

Capacity, Entropy, and Safety: A Metric-Based Framework for Urban Airspace structure Evaluation

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Abstract—The rapid expansion of Urban Air Mobility (UAM) demands safe and efficient airspace designs capable of balancing capacity, safety, and reliability. This work introduces a set of lightweight, graph-based metrics: entropy, capacity, and safety. These indicators enable systematic evaluation of urban airspace structures without relying solely on extensive simulations. Synthetic layouts and real urban districts of Barcelona are analyzed to assess the behavior of these metrics under both controlled and realistic conditions. Results show that the capacity metric provides the most consistent predictor of network performance, while the entropy metric offers complementary insights into its reliability. Safety is quantified through contingency and conformance scenarios, revealing that contingency-related return-to-launch maneuvers consistently generate conflicts, whereas conformance deviations are largely mitigated under current operational assumptions. Overall, the proposed framework demonstrates that combining capacity with entropy yields robust assessments of UAM network designs, while safety analysis highlights the necessity of integrating contingency management strategies into airspace planning.

Keywords—UAM, Graphs, Entropy, Capacity, Safety, Contingency, Conformance, Simulation

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are revolutionizing urban transportation, enabling new services for mobility, logistics, and emergency response. Forecasts of the low-altitude economy anticipate rapid growth in coming years, with the global UAM market projected to reach USD 14.64 billion by 2032 at a CAGR of 16.6% [1]. City-level projections suggest that shuttle services to airports alone could capture up to 5% of trips, with additional demand for air-taxis and intercity connections [2].

Such growth requires safe and efficient management of urban airspace, where physical obstacles, CNS infrastructure, and societal acceptance play decisive roles [3]. Current research also emphasizes that public concerns over safety, noise, environmental impact, and fairness must be addressed for large-scale deployment [4].

To face these challenges, different airspace designs must be compared to determine which best balance capacity and safety. In this work, we propose metrics that allow such designs to be evaluated in a systematic and computationally light way, reducing reliance on extensive simulations.

II. AIRSPACE MODELING

A. State of the Art

The Metropolis project remains a central reference for urban airspace design. It explored four operational concepts: Full Mix (free flight), Layers (altitude bands segregating flows by direction), Zones (partitioned into circular and radial sectors), and Tubes (structured 4D corridors) [5]. Among these, the Tubes concept is especially relevant for this work, as it introduces structured air corridors that can provide predictability and safety in dense urban environments [6].

Further work has showed that centralized separation management can further enhance safety and capacity in dense traffic conditions [7]. At the same time, real urban environments introduce irregularities such as restricted areas (e.g., government buildings or prisons) and tall obstacles. In this context, tube-like layouts that follow existing road networks become especially interesting, as they offer a way to integrate aerial corridors with the urban fabric while naturally connecting low-altitude airspace to distributed vertiport infrastructure.

B. Graphs

In practice urban areas introduce constraints and irregularities such as restricted flying areas (e.g., government buildings, prisons, or sensitive facilities) and obstacles like tall buildings. In this context, it becomes interesting to explore tube-like layouts that align more closely with existing urban roads, as these could provide a natural way of integrating aerial corridors into the city while adapting to such irregularities as well as ground infrastructure.

For corridor-based urban airspace structures, graph models provide a natural way to represent the network of possible routes and intersections [5], [6]. In this framework, nodes correspond to junctions or entry/exit points, while edges represent the available flight corridors. Although such structures can ultimately extend into three dimensions, in this work the focus is placed on two-dimensional layouts as a starting point, enabling the testing of metrics and simulation approaches in a controlled manner. By grounding the analysis in the geometry of existing city layouts, the models can capture realistic structural properties while also simplifying assumptions about how takeoff and landing infrastructure would integrate into the network.



1) *Control Layouts*: To complement the analysis of real neighborhoods, we also construct a set of synthetic graph layouts based on regular patterns, Fig. 1. These are designed to be scalable in size and to provide clear benchmarks against which real city structures can be compared. By applying the proposed metrics to such controlled configurations, we can better understand their behavior and interpretation before dealing with the complexity and irregularities of actual urban networks.

The four synthetic patterns are shown in Fig. 1. The structureless control layout (top left) consists only of nodes without edges in order to test metrics sensitive to the number of nodes, it will be referred as 'Base'. The square grid layout 'S' (top right) represents a perfectly regular and orthogonal pattern, typical of many planned urban areas, and is expected to provide the closest baseline to real-world designs. The hexagonal/triangular grid layout 'H' (bottom left) shifts node placement to form hexagons and triangles instead of squares, allowing us to test how more compact and isotropic connectivity affects the metrics. Finally, the spider web layout 'W' (bottom right) is less realistic as an actual city structure but is included to explore whether the metrics can be "fooled" by geometries that look organized but differ significantly in structural properties. These patterns are scalable, to keep track of the size, a number will be displayed along with S and H to indicate the number of nodes in each row/column, and the number of concentric rings in W.

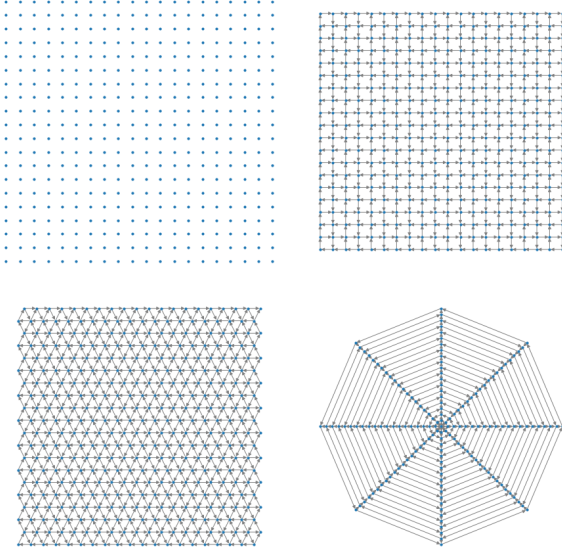


Figure 1. Top left: Structureless control layout. Top right: Square grid layout. Bottom left: Hexagonal/triangular grid layout. Bottom right: Spider web layout.

2) *Vertiports, Vertistops & Missions*: To support the evaluation of airspace performance under different network structures, a minimal and abstract model of urban air mobility demand is defined. The nodes of the network are divided into two types: vertiports and vertistops. Vertiports represent major infrastructure hubs, fewer in number and responsible

for handling most of the system's traffic, reflecting centralized logistics or aerotaxi terminals. The remaining nodes are treated as vertistops, which function as smaller, more temporary stops distributed across the network.

Aircraft missions are defined either between two vertiports or between a vertiport and a vertistop (in both directions). This structure loosely reflects the dual nature of anticipated urban air services, such as cargo delivery and short-range passenger trips. However, no spatial or temporal demand distribution is modeled: there is no variation based on population density, land use, or time-of-day. The objective is not to reproduce realistic demand patterns, but rather to create a consistent and neutral testing environment for evaluating different structural configurations.

C. Entropy

Extrinsic complexity measures for graphs can be defined by using Shannon's entropy [8]. A probability value is assigned to each vertex by employing functions which capture structural information [9]. In our case, the parametric function that captures this information is based on the idea of flow through a node.

Flow F , Eq. 1, is the rate at which aircraft can pass through a node for a given time. It is proportional to the aircraft speed v and inversely proportional to the minimum separation distance d between aircraft.

$$F := \frac{v}{d} \quad (1)$$

The bearing shift α in the corridors at a given node, has an impact on the flow rate when $\alpha > 0$ as it is necessary to increase the interval of time between two passing aircraft in order to respect the minimum separation distance. Since aircraft are assumed to move at a constant v , it is necessary to find the maximum distance d' along the corridor that will be required in order to guarantee that there is no conflict at any point between the two aircraft, Fig. 2. This will happen when the two aircraft and the node form a triangle of maximum perimeter.

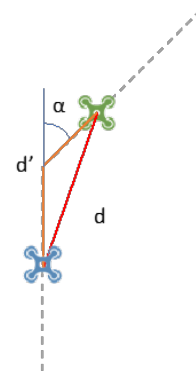


Figure 2. Flow of two aircraft through a node, where the separation through the path d' has to increase in order to respect d at all times.

We use $P = AB + AC + BC$, where $BC = d$ and $A = \pi - \alpha$. Applying the law of sines we obtain the expression:

$$P = d + \frac{d \sin C}{\sin A} + \frac{d \sin B}{\sin A} \quad (2)$$

Maximizing P implies maximizing $\sin B + \sin C$. Given the constrain $B + C = \pi - A$, P will be maximum when $B = C$. Therefore, the maximum spacing needed between aircraft happens when they form an isosceles triangle. Now $\sin B = \sin C = \sin(\frac{\pi-A}{2}) = \sin(\frac{\alpha}{2})$, applying this to Eq. 2:

$$P = d + \frac{2d \sin(\frac{\alpha}{2})}{\sin(\pi - \alpha)} \quad (3)$$

denoting the spacing with d' we see that:

$$d'(\alpha) = \frac{2d \sin(\frac{\alpha}{2})}{\sin(\pi - \alpha)} \quad (4)$$

Now using Eq. 1 and using Eq. 4 instead of d we obtain that the maximum flow adjusted by geometry is:

$$F = \frac{v \sin(\pi - \alpha)}{2d \sin \frac{\alpha}{2}} \quad (5)$$

Borrowing from this idea, we can define the parametric function, Eq. 6, that will be applied on Shannon's entropy, Eq. 7. We need to keep in mind that the impact of the flow through a node n depends on the length L of the outgoing edges from the node, the length of the edges is directly proportional to the final impact of the node. For nodes that have multiple outgoing and ingoing edges we will take the average of all possible combinations E .

$$f(n) := \sum_{i=1}^{|E|} \frac{L_i \sin(\pi - \alpha_i)}{2E \sin(\frac{\alpha_i}{2})} \quad (6)$$

$$I_f(G) := - \sum_{i=1}^{|N|} \frac{f(n_i)}{\sum_{j=1}^{|N|} f(n_j)} \log \left(\frac{f(n_i)}{\sum_{j=1}^{|N|} f(n_j)} \right) \quad (7)$$

$$I_f(G) := - \sum_{i=1}^{|N|} \frac{\sum_{k=1}^{|E_i|} \frac{L_k \sin(\pi - \alpha_k)}{2E_i \sin(\frac{\alpha_k}{2})}}{\sum_{j=1}^{|N|} \sum_{k=1}^{|E_j|} \frac{L_k \sin(\pi - \alpha_k)}{2E_j \sin(\frac{\alpha_k}{2})}} \log \left(\frac{\sum_{k=1}^{|E_i|} \frac{L_k \sin(\pi - \alpha_k)}{2E_i \sin(\frac{\alpha_k}{2})}}{\sum_{j=1}^{|N|} \sum_{k=1}^{|E_j|} \frac{L_k \sin(\pi - \alpha_k)}{2E_j \sin(\frac{\alpha_k}{2})}} \right) \quad (8)$$

The total entropy I of a graph G using Eq. 8 dependent on the total number of nodes. Because of this, if we want to compare graphs of different size it is necessary to normalize it and use the resulting entropy density D , Eq. 9.

$$D := \frac{I}{N} \quad (9)$$

Intuitively, the entropy reflects the overall balance or uniformity in the capacity of nodes to handle flow across the graph. Higher entropy values indicate that the contribution of flow is more evenly distributed among the nodes, leading to a system

where circulation is smoother and less prone to bottlenecks. Conversely, lower entropy suggests that only a few nodes dominate the flow, creating structural imbalances that may hinder circulation and increase the likelihood of congestion or inefficiencies within the network.

D. Capacity

Capacity of an airspace is the amount of simultaneous active missions at any given time. A first approximation of the maximum capacity is done by considering the minimum space required by each aircraft and seeing how many aircraft fit in every edge:

$$C := \sum_{i=1}^E \frac{L_i}{d + vt} \quad (10)$$

The minimum space is composed of the minimum separation distance between aircraft d and an extra buffer space derived from the tolerance time t for starting a mission and its velocity v . Borrowing the concept of flow 1 it is possible to define a new separation distance d' which takes into consideration the geometric properties of the graph.

$$C = \sum_{i=1}^E \frac{L_i}{d'_i + vt}, \quad \text{where } d'_i := d \frac{2 \sin(\frac{\alpha_i}{2})}{\sin(\pi - \alpha_i)} \quad (11)$$

When $d' + vt < L$, the space occupied by one single aircraft spans over multiple edges and nodes. Only one single active mission can occupy a node, if the node has multiple edges, only one the contribution of one pair of incoming/outgoing edges should be counted. In order to consider this effect, it is necessary to make further adjustments to the capacity calculation.

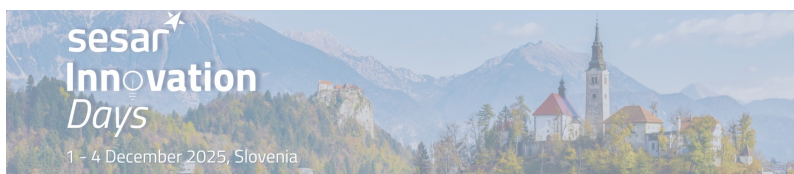
To refine the capacity estimate by accounting for the space occupied by active missions across multiple edges and nodes, a correction factor is introduced. This factor reduces the effective capacity based on the average number of nodes occupied during a mission, as well as the typical branching structure of the graph. Specifically, each mission occupies approximately $\frac{t}{\bar{L}}$ nodes, where $\bar{L}$ is the mean edge length. At each occupied node, the mission utilizes one incoming and one outgoing edge, so these are excluded from the total edge count to avoid double-counting. The contribution of the remaining edges is discounted from the total in the following way:

$$C' := \frac{C_{\text{flow}}}{\left(\frac{t}{\bar{L}}\right) ((\bar{m}_{\text{in}} - 1) + (\bar{m}_{\text{out}} - 1))} \quad (12)$$

Here, C_{flow} is the unadjusted flow-based capacity, $\bar{m}_{\text{in}}$ and $\bar{m}_{\text{out}}$ are the average in-degree and out-degree of the nodes, and t is the tolerance time.

E. Safety

Safety in airspace networks is inherently a qualitative concept, often associated with minimizing risk and ensuring reliable operation. However, to make informed design and operational decisions, it is necessary to translate this idea into



measurable terms. In this work, safety is defined through two complementary quantitative approaches that capture different aspects of operational risk related with non nominal flights. The first relates to the potential for conflict during Return-To-Land (RTL) maneuvers in contingency scenarios, while the second assesses risk arising from loss of conformance, that is, deviations from intended flight paths. Both approaches leverage the structure of the airspace network to evaluate how spatial factors influence the likelihood and severity of unsafe situations.

1) *Contingency*: When a contingency occurs a UAV must execute a Return-To-Launch (RTL) maneuver. These procedures deviate from the planned airspace structure and pose a risk of uncoordinated conflicts with other aircraft when RTL path intersects active corridors. To quantify this risk, it is necessary to consider the spatial distribution of landing infrastructure.

A subset of graph nodes are designated as vertiports, which serve as hubs for mission origin and destination. Every mission begins or ends at a vertiport. The 2D map of the network is divided into Voronoi regions using the Euclidean distance to the set of vertiports. Each edge is assigned to the region of its closest vertiport, determined by the midpoint of the edge geometry. We assume that, in the event of a contingency, the UAV will return directly, following a straight-line path through the airspace, to the vertiport associated with the region where the incident occurs. This path is not constrained by the existing graph structure and may intersect other corridors.

To evaluate the risk introduced by RTL maneuvers, we compute how many existing corridors (i.e., edges in the graph) are crossed by the straight-line RTL path from each edge to its assigned vertiport. Each of these crossings represents a potential point of conflict. Let e_i denote an edge of the network, and let $\text{Cross}(e_i)$ denote the number of graph edges intersected by the direct line from the midpoint of e_i to the corresponding vertiport. The average number of crossings per edge is then defined as:

$$C_{\text{RTL}} := \frac{1}{|E|} \sum_{i=1}^{|E|} \text{Cross}(e_i) \quad (13)$$

This metric captures the overall disruption potential of RTL maneuvers across the network. Higher values of C_{RTL} indicate that RTL procedures frequently intersect existing traffic corridors, leading to increased risk of conflict. Lower values suggest that the airspace layout allows safer isolation of contingency routes from planned operations.

It is worth noting that RTL procedures could, in principle, be designed to minimize conflict by first ascending vertically before proceeding horizontally toward the designated vertiport. Since contingency scenarios still assume some level of control over the aircraft, such structured maneuvers could avoid intersecting operational corridors, but only under the assumption of a two-dimensional airspace design. However, this introduces a discrepancy: while the airspace is designed and evaluated as a flat network, safety is preserved through

implicit use of 3D maneuvers. As urban airspace systems evolve toward fully three-dimensional designs, with traffic separated across altitude layers, these assumptions will no longer hold. In such contexts, vertical RTL maneuvers may still intersect other active layers, reintroducing the problem of uncoordinated crossings. This highlights the importance of extending RTL crossing analysis to 3D network structures in future work, particularly for layered or multi-altitude corridor systems.

2) *Conformance*: Loss of conformance refers to situations where an aircraft deviates from its planned trajectory due to failure to adhere to control inputs or navigation guidance. This can occur as a result of onboard system malfunctions—such as GNSS degradation, control loss, or sensor drift—or due to external, localized anomalies in the environment (e.g., interference zones or degraded positioning coverage). In this study, we focus exclusively on loss of conformance caused by aircraft-side malfunctions, assuming the environment remains nominal.

To evaluate the structural risk posed by conformance issues, we analyze how aircraft deviations may lead to unintended proximity with other flight paths. The key idea is that deviations occurring in isolated segments of the network are less dangerous than those near dense intersections or closely packed corridors. To capture this, we define a safety buffer around each edge in the graph. This buffer corresponds to a corridor of minimum safe separation: for an edge of length L , a rectangular polygon is created of width $2d$ (with d being the minimum separation distance) and length L , centered on the edge.

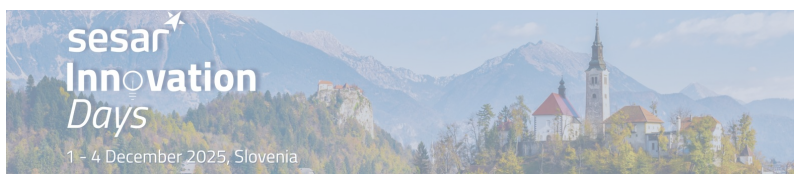
Once the buffer areas for all edges are generated, we analyze how much of this space overlaps. Overlapping buffer regions indicate zones where deviations from one corridor could enter the safety zone of another, creating a potential for conflict in the event of a loss of conformance. The total conflicting area is defined as the union of all overlapping regions, and the conformance risk metric is given by the percentage of the total buffered area that is involved in a conflict:

$$C_{\text{conf}} := \frac{A_{\text{overlap}}}{A_{\text{total}}} \quad (14)$$

Here, A_{overlap} is the total area where buffer polygons intersect, and A_{total} is the sum of the areas of all individual buffer polygons. The metric C_{conf} ranges from 0 (no overlaps, ideal separation) to 1 (complete overlap, maximal conflict potential). High values of C_{conf} indicate that the network design places corridors too close together, leaving little margin for safe deviation in the event of conformance loss.

III. SIMULATION STUDY

To evaluate the validity and usefulness of the proposed entropy, capacity and safety metrics for assessing airspace structures, it is necessary to test them under controlled and realistic scenarios. While the metrics are defined from structural and geometric considerations, their practical interpretation depends on how they behave when applied to different types



of airspace layouts. Simulations allow us to observe these behaviors and verify whether the metrics reflect meaningful differences in network performance and design.

Using the DronAs platform, simulations were carried out to test the metrics under realistic U-space scenarios. DronAs provides USSP functionalities such as traffic generation, mission planning, and demand–capacity balancing, making it well suited for evaluating airspace structures in a controlled environment [10].

A. Parameters

Theoretical capacity estimates and simulations were carried out using a consistent set of parameters to ensure comparability across scenarios, Tab. I. The tolerance time (a buffer allowing missions to begin within a flexible time window around their assigned start) was set to 60 seconds, reflecting realistic operational uncertainty. The minimum separation distance between aircraft was defined as 50 meters, and all missions were assumed to travel at a constant operating speed of 10 m/s. For each simulation run, vertiports were allocated randomly within the available network to prevent structural bias and to better reflect varying deployment scenarios. These parameters were used uniformly across both synthetic layouts and real district networks

TABLE I. PARAMETERS USED IN THEORETICAL AND SIMULATION MODELS

Parameter	Value
Tolerance time	60 seconds
Minimum separation distance	50 meters
Operating speed	10 m/s (constant)
Vertiport allocation	Random per simulation

B. Theoretical Results

To better understand the structural characteristics of both synthetic layouts and real neighborhoods, we analyze a set of graph-based metrics, seen in Tab. II, that describe their geometry and capacity. The basic structural properties include the number of nodes and edges, as well as the mean bearing (MB), which captures angular variation at intersections, and the mean edge length (ML). Complementary metrics quantify, seen in Tab. III, broader network properties: the base entropy, the actual entropy, capacity (maximum traffic simultaneous that the network can support), crossings (number of edge intersections), and the overlap ratio, which measures the extent to which trajectories share the same space.

The synthetic neighborhoods are constructed from regular, expandable patterns, which makes their structural properties predictable as the size of the grid increases. Because of this, their results can be extrapolated into curves that capture the evolution of each metric under controlled conditions. These curves serve as benchmarks or reference points against which the values of actual neighborhoods can be compared. In this way, deviations observed in real urban structures can be interpreted relative to an idealized baseline, allowing us to distinguish between features that arise from geometric

TABLE II. STRUCTURAL PROPERTIES OF THE GRAPH

Neighborhood	Nodes	Edges	MB	ML
S30	900.0	1740.0	45.20	100.0
S40	1600.0	3120.0	45.11	100.0
S50	2500.0	4900.0	45.07	100.0
H30	900.0	2581.0	80.41	100.0
H40	1600.0	4641.0	80.29	100.0
H50	2500.0	7301.0	80.23	100.0
W30	241.0	480.0	57.14	643.2
W40	321.0	640.0	56.92	834.5
W50	401.0	800.0	56.78	1025.8
Ciutat Vella	434.0	737.0	62.18	82.41
Eixample	789.0	1426.0	51.30	99.73
Horta-Guinardó	1065.0	1966.0	78.03	97.42
Les Corts	607.0	1160.0	73.68	93.91
Nou Barris	834.0	1523.0	69.94	93.95
Sants-Montjuïc	1259.0	2293.0	66.40	103.57
Sant Andreu	777.0	1389.0	66.85	91.03
Sant Martí	1094.0	1952.0	61.77	96.74

TABLE III. ENTROPY AND CAPACITY METRICS

Neighborhood	Base	Entropy	Capacity	Crossings	Overlap
S30	6.80	4.52	20.39	10.15	0.33
S40	7.38	4.79	35.93	10.02	0.33
S50	7.82	5.01	55.85	9.98	0.33
H30	6.80	3.44	12.69	13.48	0.52
H40	7.38	3.62	22.44	13.25	0.52
H50	7.82	3.76	34.96	12.55	0.53
W30	5.48	3.50	208.53	17.54	0.08
W40	5.77	3.60	466.70	18.23	0.06
W50	5.99	3.68	879.93	20.05	0.05
Ciutat Vella	6.07	4.11	6.81	8.66	0.51
Eixample	6.67	4.46	18.21	9.21	0.34
Horta-Guinardó	6.97	4.22	18.21	10.60	0.56
Les Corts	6.41	3.97	9.69	8.71	0.57
Nou Barris	6.73	4.28	13.84	9.86	0.54
Sants-Montjuïc	7.14	4.51	27.06	9.69	0.58
Sant Andreu	6.66	4.39	13.63	10.04	0.51
Sant Martí	7.00	4.54	22.74	8.81	0.43

regularity and those that are specific to the complexity of real city layouts.

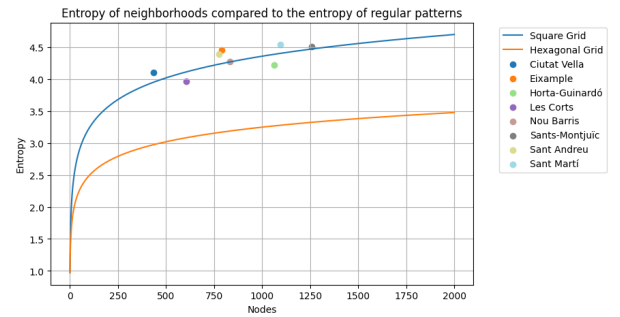


Figure 3. Entropy of neighborhoods compared to the extrapolated curve of the square grid and hexagonal grid patterns.

The entropy values Fig. 3 show that the neighborhoods closely follow the extrapolated curve of the square grid pattern. Despite their irregularities, the structural diversity of the real layouts behaves in a manner consistent with the theoretical baseline of a square grid.

The capacity values Fig. 4 follow the trend of the square grid extrapolation closely, with all neighborhoods positioned

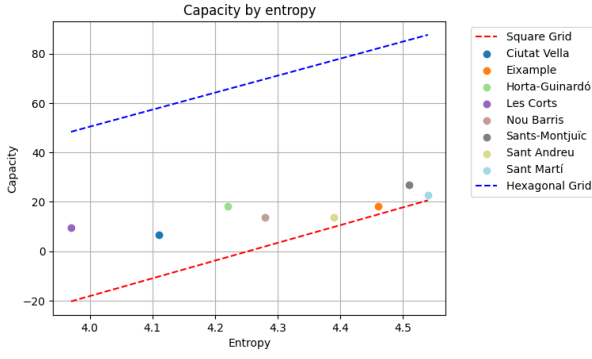


Figure 4. Capacity of neighborhoods compared to the extrapolated curve of the square grid and hexagonal grid patterns.

slightly above the curve. The results suggest that there is a positive correlation between entropy and capacity.

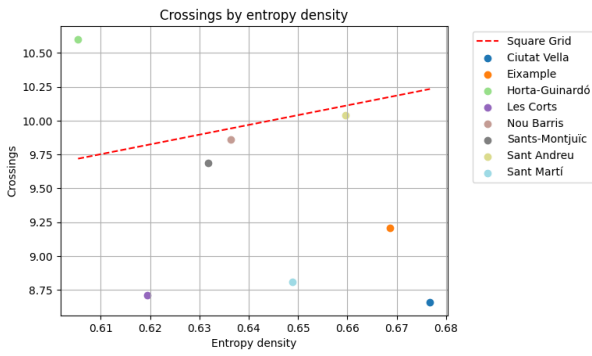


Figure 5. Crossing count for the real neighborhoods compared to the extrapolated curve of the square grid pattern.

The crossing values Fig. 5 show a slight positive correlation for the square grid extrapolation. However, such tendency cannot be observed for real neighborhoods.

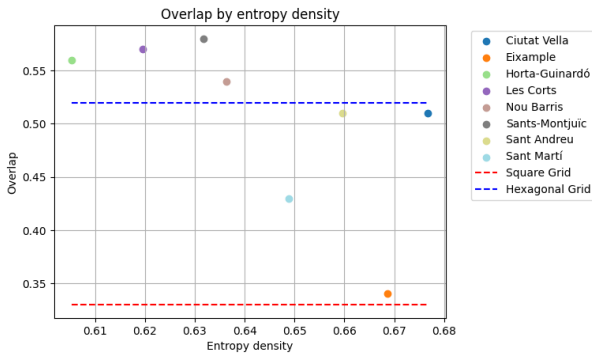


Figure 6. Overlap ratio of neighborhoods compared to the benchmark of the square grid and hexagonal grid patterns.

The overlap ratio results Fig. 6 show that is not possible to observe any tendency as the value of entropy increases.

C. Simulation Results

To evaluate the operational capacity of each neighborhood, simulations were conducted using the DronAS framework.

Since vertiport locations were assigned randomly within the available network, multiple runs were performed to mitigate location bias. In each simulation, the maximum traffic level for the layout was determined by gradually increasing the number of planned missions within a one-hour period until the DronAS demand–capacity balancing (DCB) mechanism converged on the number of accepted missions. For capacity measurement, the simultaneous traffic was monitored throughout each run, and the peak value was taken as the result, Tab. IV.

TABLE IV. SIMULATION RESULTS: SIMULTANEOUS MISSION COUNT

Neighborhood	Missions	Standard deviation
S30	23.6	0.92
S40	35.7	1.62
S50	42.4	1.91
H30	22.1	1.14
H40	33.1	1.30
H50	39.9	2.34
W30	12.9	1.04
W40	17.6	0.92
W50	36.6	1.96
Ciutat Vella	10.3	0.78
Eixample	18.4	1.43
Horta-Guinardó	18.4	1.28
Les Corts	14.4	0.80
Nou Barris	16.0	1.10
Sants-Montjuïc	16.6	1.20
Sant Andreu	20.9	1.14
Sant Martí	24.4	1.85

When comparing the theoretical capacity (Tab. III) with the simulation results, the overall Pearson correlation is very low $r = 0.213$ and determination coefficient $R^2 = 0.045$, suggesting poor agreement. However, this discrepancy is largely driven by the web layouts, which consistently exhibit much higher theoretical capacity than simulated. When excluding the W layouts from the analysis as in Fig. 7, the Pearson correlation between the estimated capacity and simulation mean rises sharply to $r = 0.904$ and the determination coefficient is $R^2 = 0.817$. Now it is possible to see that the capacity metric closely aligns with the simulations. It is possible to observe that the theoretical metric has a slight tendency to underestimate in lower capacity layouts and overestimate in layouts that perform better. The big difference before and after removing the W layouts suggest that the metric might be vulnerable to some extreme outlier designs.

It is not straightforward to assess the relationship between capacity and entropy, as both variables are greatly impacted by node and edge count. Using the entropy density, Eq. 9, and adjusting the capacity by edge count it becomes possible to compare them more intuitively, Fig. 8. The correlation between entropy density and simulated capacity density is $r = 0.736$, indicating a moderate positive relationship. In contrast to the capacity metric, it was not necessary to remove W layouts in this case. This suggests that it is possible to use the entropy metric as a reliability indicator for the capacity metric. It is interesting to note that the best performing layouts in Fig. 7, have lower values in Fig. 8.

Tab. V presents the outcomes of the safety simulations for urban airspace traffic. The traffic scenarios for the capacity

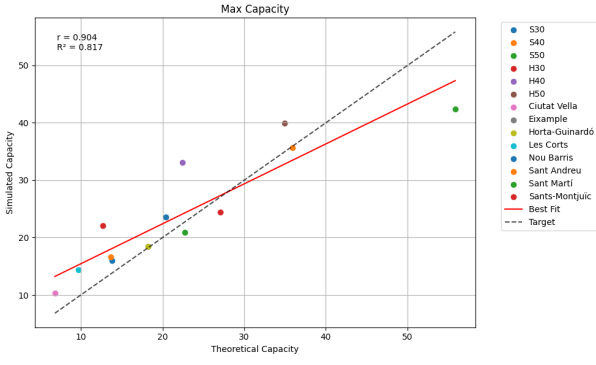


Figure 7. Comparison between theoretical and simulated capacity, excluding W layouts.

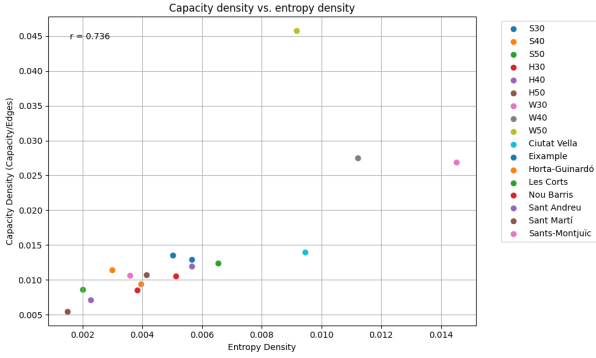


Figure 8. Comparison between entropy density and simulated capacity.

TABLE V. CONTINGENCY AND CONFORMANCE SIMULATION RESULTS. AVERAGE NUMBER OF CONFLICTS AFTER 200 SIMULATIONS.

Neighborhood	Contingency	Conformance
H30	1.804	0.010
H40	1.685	0.005
H50	1.688	0.000
S30	2.041	0.015
S40	2.019	0.010
S50	2.026	0.010
W30	1.346	0.005
W40	1.827	0.010
W50	2.349	0.000
Ciutat Vella	1.280	0.020
Eixample	1.529	0.015
Horta-Guinardó	1.515	0.010
Les Corts	1.172	0.005
Nou Barris	1.270	0.010
Sant Andreu	1.321	0.020
Sant Martí	1.475	0.005
Sants-Montjuïc	1.050	0.005

simulations were used. In each case, 200 simulations were run, and the reported values correspond to the average number of conflicts per scenario under different conditions. Two types of anomalies were considered: contingency events, in which a mission must perform a return-to-launch procedure, and conformance deviations, in which the positioning system malfunctions and produces errors in a radius of 50 m.

The results show a clear contrast between contingency and conformance scenarios. In the contingency case, conflicts are almost guaranteed: across all layouts, the average number of

conflicts per scenario is always above one. This indicates that a sudden return-to-launch maneuver generates significant disruption to surrounding traffic, regardless of the local network structure. By contrast, in the conformance scenarios, the tolerance time of the mission is highly effective in reducing conflict rates. At 50 m deviation, the system is robust, producing only a handful of minor conflicts across 200 simulations.

TABLE VI. CORRELATION AND STANDARDIZED LINEAR REGRESSION COEFFICIENTS FOR FEATURES IN THE CONTINGENCY SCENARIO.

Feature	Correlation	Importance
Mean Length	0.4125	-0.7557
Capacity	0.5372	0.5349
Mean Bearing	-0.4265	-0.3699
Entropy	-0.0115	-0.3405
Crossings	0.4715	0.3237
Base	0.1466	0.2961
Edges	0.2385	-0.2956
Nodes	0.2337	0.1816

Since there are no direct theoretical measures to predict the emergence of conflicts in urban airspace, it is necessary to rely on structural and spatial features of the network to approximate how conflicts originate. The correlation analysis and feature importance coefficients for a lineal regression model provide complementary perspectives into how each theoretical variable correlates to the safety results, Tab. VI and Tab. VII.

In the results for the contingency simulations, Tab. VI, it is possible to note the most relevant variables. The mean length of the edges and the capacity stand out as the heaviest importance coefficient weights and strong correlations. Size of the network and traffic are possible explanations of the relevance of these parameters, suggesting that the density of missions may be the key to evaluating safety from a theoretical point of view. Also, the metric that was developed for the contingency scenarios 'Crossings', also has the second strongest correlation along with a significant weight for the importance coefficient. This makes sense because a higher amount of crossings should translate to more opportunities for conflicts, although it is not enough by itself as it is necessary to account for traffic for these conflict opportunities to materialize.

TABLE VII. CORRELATION AND STANDARDIZED LINEAR REGRESSION COEFFICIENTS FOR FEATURES IN THE CONFORMANCE SCENARIO.

Feature	Correlation	Importance
Mean Length	-0.3652	-0.010609
Base	-0.1446	-0.005615
Capacity	-0.3940	0.003363
Overlap	0.1637	-0.003012
Edges	-0.3626	0.003003
Nodes	-0.2618	-0.002798
Entropy	0.3732	0.002288
Mean Bearing	-0.2885	-0.000085

Conformance scenarios under current simulation parameters have been shown to present a way lower number of conflicts than expected. This makes correlating them with other variables slightly more challenging than in the contingency scenarios. However, the results shown in Tab. VII seem to

align with what was observed in the contingency results. The length of edges and the total capacity are again the most important variables, suggesting that conformance conflicts are also sensitive to spatial traffic density. 'Base' (entropy without structure) is mainly a size dependent variable and seems to be used by the model in the same way as the mean length. The overlap variable that was designed for these scenarios seems to play a more modest role.

It is important to note that safety simulations were based on scenarios for maximum capacity in each layout, causing each layout to have a different spatial traffic density. Given the sensitivity of both metrics to spatial traffic density, it might be necessary to control this variable to have a definitive understanding of these metrics.

IV. CONCLUSION

The proposed metrics for urban airspace design evaluation have shown varying degrees of success, with clear strengths in some areas and limitations in others.

The capacity metric provided the most consistent and interpretable results. It aligned well with theoretical expectations, proving particularly effective at capturing the differences in urban structures. The only major exception was the spider web layout, where the metric completely failed to reflect the actual traffic behavior, suggesting that overly unrealistic geometries can undermine its validity. Despite this, for practical applications in real urban environments, capacity appears to be a robust and reliable measure.

Entropy demonstrated more modest results. It was successful in predicting capacity trends and, importantly, was not misled by artificial designs such as the spider web layout. However, its lack of a direct quantification of network throughput limits its usefulness. Instead, entropy seems best suited as a complementary indicator of reliability: while capacity should be used as the primary measure of traffic potential, entropy can serve as a check on whether the structure of the network is well-balanced or prone to irregularities.

For contingency analysis, no direct theoretical metric could be established. Instead, simulation results were correlated with several features. The analysis highlights two key aspects: capacity must be used to infer effective traffic density, since higher density increases the likelihood of potential conflicts materializing, and the number of crossings is a useful predictor of where those potential conflicts may occur. The results also showed that contingency events almost always lead to conflicts, with an average of one conflict per simulation. This indicates that a contingency followed by an RTL (return-to-launch) maneuver effectively guarantees an incident unless mitigated. It is therefore essential to not only develop dedicated contingency management services but also to embed solutions into the airspace design itself, for example through predefined RTL corridors and procedures, rather than relying on the shortest path to a vertiport.

Conformance issues turned out to be less critical than initially expected. The tolerance time for missions acted as a natural buffer, absorbing most trajectory deviations without

generating conflicts. Only very large deviations caused significant issues. Nevertheless, future scaling of the network may require reducing tolerance times to increase capacity, which could reintroduce conformance-related risks. Studying how such reductions affect conflict generation will therefore be an important line of research.

Taken together, the findings suggest that capacity is the most reliable metric for evaluating urban airspace designs, while entropy can serve as a secondary indicator of network balance. For contingency management, a combination of capacity (to infer density) and crossings (to locate potential conflicts) provides the most insight, though these need to be paired with operational solutions such as RTL corridors. Conformance issues currently appear manageable under the chosen parameters, but may become more relevant under higher-capacity scenarios.

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