A Modelling-Mapping Approach for Fine-Scale Wind Assessment in High Density Cities

Presenter: Chao Yuan 袁超
Leslie Norford, Rex Britter, Steve Yim, Edward Ng
Department of Architecture, Massachusetts Institute of Technology (MIT)
Architecture and Sustainable Design, Singapore University of Technology and Design (SUTD)

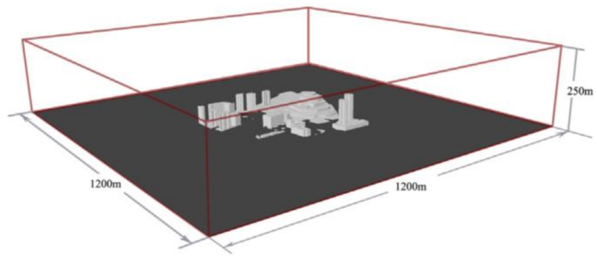
INTRODUCTION

Background

INTRODUCTION

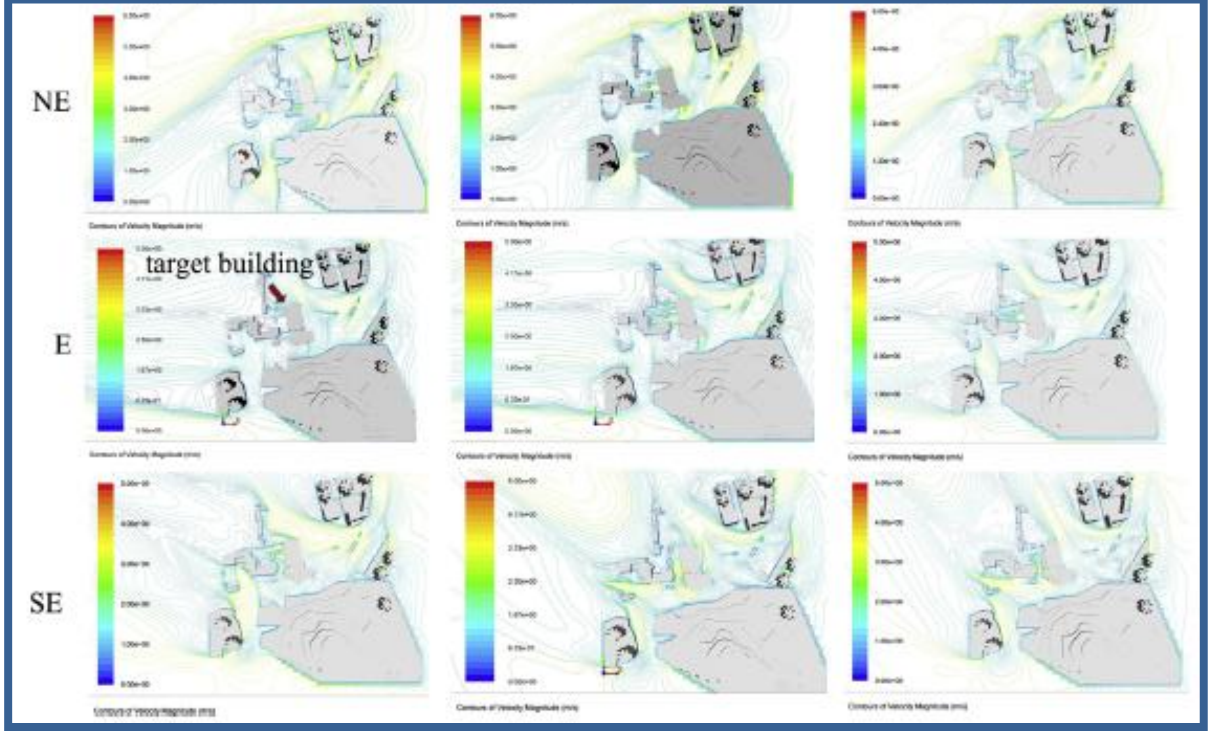
Current Methods

CFD Simulation



Wind Tunnel

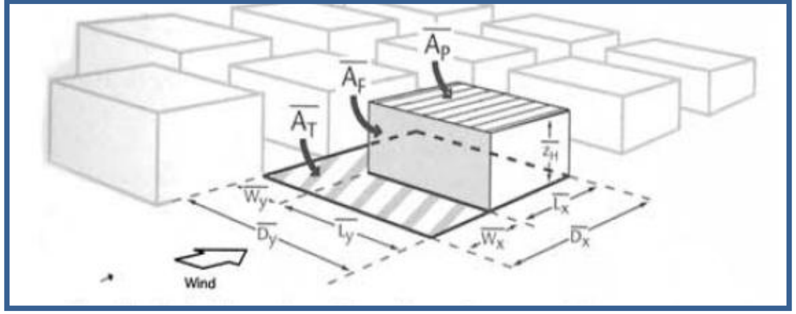
Modelling results with three input wind directions



- **Advantages**: Accurate modelling results, high resolution information
- **Disadvantages**: Time-consuming, Need for intensive technical support

INTRODUCTION

Morphological model



(Grimmond and Oke, 1999)

Raupach (1991):

$$\mathrm{Rt}_d \quad \text{is} \quad z_d = f_d \overline{z_H}$$

$$\mathrm{Rt}_0 \quad \text{is} \quad z_0 = f_0 \overline{z_H},$$

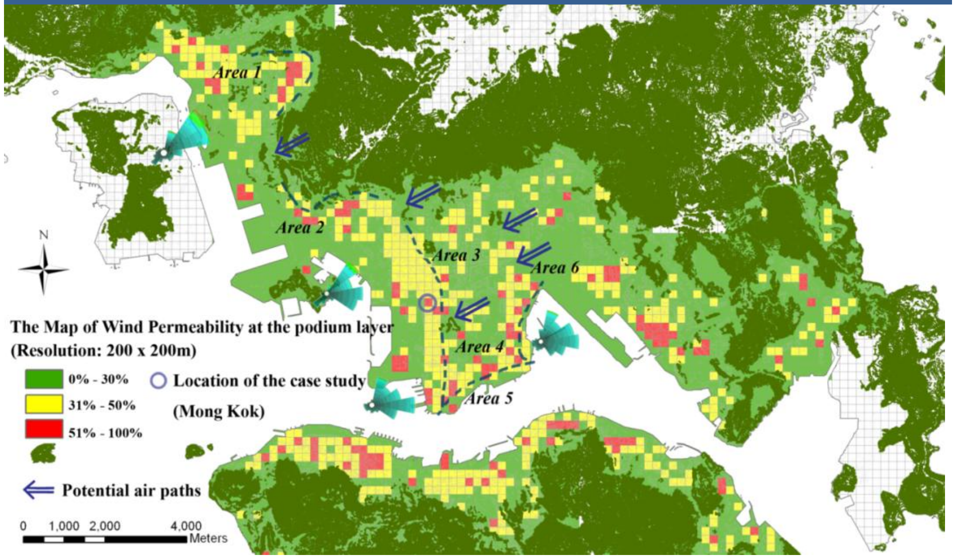
Macdonald (1998):

$$\mathrm{Ma}_d \quad \text{is} \quad \frac{z_d}{z_H} = 1 + \alpha^{-\lambda_P}(\lambda_P - 1)$$

and Ma_0 is

$$\frac{z_0}{z_H} = \left(1 - \frac{z_d}{z_H}\right) \exp\left\{-\left[0.5\beta \frac{C_D}{k^2}\left(1 - \frac{z_d}{z_H}\right)\lambda_F\right]^{-0.5}\right\}$$

Map of pedestrian-level wind permeability



(Ng, E., et al., 2011)

- **Advantage:**

  Low computational cost

  Quick decision-making

- **Disadvantage:**

  Low resolution

OBJECTIVE

To develop the fine-scale morphological modelling-mapping approach

- **Lower computational costs** than that of Computational Fluid Dynamics (CFD) simulation and the wind tunnel experiment.

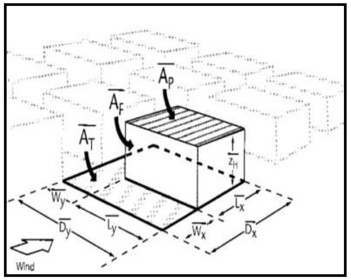
- **Higher resolution of modelling results**, providing the information about the air flow between buildings, compared with spatially-averaged results in the conventional morphological models .

To bridge the gap between the current modelling methods and requirements of practical planning and design.

MODEL DEVELOPMENT

Frontal area density

Definition:



Frontal area density at the wind direction of θ:

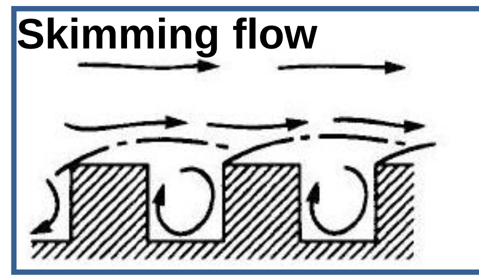
$$\lambda_{f(\theta)} = \frac{A_F}{A_T}$$

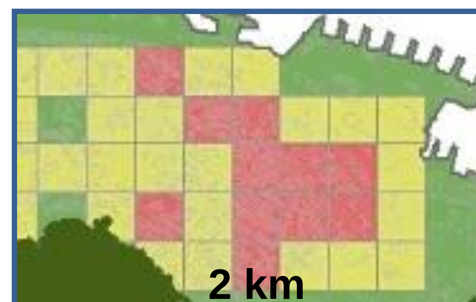
Drag force acting on the control volume (Bentham and Britter, 2003):

$$\tau_w A_T = 0.5 \rho U_c^2 \sum_N C_d A_F$$

Problems:

- **To apply λ_f at high density areas:**
  Most of morphological models are not valid when $\lambda_f > 0.3 - 0.4$.
- **To increase the resolution of modeling results:**
  The spatial resolution is too low to the neighborhood-scale analysis.

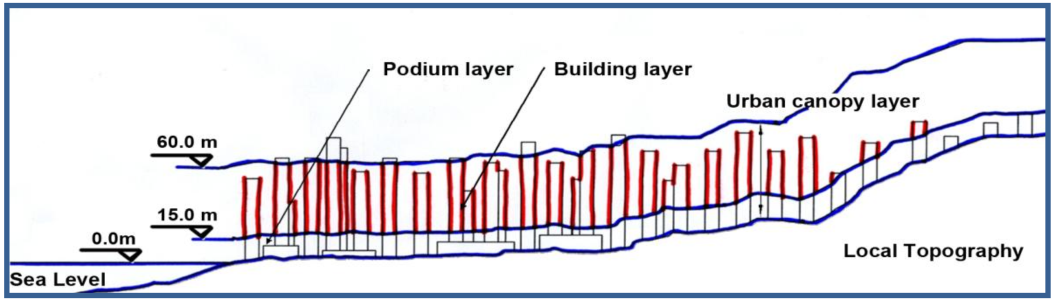




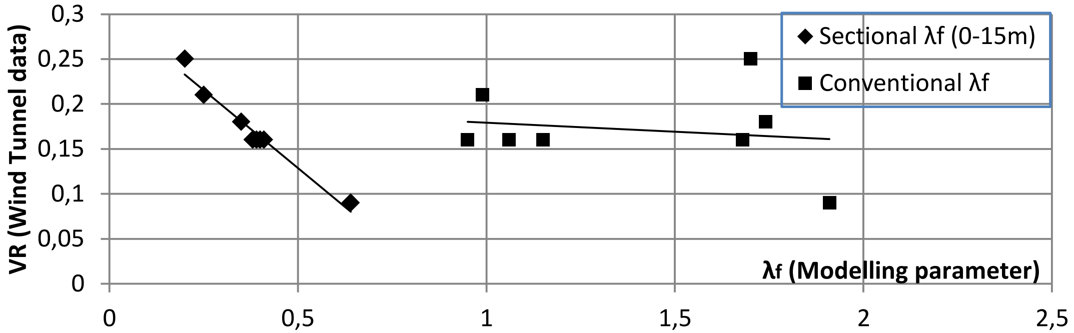
1 km

MODEL DEVELOPMENT

Sectional frontal area density (λ_f) (Ng, et al., 2011)



Podium layer and urban canopy layer
(Ng, et al., 2011)



Relationship between velocity ratio and λ_f

Sectional frontal area density at the wind direction of θ:

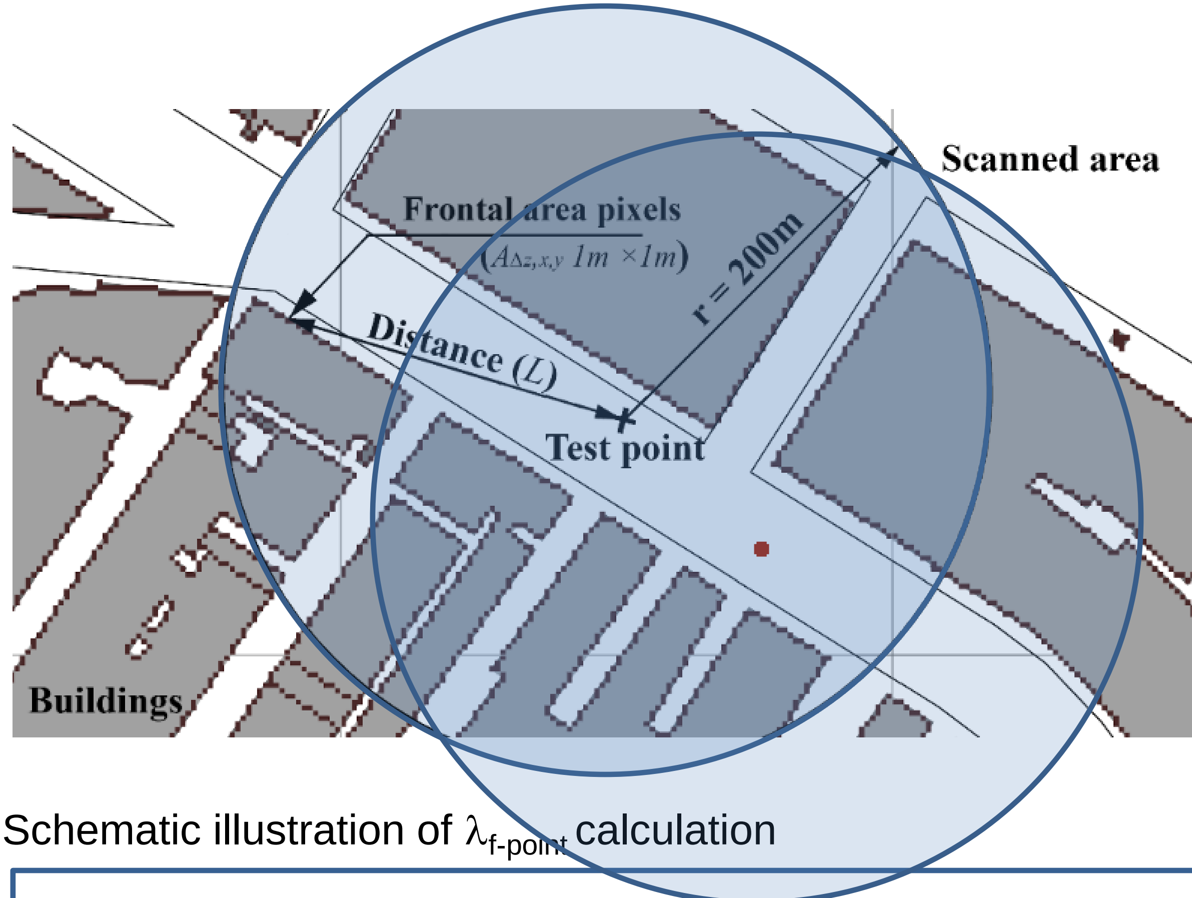
$$\lambda_{f(Z,\theta)} = \frac{A(\theta)_{proj(\Delta z)}}{A_T}$$

Sectional frontal area density with the annual wind frequency (P_θ):

$$\lambda_{f(z)} = \sum_{\theta=1}^{16} \lambda_{f(z,\theta)} \cdot P_\theta$$

MODEL DEVELOPMENT

Point-specific λ_f



Schematic illustration of $\lambda_{f\text{-point}}$ calculation

Spatially-averaged Parameter

$\lambda_{f(z)}$

Distance index (L)

λ_{f_point}

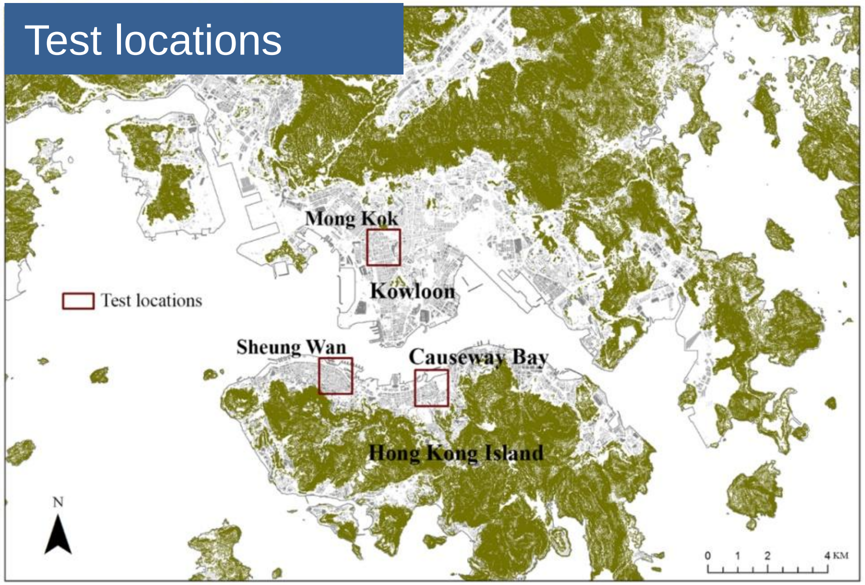
Point-specific Parameter:

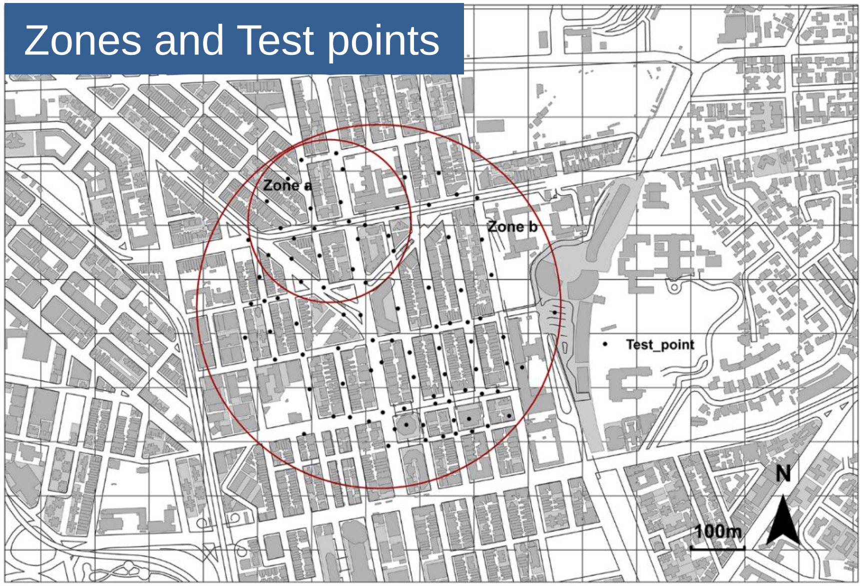
Effect of the neighbourhood on the wind speed at the particular point

$$\lambda_{f\_point} = \frac{\iint_D l^{c}_{x,y}(A_{\Delta z,x,y}/A_t)\,dxdy}{A_t},\quad D = \{x^2 + y^2 \le r^2\}$$

$$A_{\Delta z,x,y} = \sum_{1}^{i=16} A_{\Delta z,i}\,p_i\ ;\ l_{x,y} = \frac{r-L}{r}\ ;\ A_t = \pi \cdot r^2$$

A_t: site area
$A_{\Delta z,x,y}$: frontal area
r: scan radius
L: distance





VR: Ratio between wind speeds at the pedestrian level and 500 m above ground

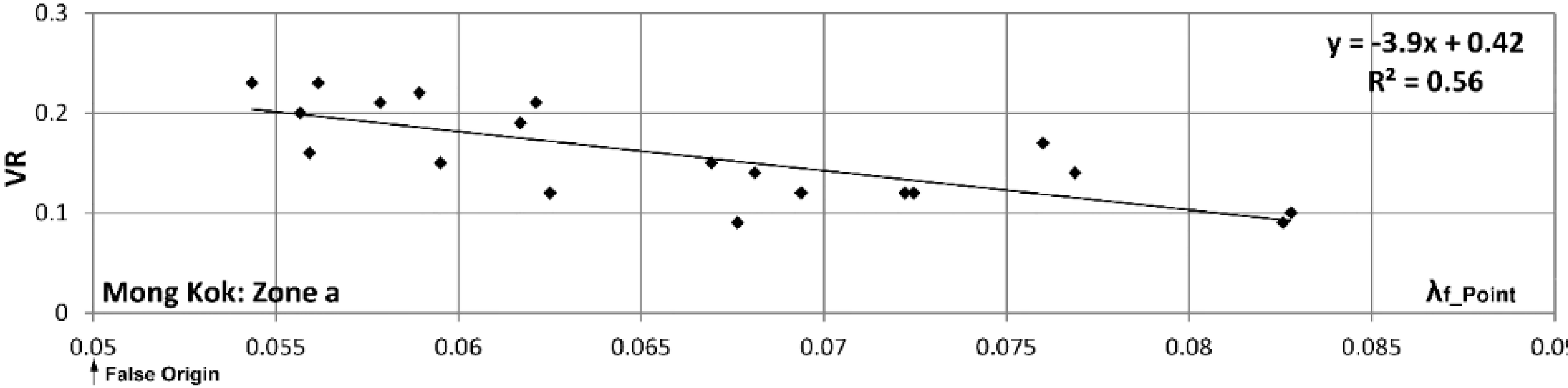
$$VR = \sum_{i=1}^{16} P_i \cdot VR_{500,i}$$

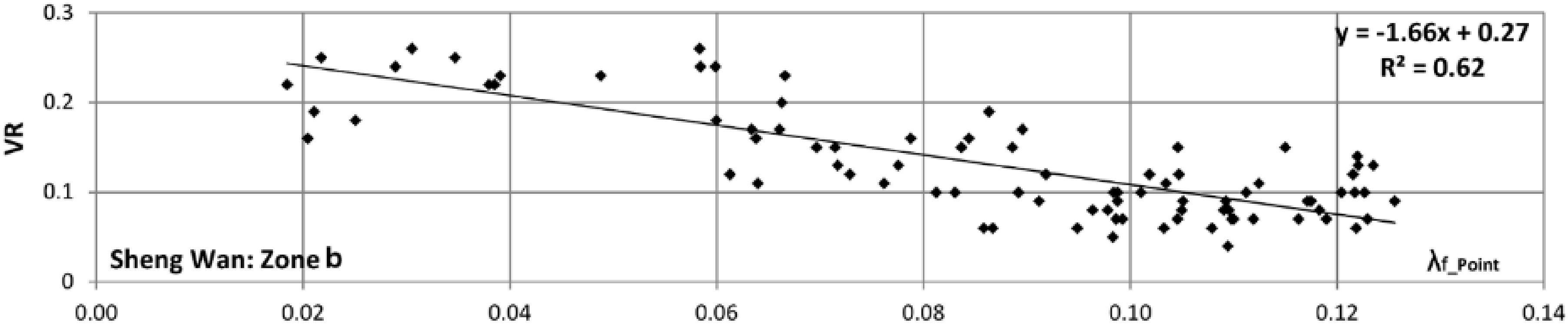
$\boldsymbol{VR_{500,i}}$: directional wind velocity ratio

$\boldsymbol{P_i}$: annual wind frequency in the i^th wind direction

MODEL TEST

Linear Regression





- The wind VR is negatively associated with the distance-weighted λ_{f_point}.
- The more and closer surrounding roughness elements to the particular point, the more air flow would be impeded, and the slower the pedestrian-level wind speed at the particular point.

MODEL TEST

Linear Regression

Districts	Zones	R^2 (exponent c=2.0)	SE of predicted VR	SE of predicted U_p (m/s)	Slope Coefficient	Intercept
Mong Kok (Regular street grid)	Zone a	0.56	0.03	0.20	-3.9	0.4
	Zone b	0.42	0.04	0.27	-3.8	0.4
Sheung Wan (Irregular street grid)	Zone a	0.49	0.05	0.33	-1.7	0.3
	Zone b	0.62	0.04	0.27	-1.7	0.3
Causeway Bay (Irregular street grid)	Zone a	0.49	0.03	0.20	-1.9	0.3
	Zone b	0.40	0.04	0.27	-1.6	0.3

Note: In the calculation of SE of predicted pedestrian level wind speed (U_p), the annually averaged wind speed at the reference height (500 m above the ground) at study areas is 6.67 m/s, which was obtained from wind tunnel experiment.

For districts with regular street grids (main streets perpendicular with each other)

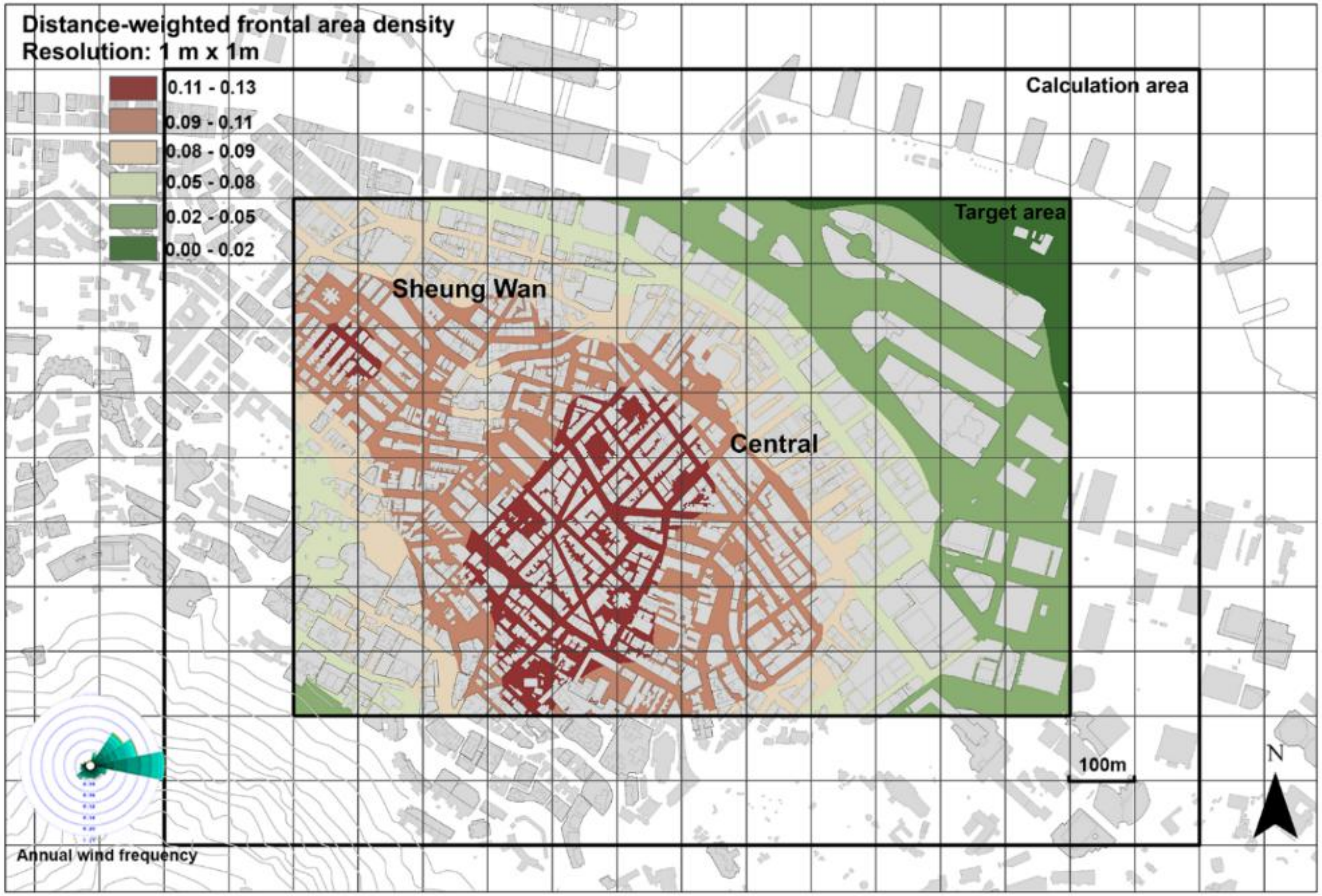
$$\mathrm{VR} = -3.9\lambda_{\mathrm{f\_point}} + 0.4$$

For districts with irregular street grids

$$\mathrm{VR} = -1.7\lambda_{\mathrm{f\_point}} + 0.3$$

MAPPING

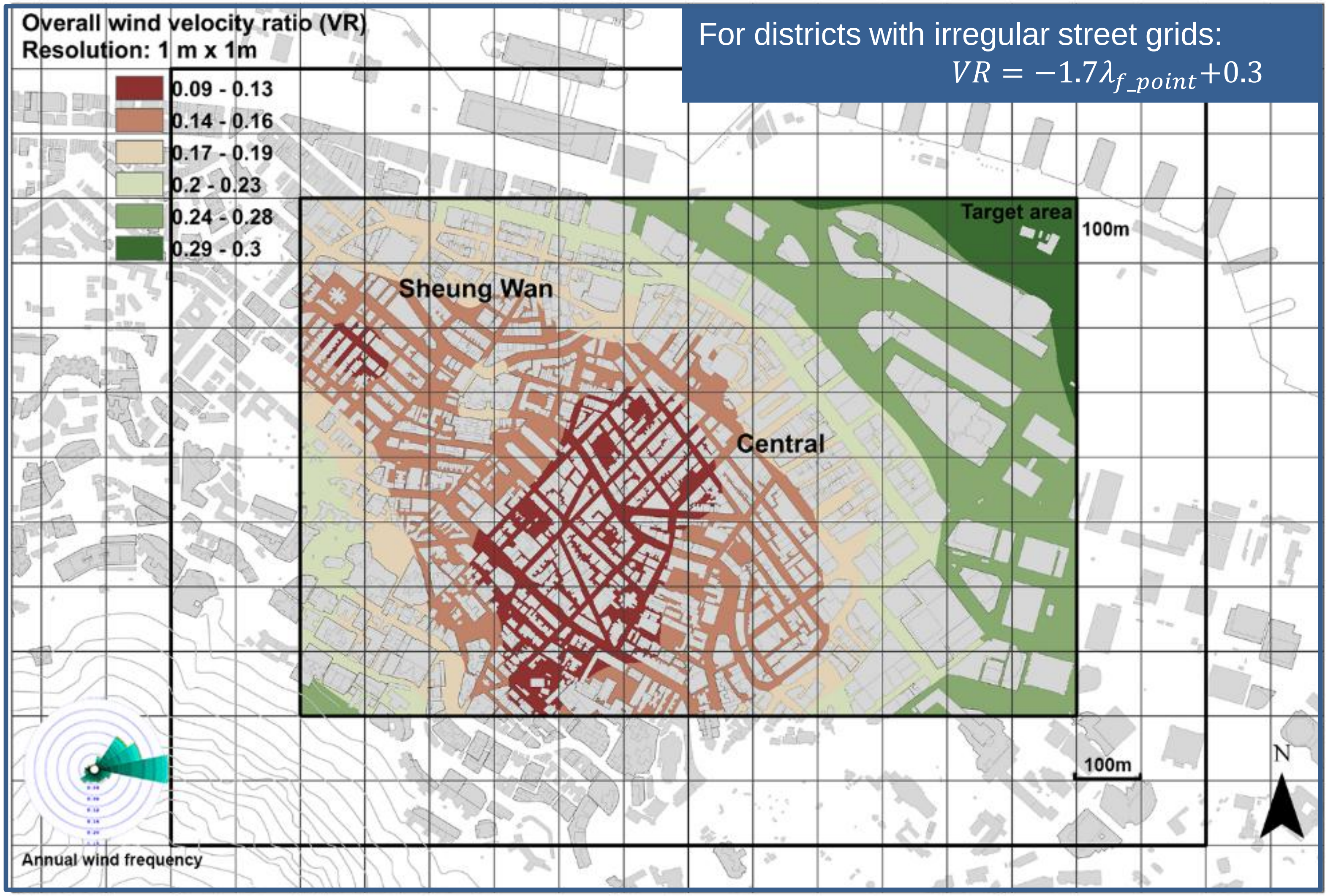
$\lambda_{f\text{-point}}$



Pixel by pixel (1 m × 1 m)
by a Visual Basic for Applications (VBA) script in the ArcGIS System

MAPPING

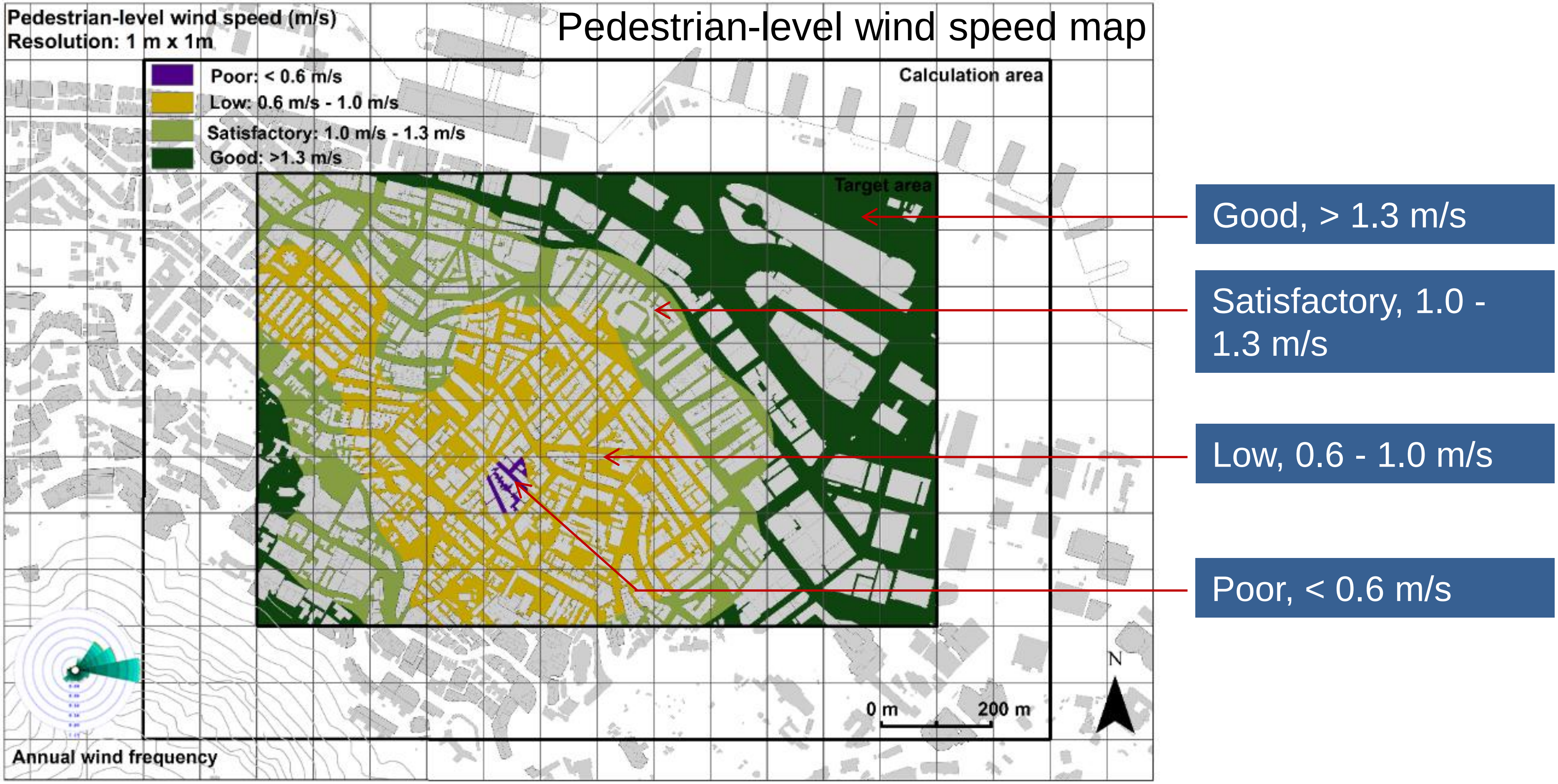
Overall Wind Velocity Ratio



For districts with irregular street grids:

$$VR = -1.7\lambda_{f\_point} + 0.3$$

Pedestrian-level wind speed

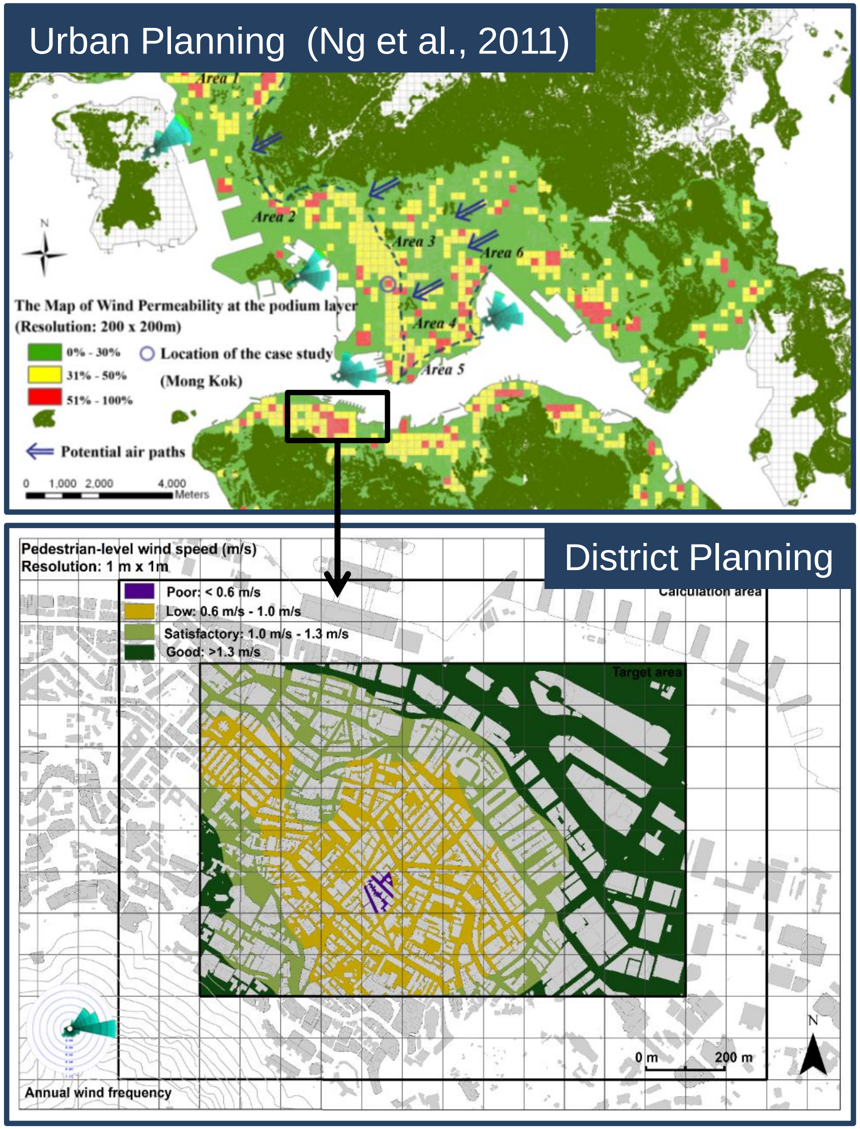


From the perspective of the outdoor thermal comfort:

- Class 1 (Poor, <0.6 m/s)
- Class 2 (Low, 0.6 m/s -1.0 m/s)
- Class 3 (Satisfactory, 1.0–1.3 m/s)
- Class 4 (Good, > 1.3 m/s)

IMPLEMENTATION

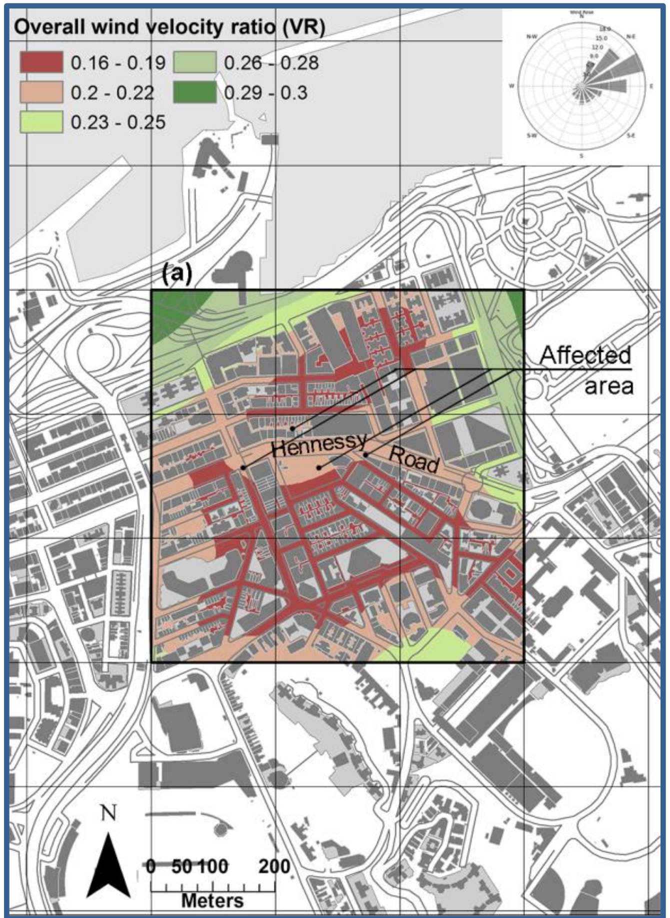
District Planning



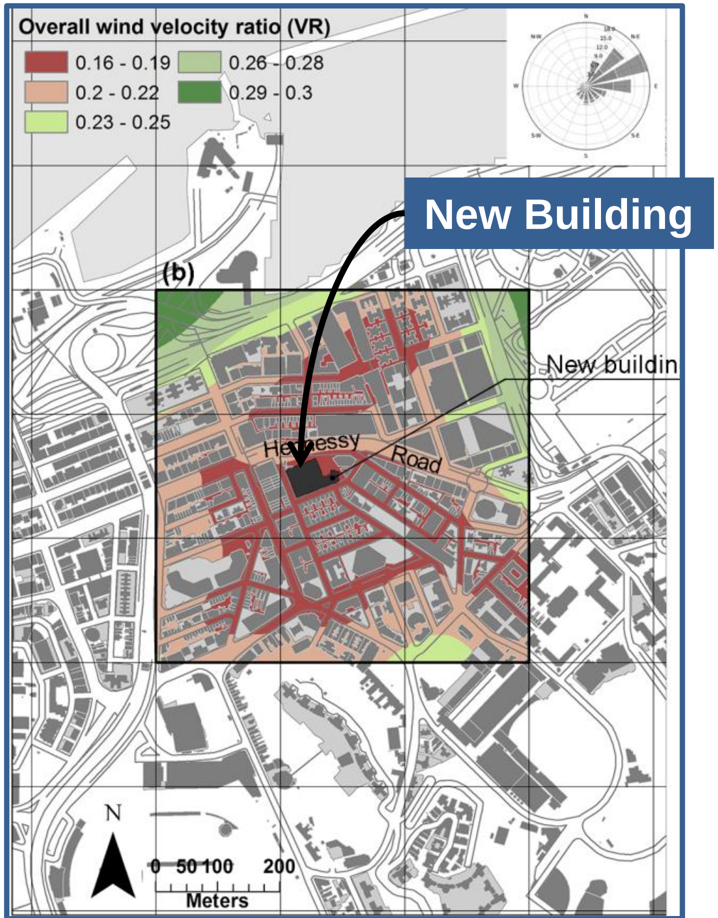
Planning Guidelines

- No new development project is allowed at the purple zone.
- New development projects should be strictly controlled at the yellow zone with the detailed study by CFD simulation or Wind tunnel experiments.
- No additional bus stops, terminus, heavy traffic roads, or other land use with pollutant sources at purple and yellow zones to avoid trapping the emitted air pollutant.

Evaluation of the effect of new buildings on the neighborhood wind environment



Original Scenario



Scenario with the new building

CONCLUSIONS

New modelling and mapping approach

To bridge the gap between the current modelling methods and requirements of practical planning and design.

A: Practical:

Geometry calculation
---based on approximation

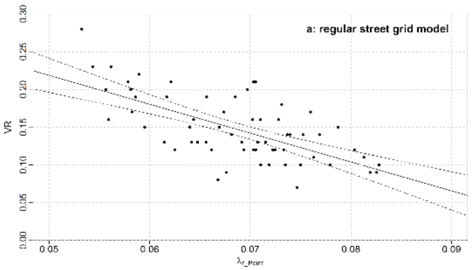
$$\lambda_{f\_point} = \frac{\iint_D l^{c}_{x,y}(A_{\Delta z,x,y}/A_t)\,dxdy}{A_t} \quad D = \{x^2 + y^2 \leq r^2\}$$

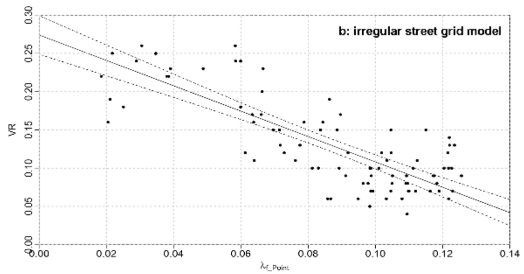
$$VR = -3.9\lambda_{f\_point} + 0.4 \quad \text{(regular street)}$$

$$VR = -1.7\lambda_{f\_point} + 0.3 \quad \text{(irregular street)}$$

B: Accurate:

Standard error is one order of magnitude smaller than the predicted values

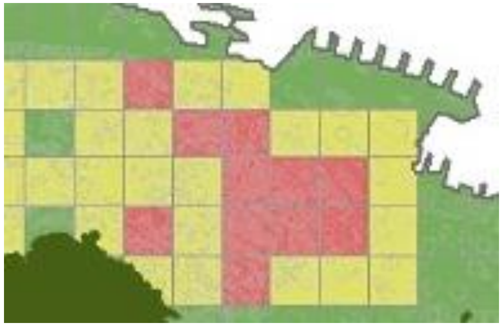


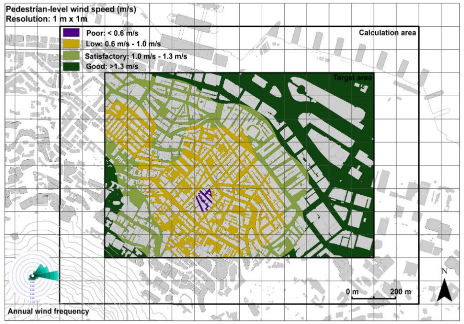


C: High resolution:

Spatially-averaged λ_f
(Ng, et, al., 2011)

Point-specific λ_f





Thank You！

yuanc@mit.edu

yuan_chao@sutd.edu.sg