System-Wide Capacity Modeling for Urban Air Mobility under Wind Effects

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1 Introduction

To unlock the full potential of Urban Air Mobility (UAM), a key consideration lies in understanding the true capacity of urban airspace. The scalability and growth of UAM are directly dependent on the available capacity of airspace, which supports both the size and operational demands of this emerging transportation system. Assessing this capacity is essential for determining how UAM can be integrated into urban environments efficiently and sustainably.

Significant advances have been achieved in airspace capacity analysis, which primarily bifurcates into unconstrained and constrained airspace paradigms. For unconstrained airspace, analytical models based on combinatorial mathematics (e.g., conflict-free routing permutations) or safety-oriented analyses of eVTOL physical characteristics have been developed (Ning *et al.*, 2023), focusing on local conflict resolution protocols (Cummings & Mahmassani, 2024) or theoretical separation thresholds (Denham *et al.*, 2023). Methodology likes the Macroscopic Fundamental Diagram (MFD) (Cummings & Mahmassani, 2024) has provided component-level insights into capacity modeling. Constrained urban airspaces share operational similarities with road transportation systems. Recent studies leverage network-theoretic approaches to design three-dimensional airspace structures (Zhang *et al.*, 2024), emphasizing geometric metrics such as route density or intersection throughput. Yet, as our work emphasizes, urban airspace constitutes a complex 3D environment where capacity is co-determined by building morphology, wind-structure interactions, and infrastructure topology— how do these factors collectively govern system-level urban airspace capacity?

Our work addresses this through a unified framework integrating aerodynamic interactions, network flow dynamics, bridging the divide between idealized capacity models and operational realities in dense urban settings.Our work addresses this through a unified framework integrating aerodynamic interactions, network flow dynamics, bridging the divide between idealized capacity models and operational realities in dense urban settings.

To address this gap, we propose a system-level capacity analysis framework integrating three key dimensions: (1) urban wind field dynamics modeled through zonal subregion wind estimation; (2) infrastructure-induced airspace fragmentation quantified via 3D building occlusion ratios; and (3) network flow optimization resolving maximum system throughput under spatiotemporal uncertainties. This approach advances traditional airspace capacity paradigms in three aspects: First, by replacing sector-based static capacity assumptions with physics-informed dynamic cell capacities, our model captures micro-scale wind-structure interaction propagation across networks. Second, hexagonal tessellation inherently integrates vertical routing options. Third, the maximum flow model provides policymakers with quantifiable metrics for evaluating urban system-level capacity determinants.

2 The Modeling Framework

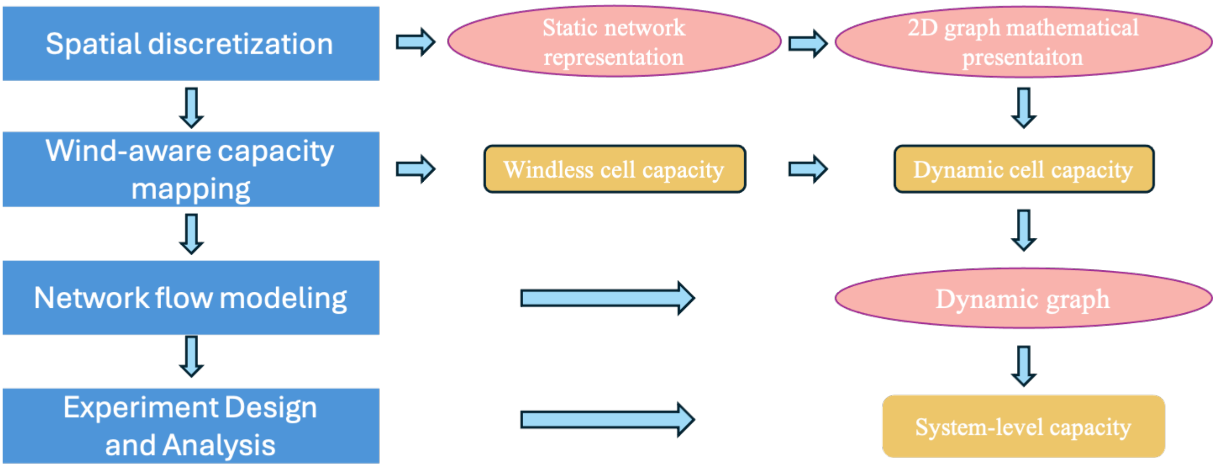

Figure 1 – *Research Flow Diagram*

As figure 1 shown, our methodology advances through four system phases: Spatial discretization partitions urban airspace into hexagonal prism cells with inter-cell connections representing traversable links; Wind-aware capacity mapping develops reduced-order models estimating cell-specific capacity thresholds based on local wind fields; Network flow modeling constructs maximum flow optimization considering time-varying cell capacities and capacity constraints; experiments design and analysis identifies critical capacity limitations through sensitivity studies of wind variations and building topology, solved via parametric maximum flow optimization.

Spatial Discretization As illustrated in Figure 2, the urban airspace is systematically partitioned into regular hexagonal prism cells with side length (L), vertically stratified into (n) discrete layers of height (H) each. This hierarchical tessellation creates a three-dimensional navigable network where each cell $i \in V(t)$ represents a fundamental operational unit. For the horizontal hexagonal topology containing buildings in the city, as shown in Figure 2a, each specific cell is shown in Figure 2b.

Inter-cell connections are modeled as directed links $(i, j) \in E(t)$ in the dynamic graph $G(t)$, representing traversable corridors between adjacent cells. Each cell's instantaneous capacity $C_i(t)$ integrates wind speed vector fields, building density within its airspace volume, and minimum safety separation requirements. Similarly, link capacities $C_{ij}(t)$ encode directional wind effects, eVTOL performance envelopes, and transient aerodynamic constraints.

Wind-Aware Capacity Mapping The wind vector field within each hexagonal cell i is first reconstructed using a logarithmic wind profile:

$$\mathbf{W}_i = \sum \theta f(\theta) \cdot V_{\text{rose}}(\theta) \cdot \frac{0.4}{u_*} \left[0.193 + \ln \left(\frac{H_i - Z_{d,i}}{Z_{0,i}} \right) \right] \cdot \hat{\mathbf{e}}_\theta \tag{1}$$

where urban morphology parameters $Z_{d,i}$ (zero-plane displacement) and $Z_{0,i}$ (roughness length) are derived from Frontal Area Index ($\lambda_{F,i}$) via empirical relations. The model aggregates directional wind contributions weighted by occurrence frequency $f(\theta)$ from wind rose data, capturing altitude-dependent speed attenuation through urban roughness effects.

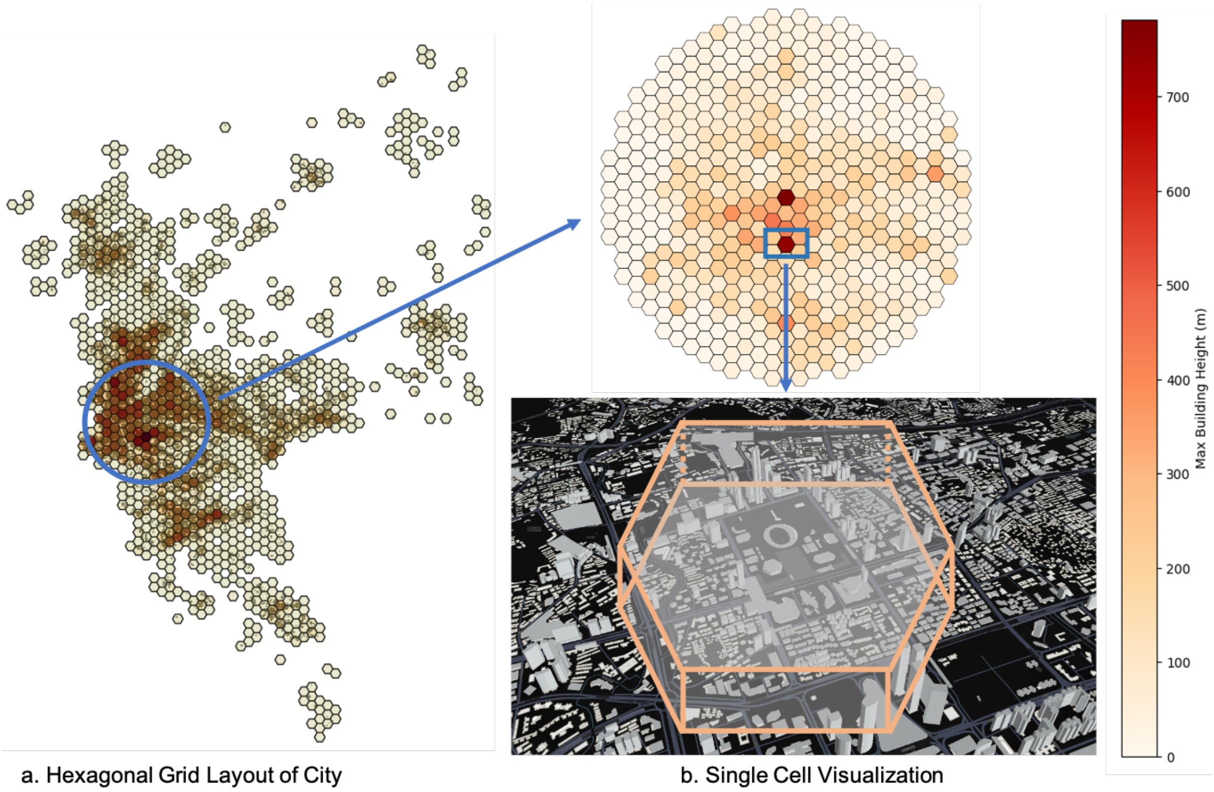

Figure 2 – *Structure Visualization*

Cell-specific capacity C_i is reduced to a function of wind magnitude and eVTOL dynamics:

$$C_i = \frac{V_i}{(d_{\text{base}} + k_1|\mathbf{W}_i| + k_2 V_{\text{cruise}})^3} \tag{2}$$

where the cubic safety volume accounts for 3D separation constraints under wind-induced position uncertainty. For inter-cell transitions, a directional decomposition of wind effects governs link capacity:

$$C_{ij} = \frac{S_{ij}}{\left(d_{\text{base}} + k_1|\mathbf{W}_{ij}^{\perp}|\right)^2} \cdot \left(V_{\text{cruise}} - |\mathbf{W}_{ij}^{\parallel}| + \alpha|\mathbf{W}_{ij}^{\perp}|\right) \tag{3}$$

distinguishing parallel ($\mathbf{W}_{ij}^{\parallel}$) and perpendicular ($\mathbf{W}_{ij}^{\perp}$) wind components relative to the interface.

Formulation of the Maximum Flow Problem We formulate the airspace network optimization using the classical single-source-sink maximum flow paradigm. Let $G(t) = (V(t), E(t))$ denote the time-varying directed graph, augmented with a virtual source node s connected to all departure zones and a virtual sink node t receiving flows from all arrival zones. The objective is to maximize the steady-state throughput $v(t)$ under wind-modulated capacity constraints:

$$\text{Maximize} \quad v(t) = \sum_{(s,j)\in E(t)} f_{sj}(t)$$

subject to the following constraints:

$$\sum_{j\in V(t)} f_{ij}(t) - \sum_{j\in V(t)} f_{ji}(t) = \begin{cases} v(t) & \text{if } i = s \\ 0 & \forall i \in V(t) \setminus \{s,t\} \\ -v(t) & \text{if } i = t \end{cases} \tag{4}$$

$$0 \leq f_{ij}(t) \leq C_{ij}(t), \quad \forall (i,j) \in E(t) \tag{5}$$

$$\sum_{j \in V(t)} f_{ij}(t) \leq C_i(t), \quad \forall i \in V(t) \tag{6}$$

We discretize time into multiple intervals, where the network state remains fixed within each interval. During each interval, we independently solve the maximum flow problem, treating the network as static within that time frame. By focusing on flow maximization at each discrete time step, we simplify the optimization process. Solving the maximum flow problem for each time period ensures that we account for time-varying factors in the system, such as changes in wind patterns and airspace usage.

3 Experiments and Results

We analyze wind effects on airspace capacity through two scenarios: (1) a windless baseline with maximum flow F_0 using theoretical lin k capacities C_{ij}; (2) a wind-adjusted scenario with reduced flow F_w, where F_w/F_0 quantifies capacity loss. Our framework is applied to Guangzhou's airspace, modeled as 499 hexagonal cells (1 km in length) across four vertical layers(100m each). Wind speed and direction data are provided by the China Surface Meteorological Observation Daily Dataset from the National Meteorological Information Center (http://data.cma.cn). Urban morphology data obtained from the Guangzhou Urban Planning Design Survey Research Institute (GZPI) (http://www.archina.com) is used to account for the physical constraints posed by buildings and land-use patterns. The experiment sets up a series of source nodes and sink nodes representing entry and exit points for airspace flows. Through this experimental setup, we aim to quantify the wind-induced reduction in capacity and understand the system-level capacity of UAM.

The results of the experiments demonstrate that in the windless baseline scenario, the maximum flow was calculated at its theoretical maximum value, yielding a flow of $F_0 = 1777.78$ units per time, with link capacities C_{ij} at their maximum and the flow primarily constrained by the link capacities between adjacent cells. However, when static wind field effects were introduced, link capacities significantly decreased as wind speed increased. Specifically, at a wind speed of 5 m/s, the maximum flow reduced to $F_w = 1234.56$ units per time, and at 10 m/s, the flow further decreased to $F_w = 1023.45$ units per time. This trend illustrates a clear reduction in airspace capacity as wind speed increases. Given that wind has a more pronounced effect on cell capacity, the primary factor influencing the maximum flow becomes the cell capacity.

Future work Our research aims to replace empirical coefficients with physics-based quantification using urban-scale CFD simulations. We will develop a nested framework coupling wind field predictions with microclimate simulations around key infrastructure. This approach integrates real-time meteorological data and CFD to analyze wind-structure interactions at operational altitudes. We will also explore machine learning to enable real-time capacity adjustments based on CFD-derived flow features.

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