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UAS path planning risk assessment: single flight vs. multiple flights

Xinyu He[a], Chengpeng Jiang[b], Henk A.P. Blom[b], Lishuai Li[b]

[a]School of Data Science, City University of Hong Kong

[b]Air Transport and Operations, Delft University of Technology

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Introduction

- Unmanned Aircraft System (UAS) operations using drones are applied for deliveries in some urban areas.
- These urban UAS operations pose Third Party Risks to people on the ground who are not involved in operations and do not profit from operations[1].
- Third party risk is considered in existing UAS path planning methods
  - Minimum risk path based on risk maps, like riskA*[2], risk-based RRT*[3]
  - Bi-objective methods: low risk and flight path[4]

[1] Blom, H.A.P., Jiang, C., 2021. Safety risk posed to persons on the ground by commercial UAS-based services, in: 14th USA/Europe Air Traffic Management Seminar.

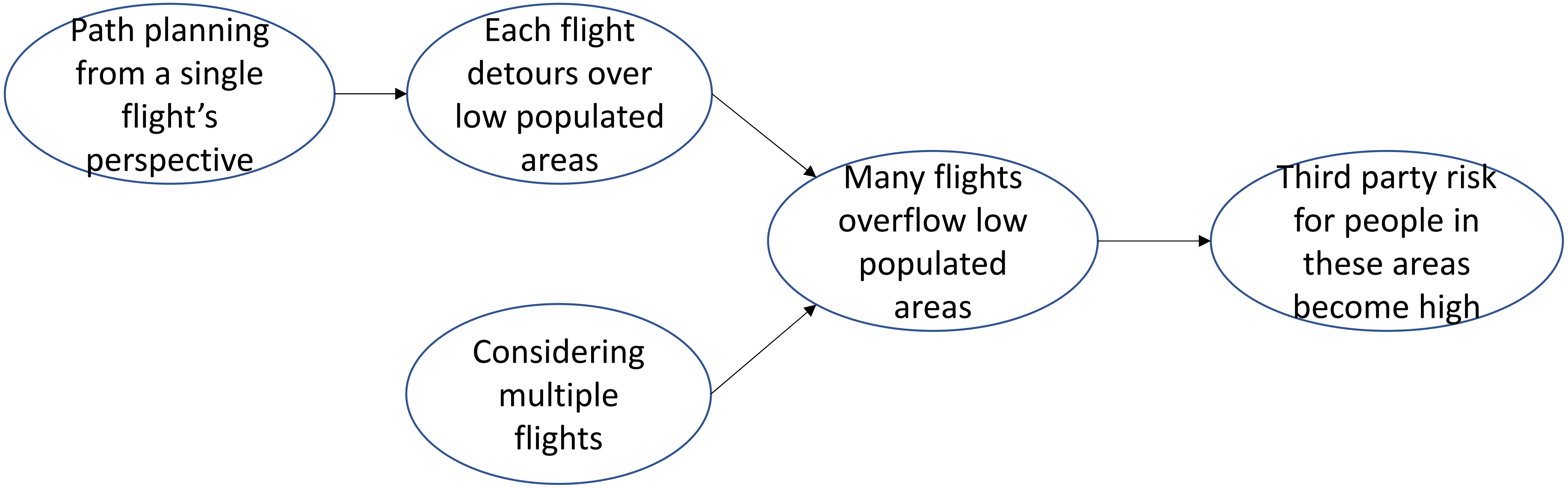
[2] Primatesta, S., Guglieri, G., Rizzo, A., 2019. A risk-aware path planning strategy for UAVs in urban environments. J. Intell. Robot. Syst. 95, 629–643.

[3] Primatesta, S., Scanavino, M., Guglieri, G., Rizzo, A., 2020. A risk-based path planning strategy to compute optimum risk path for unmanned aircraft systems over populated areas, in: 2020 International Conference on Unmanned Aircraft Systems (ICUAS). IEEE, pp. 641–650.

[4] Rudnick-Cohen, E., Herrmann, J.W., Azarm, S., 2016. Risk-based path planning optimization methods for unmanned aerial vehicles over inhabited areas. J. Comput. Inf. Sci. Eng. 16.

Potential issues of path planning with only risk per flight

- Existing UAS path planning methods consider risk per flight, which leads to a path with optimized risk from **a single flight's perspective**
- But it does not necessarily optimize risk from **the perspective of multiple flights**



Path planning from a single flight's perspective

Each flight detours over low populated areas

Considering multiple flights

Many flights overflow low populated areas

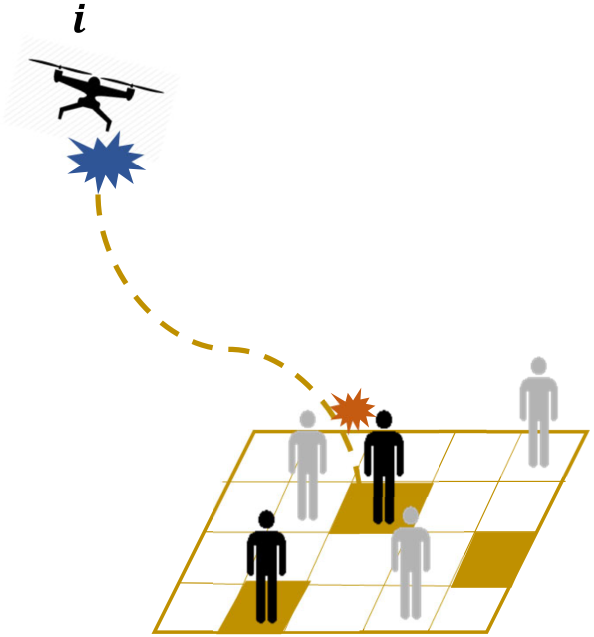
Third party risk for people in these areas become high

Research Objective

To evaluate for multiple flights, whether current path planning methods can generate paths that meet the Third Party Risk criterion or not

- Generate flight paths for an area using a typical path planning algorithm
- Evaluate how third party risks change as the volume of flight operations increases
- For a given level of flight volume, how third party risks change when adjusting the weight ratio on risk in the path planning algorithm

Third party risk indicators



CGR (Collective Ground Risk) per flight[1-3]

$$R^i_{Cground}$$

Expected number **of third party fatalities on the ground** in a **given area** due to the direct consequences of ***i*th flight** accident

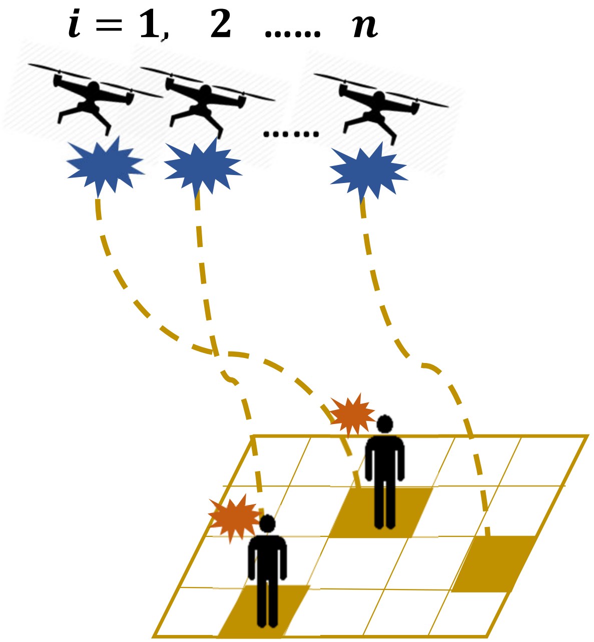
CGR per flight hour: $R^i_{Cground}/T_i$

[1] Blom, H.A.P., Jiang, C., 2021. Safety risk posed to persons on the ground by commercial UAS-based services, in: 14th USA/Europe Air Traffic Management Seminar.

[2] Ale, B.J.M., Piers, M., 2000. The assessment and management of third party risk around a major airport. J. Hazard. Mater. 71, 1–16.

[3] Blom, H.A.P., Jiang, C., Grimme, W.B.A., Mitici, M., Cheung, Y.S., 2021. Third party risk modelling of Unmanned Aircraft System operations, with application to parcel delivery service. Reliab. Eng. Syst. Saf. 214, 107788.

Third party risk indicators



CGR (Collective Ground Risk)[1-3]

$$R^{UAS}_{Cground}$$

Expected **number** of **third party fatalities on the ground** in a **given area** due to UA flight accidents during a **given annum**

CGR per annum: $$R^{UAS}_{Cground} = \sum_{i=1}^{n} R^{i}_{Cground}$$

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[1] Blom, H.A.P., Jiang, C., 2021. Safety risk posed to persons on the ground by commercial UAS-based services, in: 14th USA/Europe Air Traffic Management Seminar.

[2] Ale, B.J.M., Piers, M., 2000. The assessment and management of third party risk around a major airport. J. Hazard. Mater. 71, 1–16.

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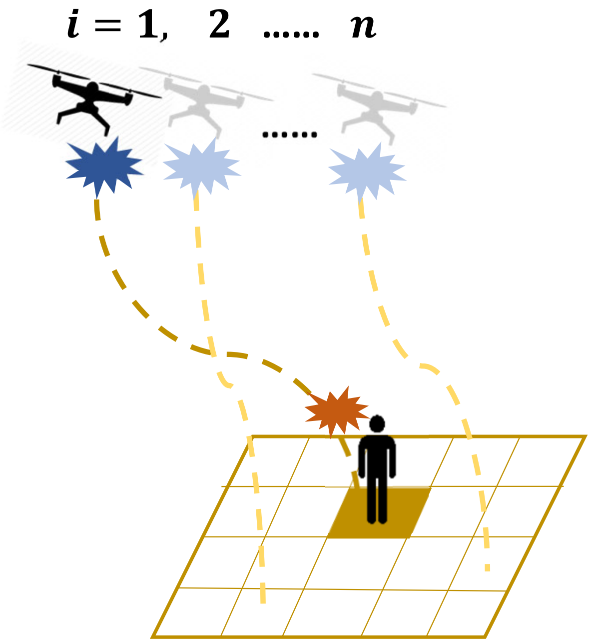
Third party risk indicators



IR (Individual Risk)[1-3]

$$R_I^{UAS}(y)$$

Probability that an **unprotected** person at **location y** is killed due to UA flight accidents during a **given annum**

IR per annum: $R_I^{UAS}(y) = \sum_{i=1}^{n} R_I^i(y)$

[1] Blom, H.A.P., Jiang, C., 2021. Safety risk posed to persons on the ground by commercial UAS-based services, in: 14th USA/Europe Air Traffic Management Seminar.

[2] Ale, B.J.M., Piers, M., 2000. The assessment and management of third party risk around a major airport. J. Hazard. Mater. 71, 1–16.

[3] Blom, H.A.P., Jiang, C., Grimme, W.B.A., Mitici, M., Cheung, Y.S., 2021. Third party risk modelling of Unmanned Aircraft System operations, with application to parcel delivery service. Reliab. Eng. Syst. Saf. 214, 107788.

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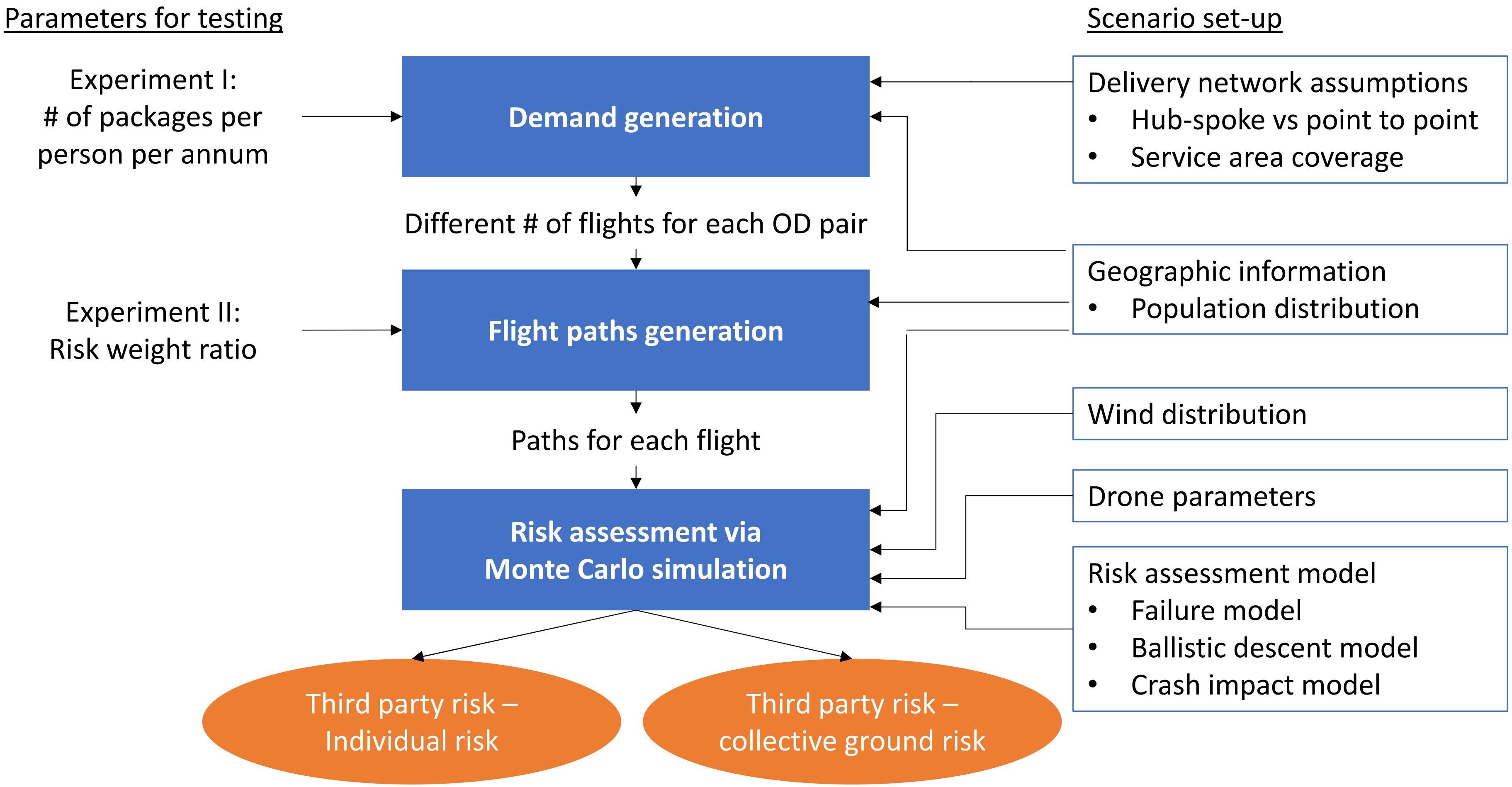
Method overview



Parameters for testing

Experiment I:
# of packages per
person per annum

Experiment II:
Risk weight ratio

Demand generation

Different # of flights for each OD pair

Flight paths generation

Paths for each flight

Risk assessment via
Monte Carlo simulation

Third party risk –
Individual risk

Third party risk –
collective ground risk

Scenario set-up

Delivery network assumptions
- Hub-spoke vs point to point
- Service area coverage

Geographic information
- Population distribution

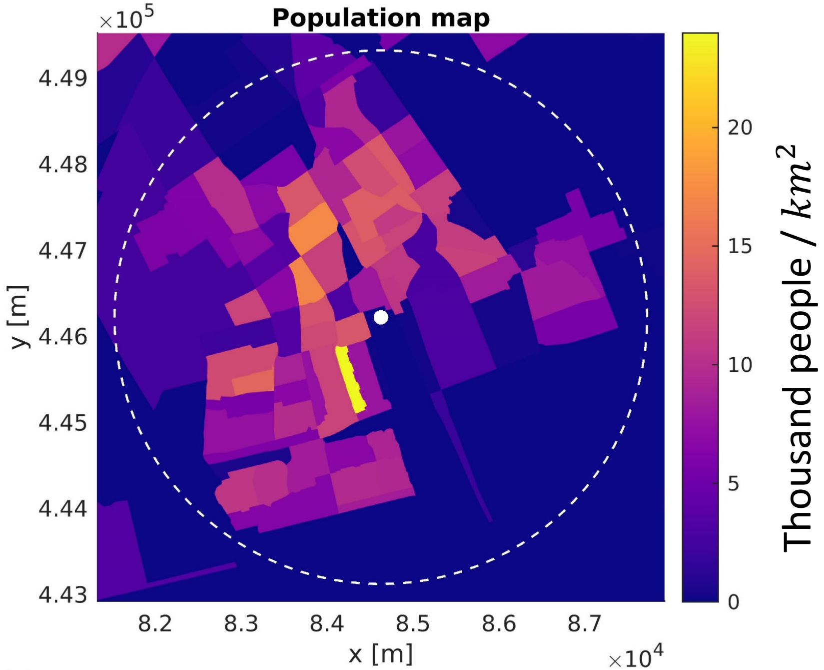
Wind distribution

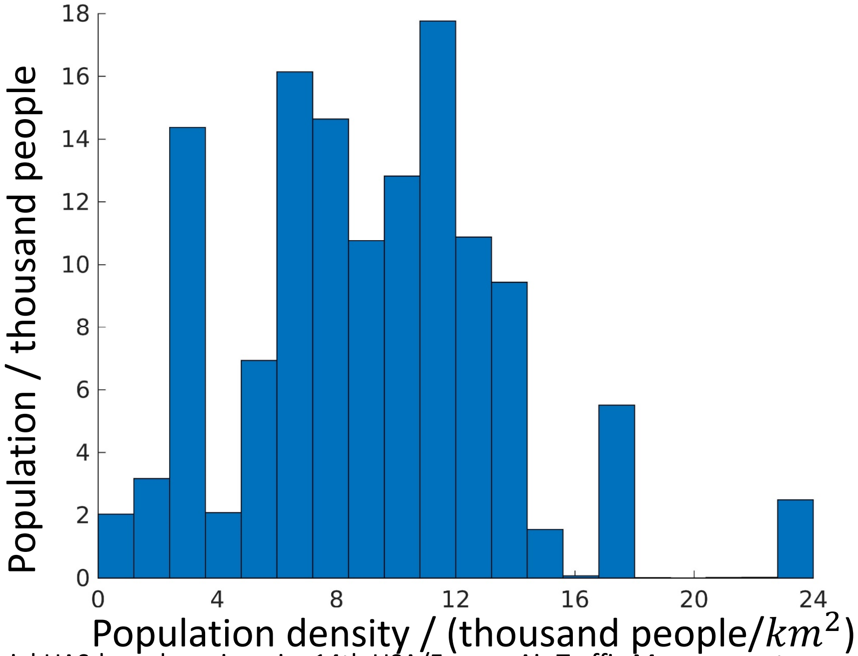
Drone parameters

Risk assessment model
- Failure model
- Ballistic descent model
- Crash impact model

Method - Demand generation

- Scenario description[1]
  - An area in Delft with 130.78 thousand people
  - Total area size is 6.6km*6.6km=43.6km^2

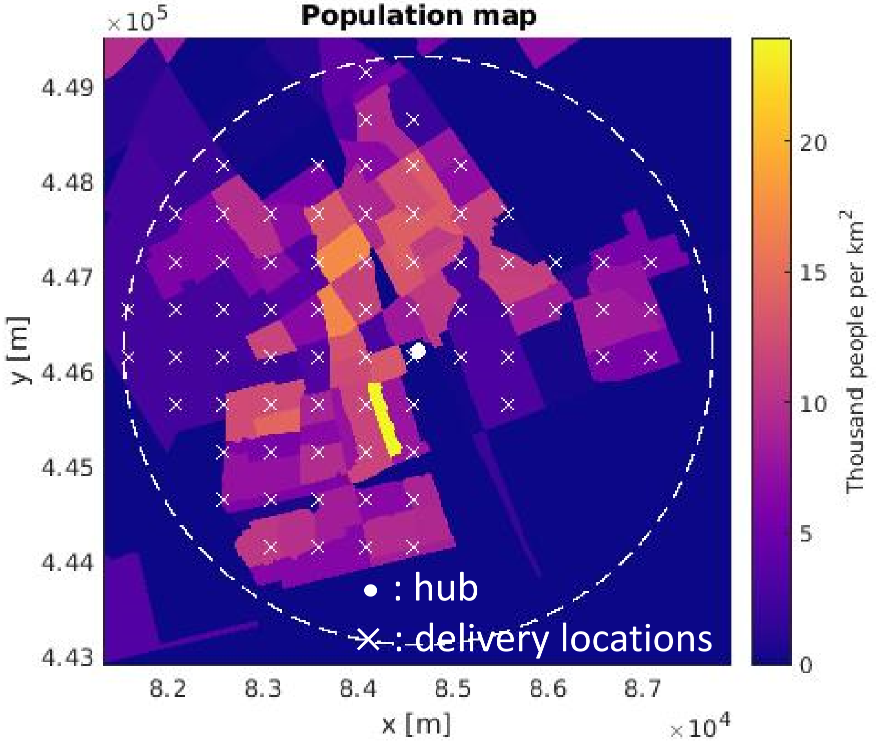




[1] Blom, H.A.P., Jiang, C., 2021. Safety risk posed to persons on the ground by commercial UAS-based services, in: 14th USA/Europe Air Traffic Management Seminar.

Method - Demand generation

- OD pair location generation
    - A hub (O) serves multiple destinations (D) inside a service radius
    - The population map is discretized into multiple grid areas.
    - If the population density of a grid area is beyond a threshold, the center of it is a destination.
    - Our experiment takes radius 3.1km, size of each grid area is 0.5km*0.5km, threshold 2000 people/km^2, 71 OD pairs are generated
- OD pair demand generation
    - We assume that each person inside service radius of the hub will be served n packages per annum
    - # of flights for each OD pair is
      $$N = n * population$$
    - $population$ is the population in the area covered by the destination



Method - Flight paths generation

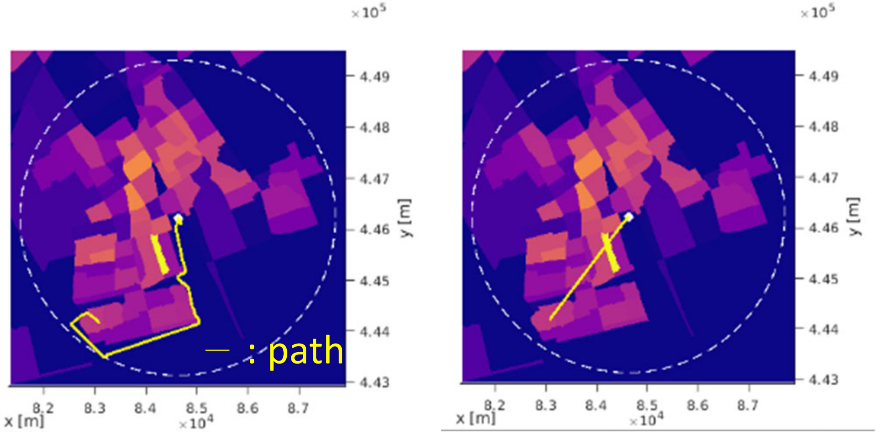
- Here we take a A*-based method to generate paths for drones, the method minimizes the following cost function to generate path p from hub to $destination$

$$p = \arg\min_{p}(\omega_r \theta_{risk}(p) + \omega_l length(p))$$

- $\theta_{risk}(p)$ is the risk for path p, $length(p)$ is the flight distance for path p

Method - Flight paths generation

- ω_r and ω_l are weights to control the risk and flight distance
  - ○ $\omega_r : \omega_l \rightarrow \infty$: $p = \arg\min_{p} \theta_{risk}(p)$, generate a path with small risk per flight through detours over low populated areas
  - ○ $\omega_r : \omega_l \rightarrow 0$: $p = \arg\min_{p} length(p)$, generate a short path



$\omega_r : \omega_l \rightarrow \infty$ $\omega_r : \omega_l \rightarrow 0$

Method - Risk assessment

- Failure model[1]
    - The probability that ground crash happens during flight i is $P_i = 1 - \exp\left\{-\int_0^{T_i} \lambda_i(t)dt\right\}$, where flight time of the i^{th} flight is $[0, T_i]$, $\lambda_i(t)$ is rate of crash event happen at moment t during the i^{th} flight
- Descent model
    - Ballistic descent model[1], the crash descending is affected by air resistance and wind velocity
- Impact model
    - RCC model[2] to describe the probability of a person being killed by the ground crash

[1] la Cour-Harbo, A., 2020. Ground impact probability distribution for small unmanned aircraft in ballistic descent, in: 2020 International Conference on Unmanned Aircraft Systems (ICUAS). IEEE, pp. 1442–1451.

[2] Range Commanders Council, 2000. Range safety criteria for unmanned air vehicles, rationale and methodology supplement; Supplement to Document 321-00, April 2000.

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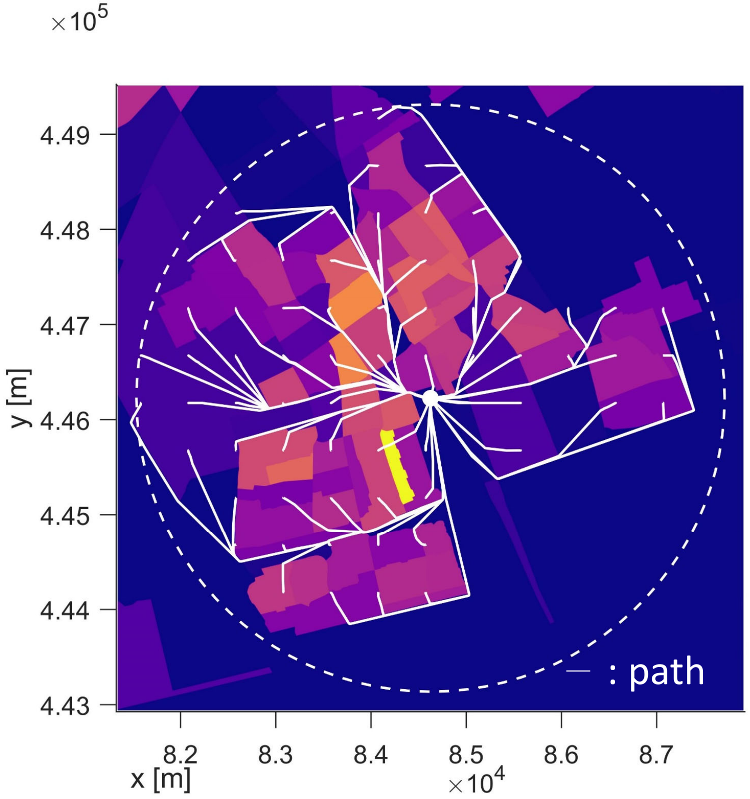
Experiment I

- Evaluate how third party risks change as the volume of flight operations increase
    - Test # of packages per person per annum to: $[0.1, 0.5, 1, 2, 5, 10]$
    - Set risk weight ratio $\omega_r : \omega_l = 1:1$

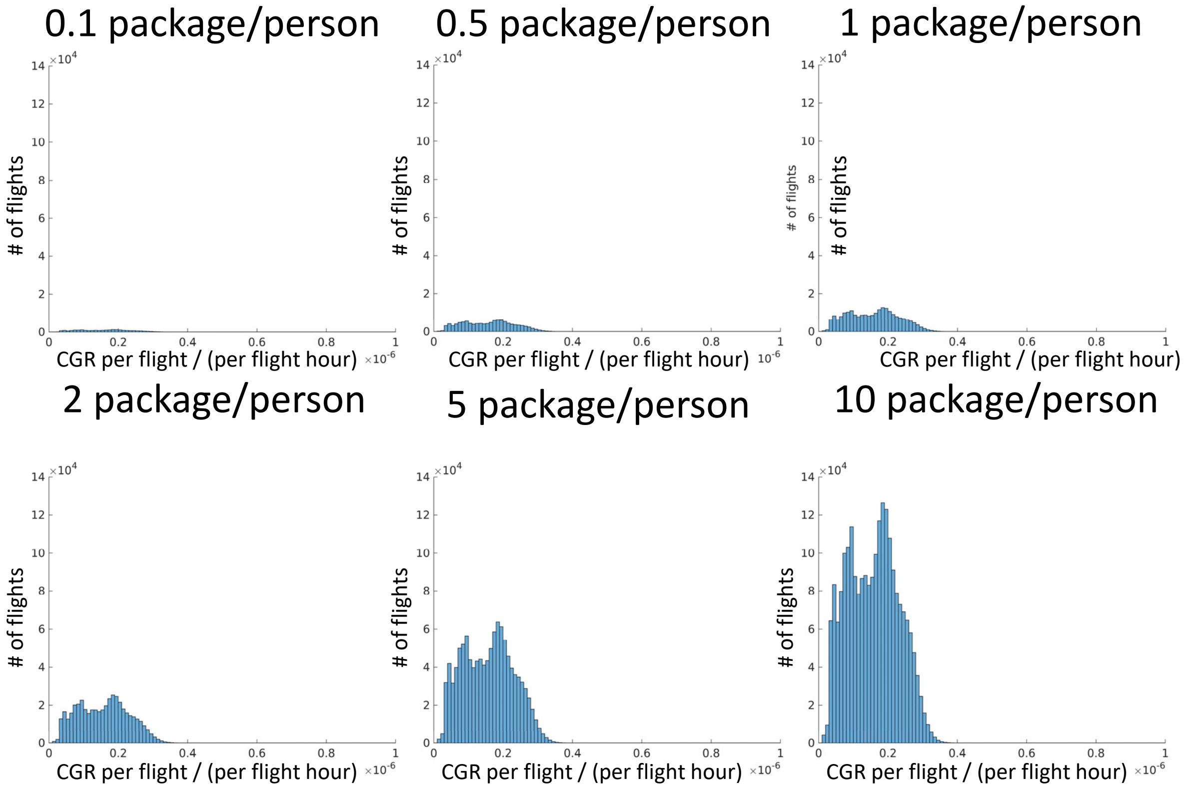
Paths do not change as the # of flights for each OD pair increases, since the environment is static



Generated paths for OD pairs

Experiment I

- Collective ground risk per flight do not change with # of flights, and they all at an acceptable level (10^{-6} fatalities per flight hour[1]).

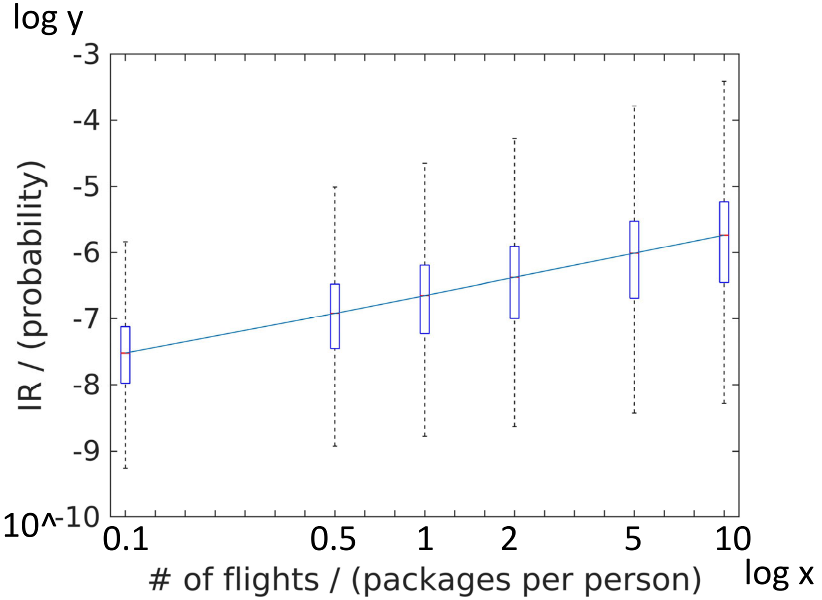


Collective ground risk per flight histogram

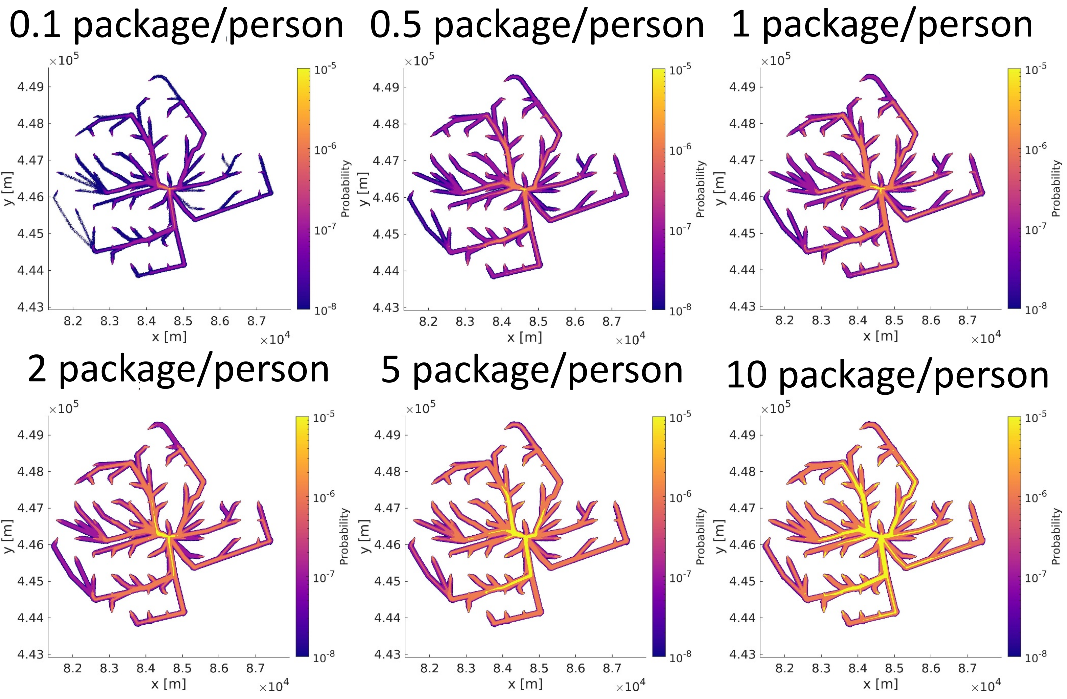
[1] Blom, H.A.P., Jiang, C., 2021. Safety risk posed to persons on the ground by commercial UAS-based services, in: 14th USA/Europe Air Traffic Management Seminar.

Experiment I

- Individual Risk increase linearly with # of flights



# of flights / (packages per person)	0.1	0.5	1	2	5	10
Area size with IR $> 10^{-6}$ (km^2)[1-2]	0.03	0.47	1.22	2.42	4.13	5.29


0.1 package/person

0.5 package/person

1 package/person

2 package/person

5 package/person

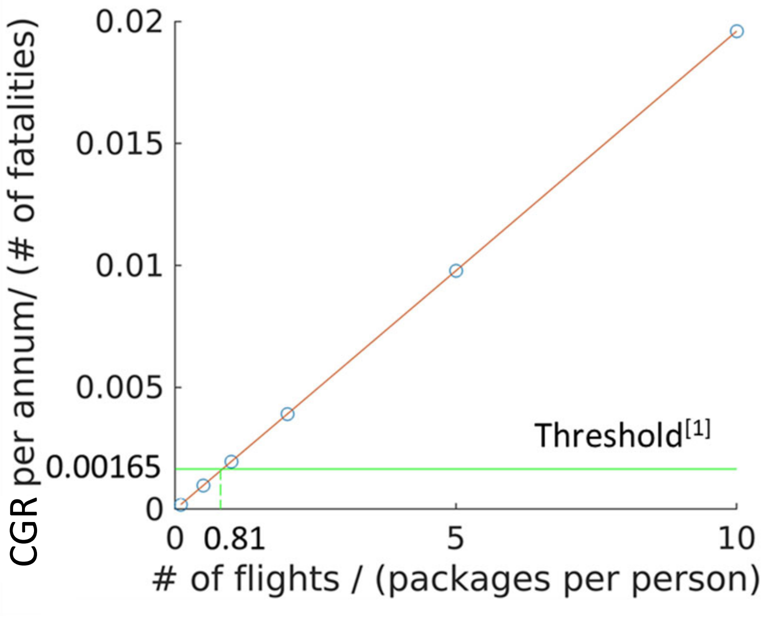
10 package/person

Individual Risk distribution

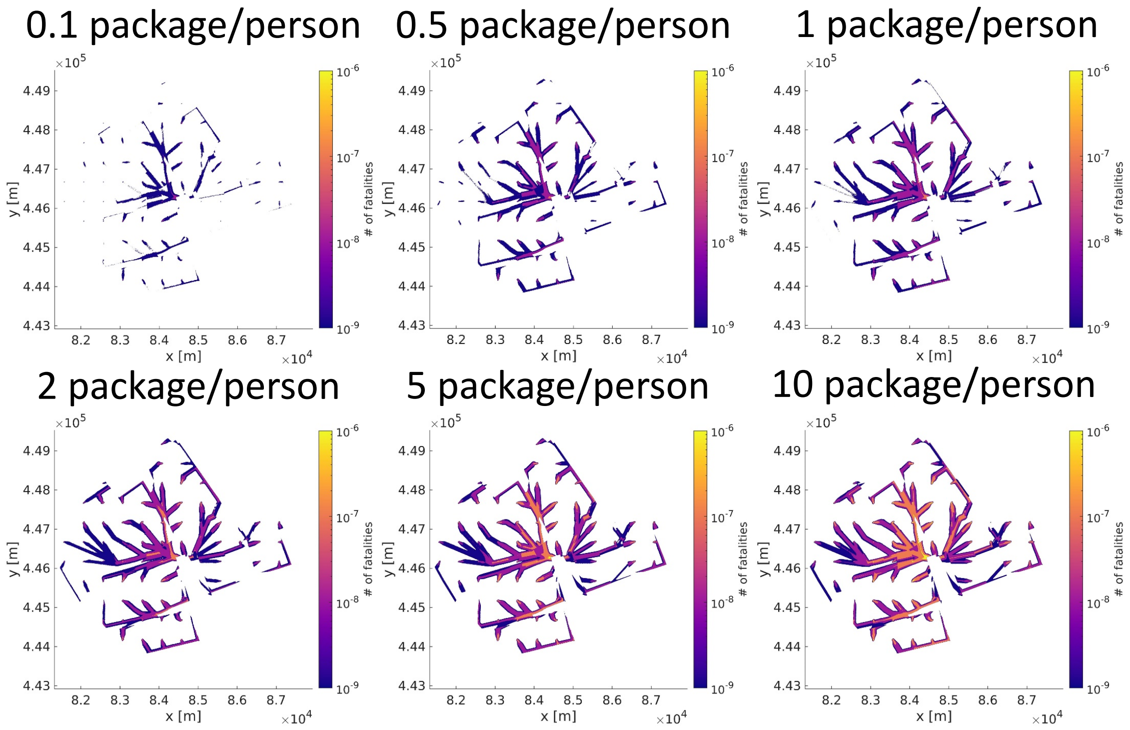
[1] Bottelberghs, P.H., 2000. Risk analysis and safety policy developments in the Netherlands. J. Hazard. Mater. 71, 59–84.
[2] Trbojevic, V.M., 2005. Risk criteria in EU. Risk 10, 1945–1952.

Experiment I

- Collective Ground Risk per annum increase linearly with # of flights



Collective Ground Risk per annum


0.1 package/person

0.5 package/person

1 package/person

2 package/person

5 package/person

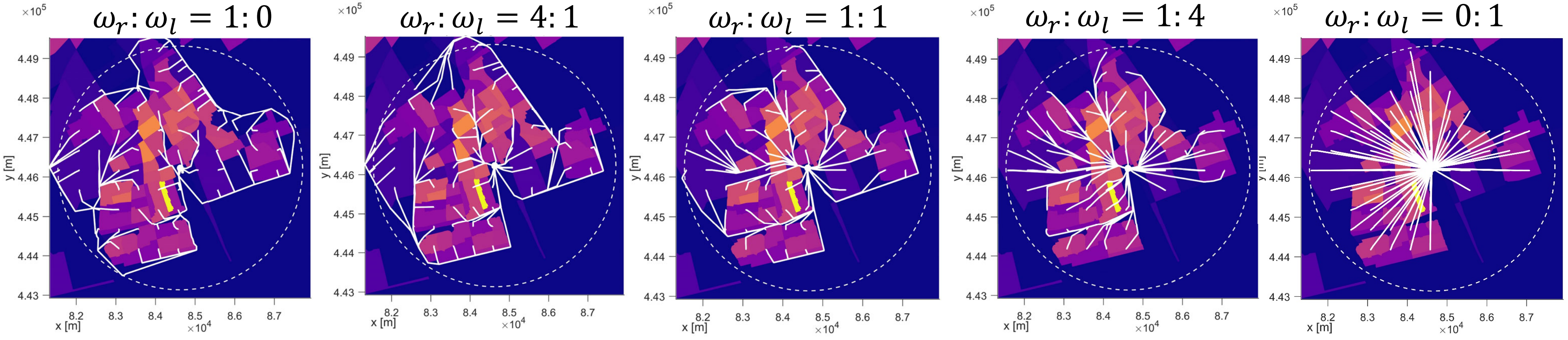
10 package/person

Collective Ground Risk distribution

[1] Blom, H.A.P., Jiang, C., 2021. Safety risk posed to persons on the ground by commercial UAS-based services, in: 14th USA/Europe Air Traffic Management Seminar.

Experiment II

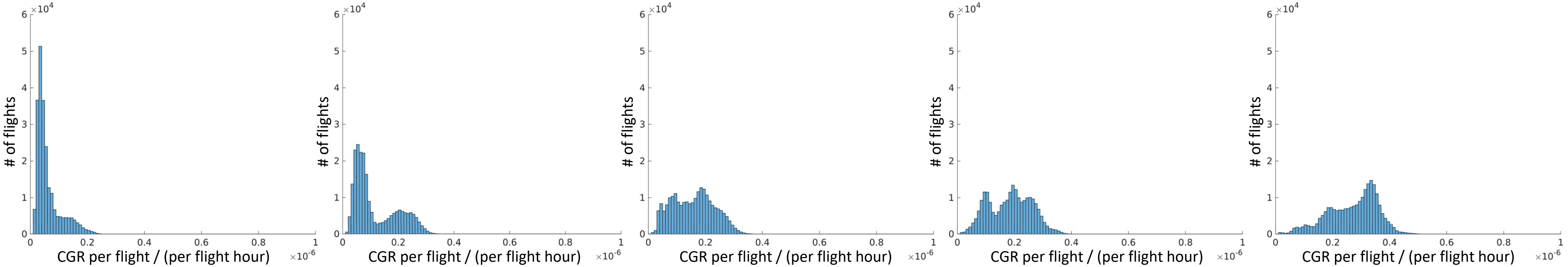
- Evaluate how Third Party Risks change when adjusting the weight ratio on risk in path planning
    - Test weight ratio $\omega_r : \omega_l$ to: $[1:0, 4:1, 1:1, 1:4, 0:1]$
    - Set # of packages per person per annum as 1



When the weight ratio on risk is high, paths are detoured to low density areas.

Experiment II

- Collective ground risk per flight reduces as weight ratio on risk increases, and they all at an acceptable level (10^{-6} fatalities per flight hour[1]).



$\omega_r : \omega_l = 1:0$ $\quad$ $\omega_r : \omega_l = 4:1$ $\quad$ $\omega_r : \omega_l = 1:1$ $\quad$ $\omega_r : \omega_l = 1:4$ $\quad$ $\omega_r : \omega_l = 0:1$

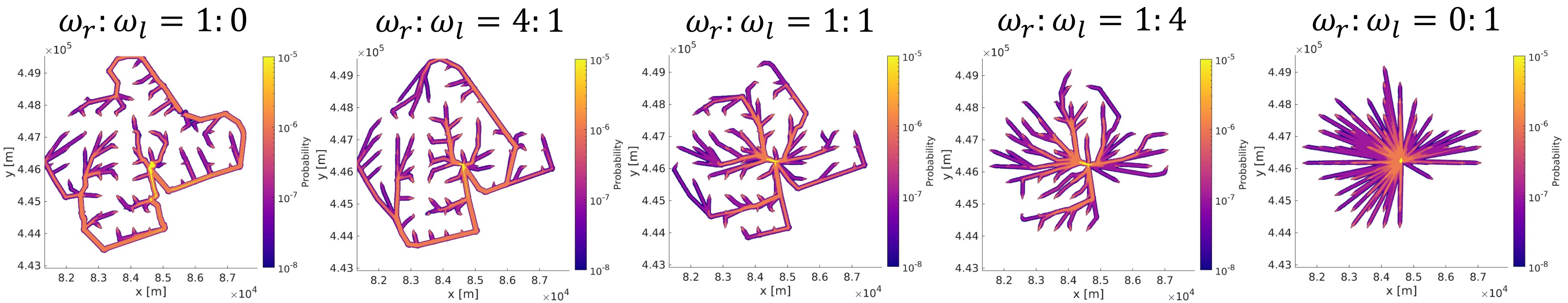
Collective ground risk per flight histogram

[1] Blom, H.A.P., Jiang, C., 2021. Safety risk posed to persons on the ground by commercial UAS-based services, in: 14th USA/Europe Air Traffic Management Seminar.

Experiment II

- Detour over low populated areas results in more areas with high individual Risk

$\omega_r : \omega_l$	$1:0$	$4:1$	$1:1$	$1:4$	$0:1$
Area size with IR $> 10^{-6}$ (km^2)[1-2]	2.47	1.86	1.22	1.06	0.75
Percentage of improvement	-102.5%	-52.5%	0%	13.1%	38.5%


$\omega_r : \omega_l = 1:0$ $\omega_r : \omega_l = 4:1$ $\omega_r : \omega_l = 1:1$ $\omega_r : \omega_l = 1:4$ $\omega_r : \omega_l = 0:1$

Individual Risk distribution

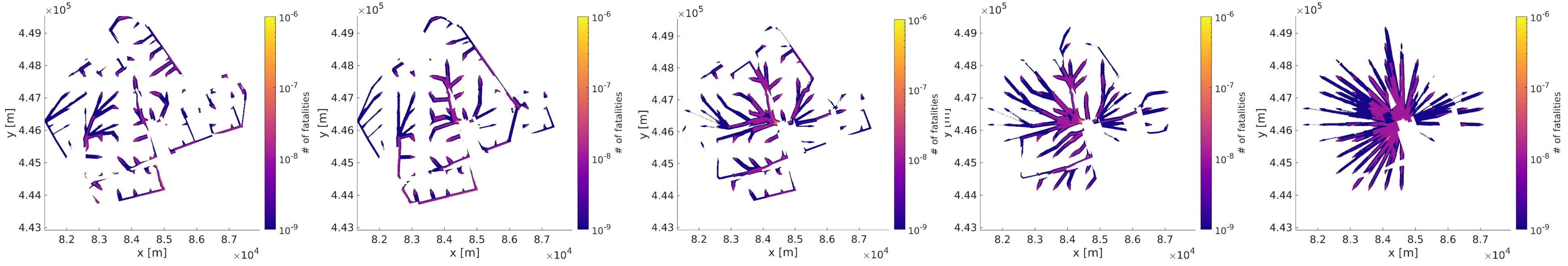
[1] Bottelberghs, P.H., 2000. Risk analysis and safety policy developments in the Netherlands. J. Hazard. Mater. 71, 59–84.
[2] Trbojevic, V.M., 2005. Risk criteria in EU. Risk 10, 1945–1952.

Experiment II

- Detour over low populated areas reduces Collective Ground Risk per annum

Threshold $1.65 * 10^{-3}$

$\omega_r : \omega_l$	$1:0$	$4:1$	$1:1$	$1:4$	$0:1$
Collective ground risk per annum	$1.57 * 10^{-3}$	$1.87 * 10^{-3}$	$1.96 * 10^{-3}$	$2.11 * 10^{-3}$	$3.00 * 10^{-3}$
Percentage of improvement	19.9%	4.6%	0%	-7.7%	-53.1%

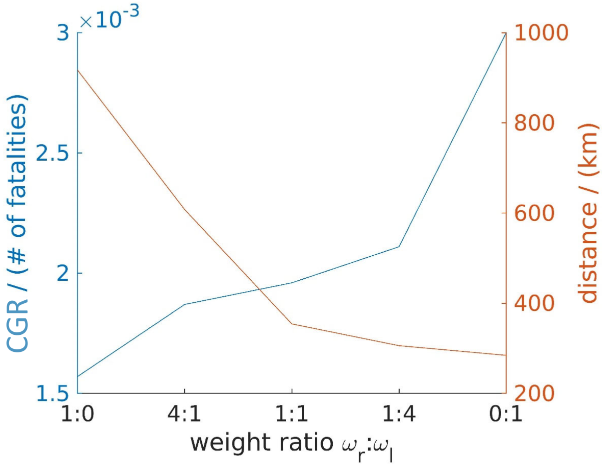


$\omega_r : \omega_l = 1:0$ $\omega_r : \omega_l = 4:1$ $\omega_r : \omega_l = 1:1$ $\omega_r : \omega_l = 1:4$ $\omega_r : \omega_l = 0:1$

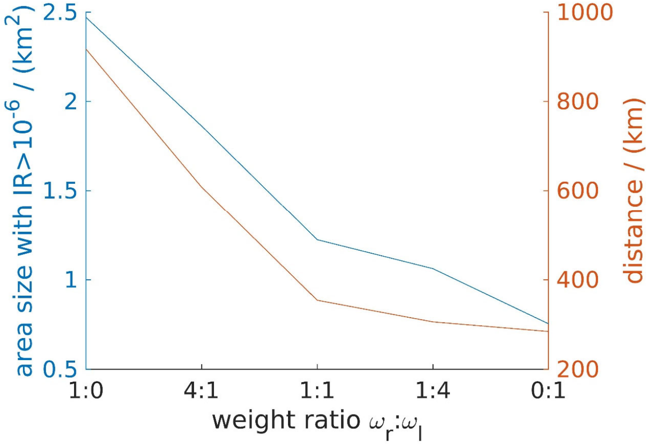
Collective Ground Risk distribution

Experiment II

- Tradeoff between Collective Ground Risk per annum and flight distance, and therefore, the total size of areas with high Individual Risk



Collective Ground risk vs. flight distance



Individual Risk vs. flight distance

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Summaries

- Conclusions
  - Insight 1: As the # of flights increases, both Individual Risk and Collective Ground Risk **increase linearly**.
  - Insight 2: Current UAS path planning can **reduce Collective Ground Risk per annum** considering multiple flights, but it may increase areas with **high Individual Risk**.

- Recommendations
  - The weight ratio for risk and flight distance should be carefully considered to get a better trade-off.
  - Other operational constraints, e.g., limiting the number of flights in high individual risk areas, should be considered to make individual risk at an acceptable level

Summaries

- Limitations
  - Adopted third party risk in the work only considers the population distribution, the risk to ground vehicles, ground infrastructures are not considered.
  - There are many assumptions and simplifications in the scenario set-up, like # of packages per person per year that determines the flight demand, etc.

- Future work
  - Risk assessment on real drone operations in urban environments to make results more convincing
  - More sensitivity analysis of the parameters in the risk assessment model to quantify their effects on the risk
  - New path planning methods considering operation volumes to make both Collective Ground Risk and Individual Risk at an acceptable level

- Thank you!

- Any question?