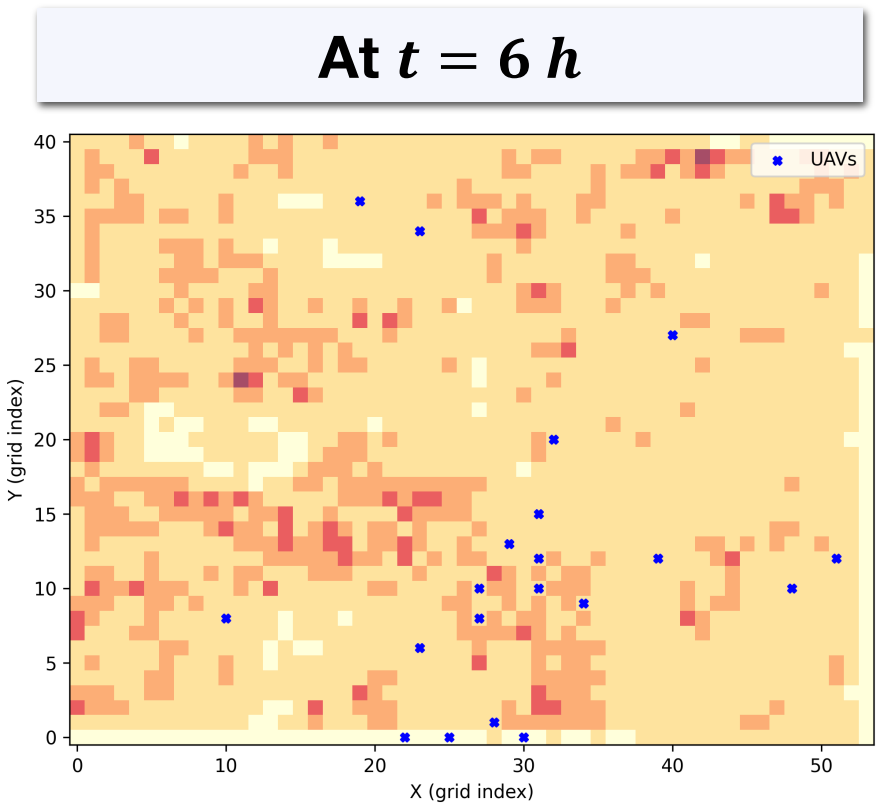
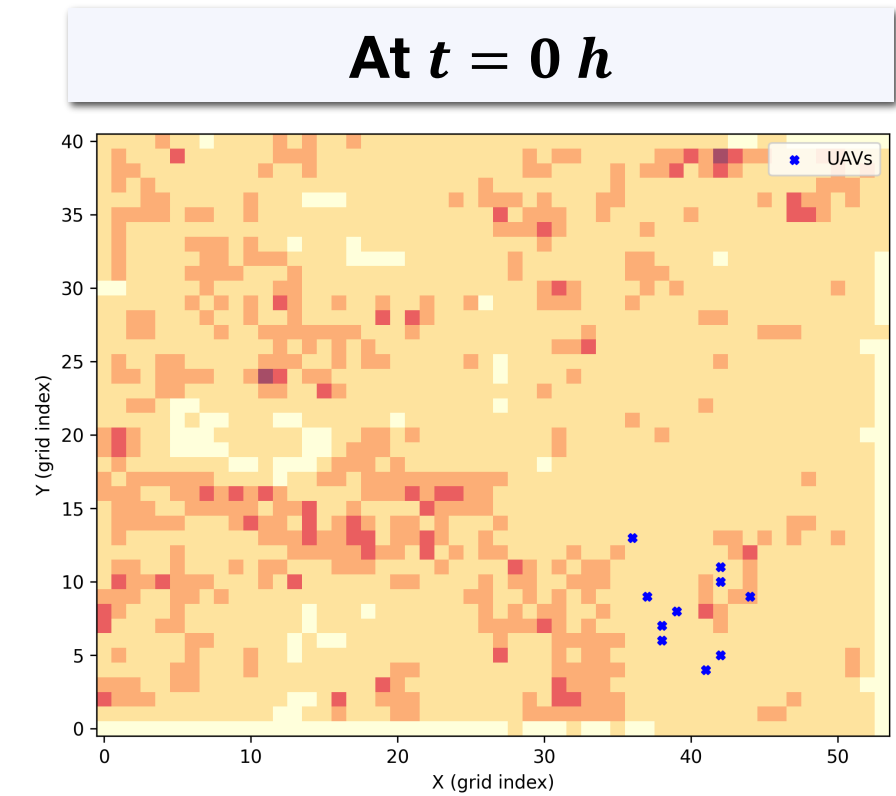
Passenger transport

Predefined m hubs are sampled uniformly; o and d are formed as $h_i \rightarrow h_j (i \neq j)$; both h_i and h_j are perturbed by Gaussian noise to capture local dispersion

Flight demand simulation

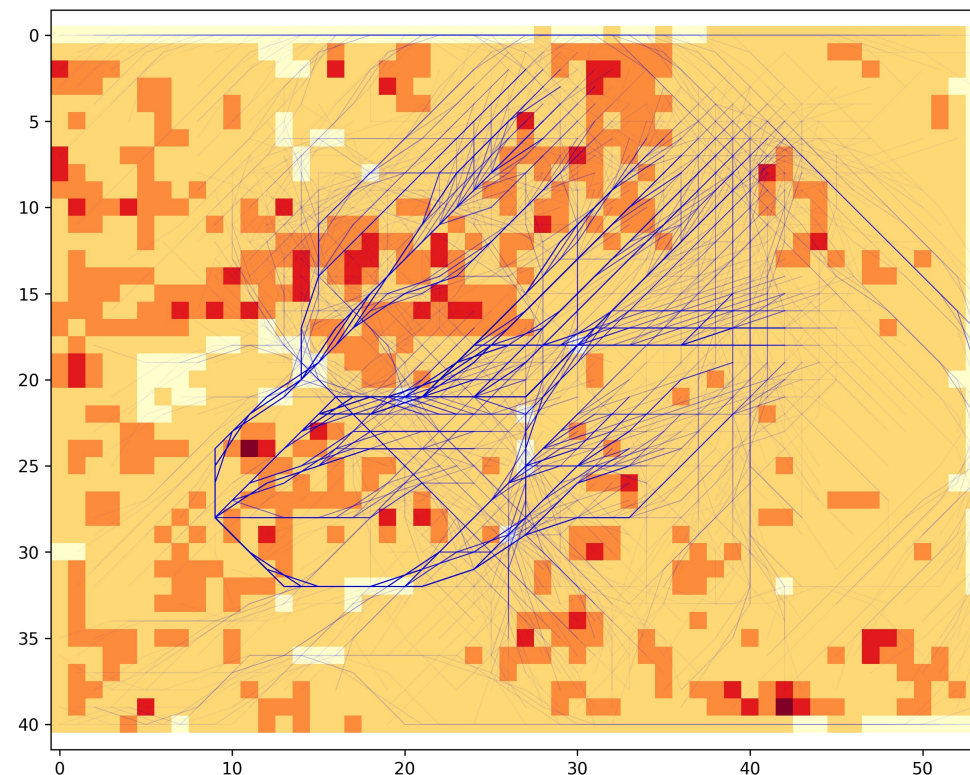
Operation category	Priority	Origin (o)	Destination (d)	Launch time (Gaussian distribution with peaks at)	Speed
Emergency response	3	$o \sim N(c_{corner}, \sigma^2 I)$	$d \sim N(c_{diag}, \sigma^2 I)$	$13:00 \pm 4h$	[20, 28]
Police activity	2	$o \sim N(c_i, \sigma^2 I),$ $i = 1, 2, \dots k$	$o \sim N(c_{(1-i)}, \sigma^2 I),$ $i = 1, 2, \dots k$	$02:00 \pm 1h$ and $22:00 \pm 2h$	[12, 20]
Delivery	1	$h \sim N(c, \sigma^2 I)$	$s_j \sim N(c_j, \sigma_{sp}^2 I)$	$10:00 \pm 2h$ and $15:00 \pm 2h$	[8, 18]
Passenger transport	1	$o \sim N(h_i, \sigma_{hub}^2 I)$	$d \sim N(h_j, \sigma_{hub}^2 I)$	$08:00 \pm 1.5h$ and $18:00 \pm 1.5h$	[16, 24]

Results - UAV Snapshots in the 15,000-flight Event

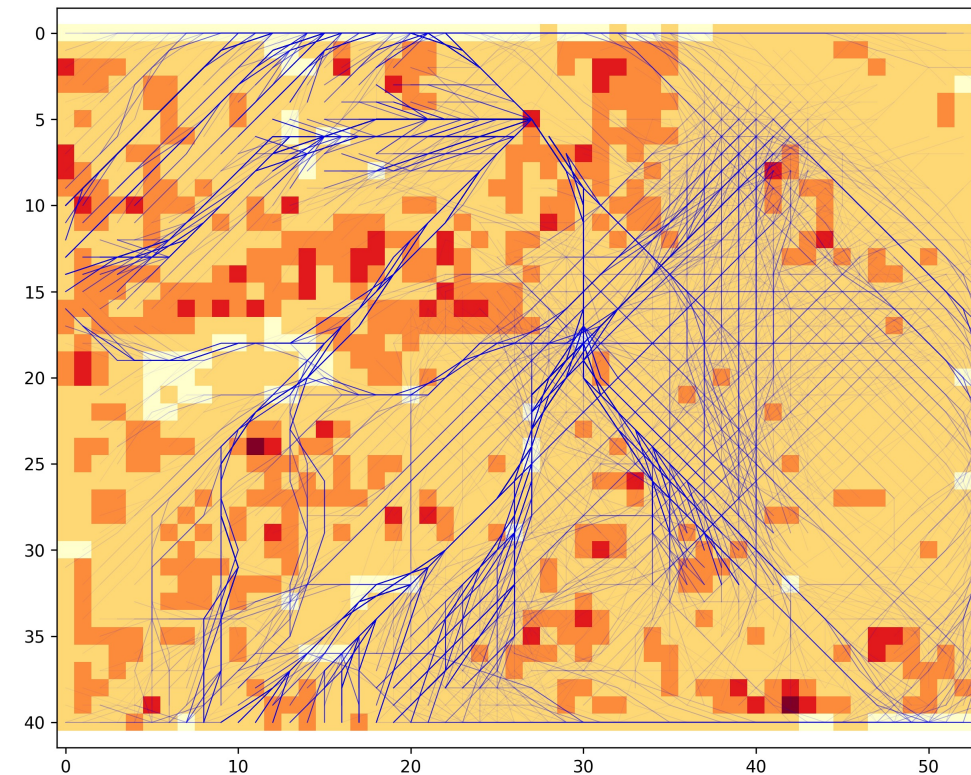


Results - Spatial Path Flows for Different Scenarios

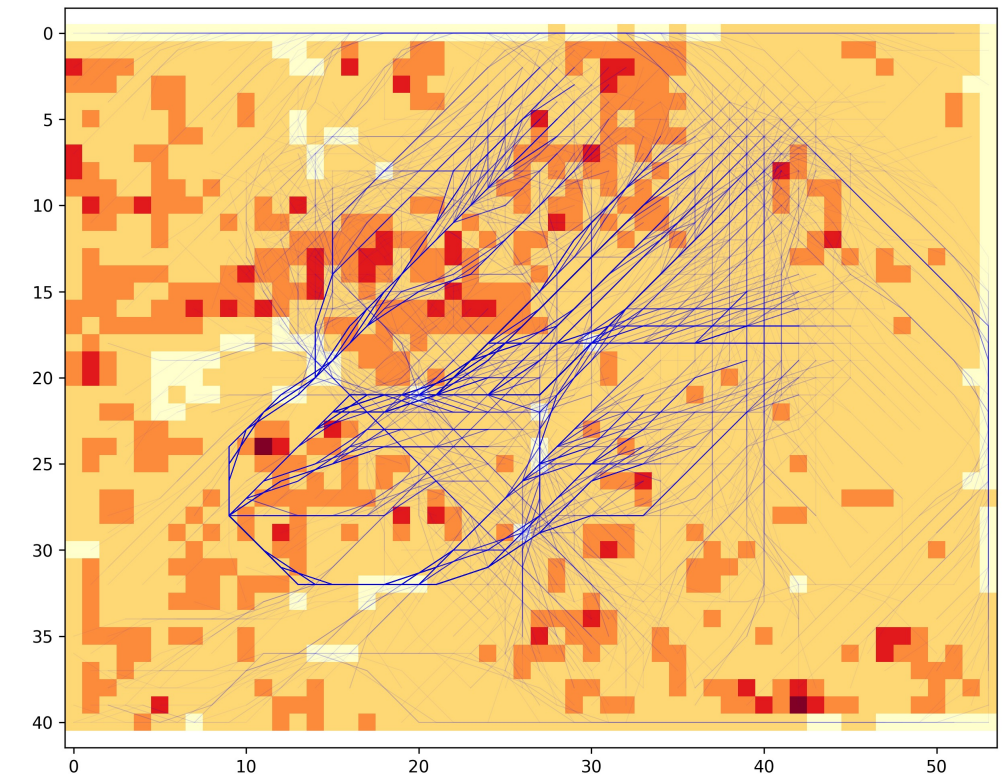
Spatial flow for 5,000 flights



Spatial flow for 10,000 flights



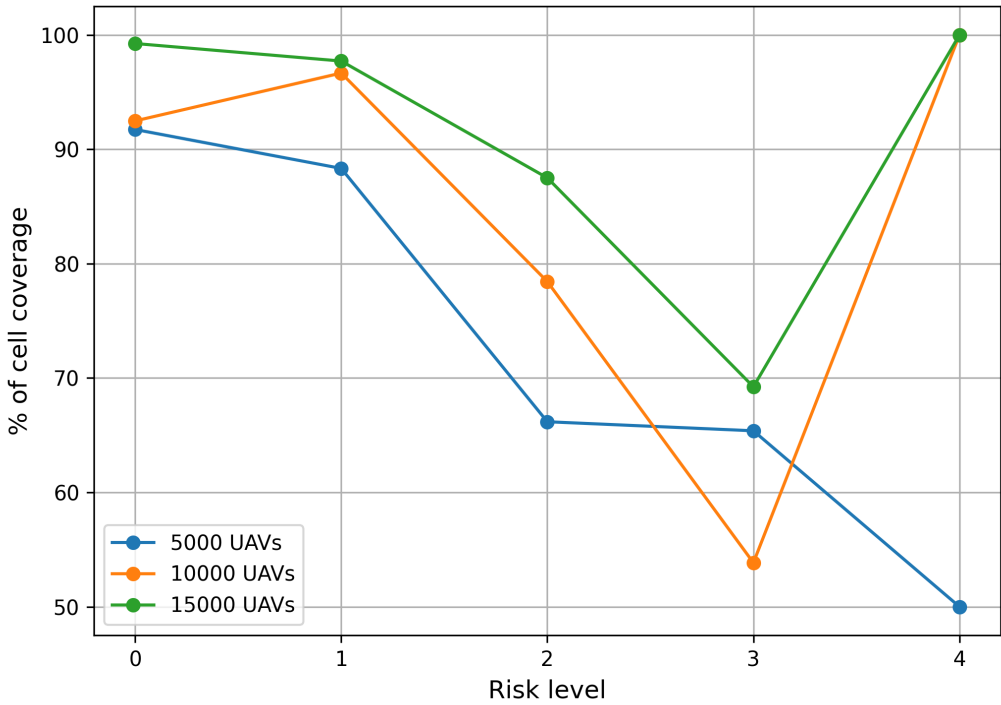
Spatial flow for 15,000 flights



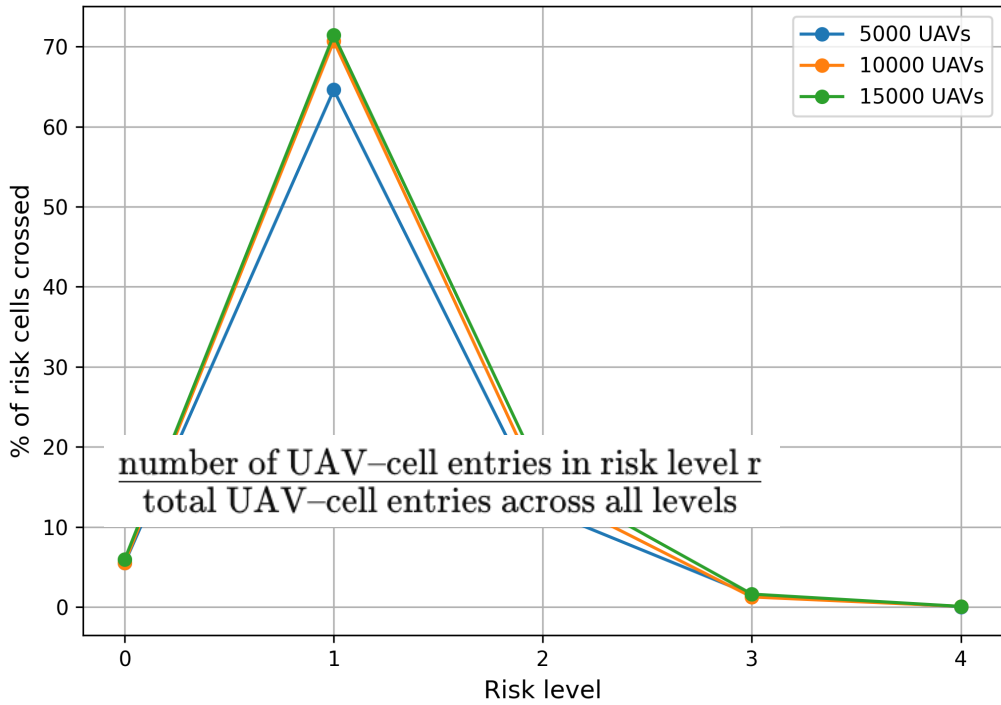
Finding: across all scales, the scheduled flows consistently avoid the highest-risk regions and concentrate primarily in lower-risk areas, demonstrating the scheduler's ability to embed risk awareness into large-scale UAV traffic planning.

Results – Risk Avoidance Capability

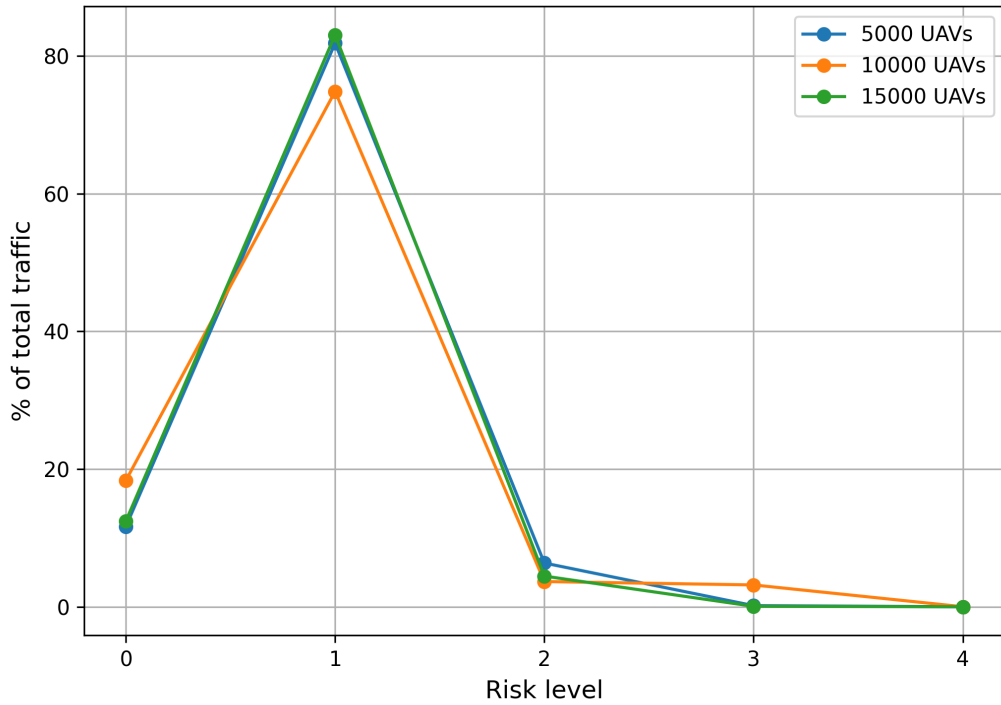
A. Cell coverage



B. Crossing distribution



C. Traffic share



A. % of cell coverage = $\frac{\text{number of unique cells in risk level } r \text{ that were traversed}}{\text{total cells in risk level } r}$

B. % of crossing distribution = $\frac{\text{number of UAV-cell entries in risk level } r}{\text{total UAV-cell entries across all levels}}$

C. % of traffic share = $\frac{\text{number of flights that entered at least one cell of risk level } r}{\text{total flights}}$

Results – Performance Comparison with Benchmark

Number of UAVs	5,000		10,000		15,000	
KPIs	Greedy-only benchmark	Hybrid Scheduler	Greedy-only benchmark	Hybrid Scheduler	Greedy-only benchmark	Hybrid Scheduler
% of scheduled flights	96.16%	100%	86.76%	100%	69.30%	100%
Number of crossings in high-risk cells	30	1	100	4	35	5
Average travel distance (km)	4.54	4.64	4.84	4.88	4.80	4.82
Average launch delays (m:s)	20:17	13:51	22:46	00:07	26:06	00:03
Runtime (h:m:s)	00:04:07	00:05:24	00:07:06	00:24:32	00:16:16	00:45:08

Results – Sensitivity analysis of R_{max}

Performance of the hybrid scheduler under different R_{max}
(In 15,000 flight scenario)

Value R_{max}	$+\infty$ (no restriction)	0.2	0.1 (default)	0.05	
% of scheduled flights	100%	100%	100%	100%	
Number of crossings in high-risk cells	110	4	4	4	—● Indicating rapid convergence towards near-optimal risk setting
Average travel distance (km)	4.81	4.82	4.88	5.11	—● Indicating more path detours to meet risk restrictions
Runtime (h:m:s)	00:24:27	00:23:27	00:24:32	00:23:19	

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