# QGIS-Based Tools to Evaluate Air Flow Rate by Natural Ventilation in Buildings at Urban Scale

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#### Abstract

Urban-scale evaluations of aerodynamic and morphological parameters allow correction of the wind speed within the urban boundary layer, as the wind profile is strongly influenced by the presence of roughness elements. This can have important implications for defining urban strategies for the reduction of buildings' energy consumption and the improvement of air quality and liveability of outdoor spaces. Among the current models for assessing the air flow rate by natural ventilation in buildings at urban scale, this study aims to define a GIS-based methodology, using existing databases and an open source QGIS plug- in. From a digital surface elevation dataset, and considering prevalent wind directions, the displacement height (zd) was determined. The wind speed was corrected, applying the logarithmic or turbulent laws of wind profile, respectively, above and below zd. This method could determine the spatial distribution of wind speed, considering each building façade characteristics and its surroundings. Resulting wind pressure on windward and leeward façades drives the air flow rate inside the buildings. Further developments of this work will improve the air flow modelling in buildings with other tools for applications at urban scale.

# 1. Introduction

Understanding and modeling the urban local wind environment has been a focus of attention for many researchers, especially in high density urban areas. Here, the heterogeneity of urban morphology, due to the presence of different type of roughness elements, strongly influences local wind performance (Peng et al., 2019). Studying air flow properties has important implications for urban design in terms of energy consumption, outdoor thermal comfort, and air quality, and building energy performance for

space heating and cooling (Suszanowicz, 2018). Relations between urban morphology and wind flow can be assessed with different methods: i) field measurements, whose high time and cost limitations mean that they are not suitable for large scale studies; ii) wind tunnel experiments, which constitute the reference dataset, despite operating costs and application limits; iii), Computational Fluid Dynamic (CFD) numerical modellings with high computational requirements (Buccolieri & Hang, 2019); iv) parametric models, mainly based on wind tunnel test or CFD simulations, having a good cost-benefit ratio but limited application field; v) Geographical Information System (GIS) and remote sensing techniques that retrieve roughness parameters based on interactions with buildings' geometries at city-scale, especially at mesoscale (Wong et al., 2010). Into the last group fits the place-based methodology presented in this work: a flexible integration of physical laws of wind phenomena and local characteristics of the urban context, based on the open-source software QGIS and existing databases, already used by urban planners. The study is part of broader research that aims to implement an hourly GIS-based engineering model to assess the energy consumption for the space heating and cooling of residential buildings at urban and district scales (Mutani & Todeschi, 2020; Mutani et al., 2022). The implementation concerns the monthly and hourly detail definition of number of air change per hour (ach) that influences thermal loads by natural ventilation in the building's thermal energy balance, considering the air flow rate for infiltration caused by winddriven effects. The wind pressure generated on a building facade is evaluated as a function of the vertical and horizontal distribution of wind speed, starting from the characterization of roughness and built environment characteristics. After a brief description of natural wind profiles in urban areas, this work aims to present some QGIS tools currently available to assess the urban wind field and its relationship with roughness parameters, applying the methodology to a case study.

# 2. Physical Laws of Wind Profiles

The wind phenomenon is influenced by the surface roughness of the ground and other objects (i.e., buildings, vegetation) that create obstacles to the undisturbed flow. A wind profile is associated with different environmental contexts (i.e., urban, sub-urban, rural areas), describing mathematically the mean wind speed ( $U_z$ ) as a function of height (z) from the ground. Reference heights individuate boundary layers that limit air flow zones in which different physical laws can be applied.

# 2.1 Boundary Layers and Heights

In this work, reference was made to an older bibliography for defining wind phenomena, and to a more recent one for applying physical laws. Considering the horizontal scale of wind influence, three scale of interest exist (Oke, 2004): i) the *mesoscale*, where weather and climate are influenced by the whole city; ii) the *local scale*, where landscape features or topography are considered; iii) the *microscale*, where variations occur over very short distances, causing great airflow perturbations around roughness elements. Regarding the vertical scale of wind influence, relevant boundary layers and heights are defined:

- Atmospheric Boundary Layer (ABL)

In the ABL, or Planetary Boundary Layer, which extends up to 1-2 km (Z<sub>ABL</sub> in Fig.1), the undisturbed wind flow present in upper layers is progressively slowed down due to friction with the ground and roughness elements. In the case of smooth soils (i.e., rural areas) the wind speed reaches upper layers values more quickly than urban areas.

#### - Urban Boundary Layer (UBL)

The UBL identifies the part of the ABL influenced by the presence of a large city. It is divided into: Mixed Layer (ML), whose upper limits coincide with the height of UBL ( $Z_i$ , in Fig.1), and Surface Layer (SL) whose depth is about a tenth of UBL ( $Z_{i/10}$ , in Fig.1), and which, in turn, is divided into two.

- Internal Sub-Layer (ISL)

In the upper layer of SL, the flow is free of individual wakes associated with roughness elements, and wind can be assumed as a constant flux with a laminar, horizontally homogeneous flow (Re <2000). Here, the wind log law can be applied to determine average wind speed (U<sub>z</sub>).

- Roughness Sub-Layer (RSL)

This extends from ground level to the blending height  $Z_{RSL}$  (Fig. 1), where effects of individual roughness elements are visible. Airflow perturbation caused by individual surface and obstacles persists for a certain distance until it is mixed with the effect of turbulent eddies. Blending distance depends on the magnitude of the effect, the wind velocity, and the stability of the flux. Minimum  $Z_{RSL} = 2 \cdot Z_H$  is suggested by observations in dense urban settings (Oke, 2004); it can vary with density, staggering, and heights of objects.

Urban Canopy Layer (UCL)

This is equivalent to the mean height  $Z_H$  (Fig. 1) of the main roughness elements. To overcome the frictional effect of surface roughness elements, the wind flux loses its momentum: turbulent flows are generated near the surfaces (Re > 4000). Lower wind speed can occur, and turbulent models are required to calculate wind velocity inside urban canyons.

#### 2.2 Aerodynamic Roughness Parameters

At local and micro scale, in the air zone where the flow is free from roughness-element turbulent wakes, two aerodynamic parameters are used to describe the wind speed profile influenced by surface roughness elements (Fig. 1):

- Zero-plane displacement height (z<sub>d</sub>)

It is intended as a new "ground level" from which the wind profile originates, after the wind passes over high-density buildings (Lv et al., 2022), and it is used for setting a base for the application of the wind log law (Oke, 2004). According to (Abubaker et al., 2018), it is the depth of still air trapped among the roughness elements. - Roughness length (z<sub>0</sub>)

This is the height above Z<sub>d</sub> at which wind velocity becomes zero when the logarithmic wind profile is applied and represents the size of the eddies produced from wind moving over a rough surface (Abubaker et al., 2018). It depends on turbulence intensity and, therefore, on the surface drag.

In urban areas, three flow regimes were classified when aerodynamic parameters are morphometrically determined (Oke, 2004): i) *isolated flow*, where buildings are individual wake generators; ii) *wake interference flow*, where wakes reinforce each other as space between buildings is close; iii) *skimming flow*, where main flow skips over the top of the great density of buildings. The wake interference regime is the one in which the greatest roughness activity can be generated. The building density ( $\lambda_P$ ) is very important in cities, where the high variability of roughness height can cause complex surface morphology and turbulent wakes that are challenging to assess.



Fig. 1 – Boundary layers and their reference height (y axis) at mesoscale (in orange) and local scale (in purple)

#### 2.3 Wind Profiles Laws at District Scale

In this work, two methods were compared to determine the wind speed (U<sub>z</sub>), from measured U<sub>ref</sub> at reference height ( $z_{ref}$ ): the *Cp methodology* and *zd methodology*, whose procedures are schematized in Fig. 2. U<sub>ref</sub> need to be adjusted considering the wind incident angle (Eq. 1, in Fig. 2) and objects and terrain roughness of the context. For wind fluxes that occur above the displacement height *zd*, two wind profiles can be applied.

The power law wind profile is based on empirical assumption for mesoscale application for large heights (30 m < z < 300 m), but it is less accurate when close to the ground. It can be determined according to Eq. 2 (Fig. 2), where Vz is the wind speed at height z [m·s-1], Uref,corr is the adjusted reference wind speed [m·s-1] at height zref, ZUBL is the height of the UBL [m], and v the terrain roughness coefficient (wind speed profile exponent) [-]. The last two parameters refer to tabular data, determined through empirical assumptions from real measurements or wind tunnel tests. Several references exist in the literature, including the unified terrain roughness categories given by (Choi, 2009). Table 1 reports typical values for roughness parameters for the most used terrain categories.

Table 1 - Referenced roughness parameters for terrain typology

Terrain roughness type	ZUBL	υ [-]	Zo [m]	Zd [m]
Level surfaces, grass land	250	0.10	-	-
Flat open country	280	0.14	0.03	0.0
Rolling/level surfaces	300	0.22	0.1	0.0
Heterogeneous surface	330	0.28	-	-
Low density suburban areas	390	0.34	0.5	0.7·zh
Mid-high density urban areas	450	0.40	1.0	0.8·zh
Very high density city areas	510	0.45	> 2.0	0.8·zh

The logarithmic law wind profile allows an approximation of the wind profile at lower boundary condition ( $z \le 200$ m). Its lower limit of application at urban local scale is identified by z<sub>0</sub> and z<sub>d</sub>, according to the logarithmic function of Eq. 3 (Fig. 2), where  $U_z$  is the wind speed  $[m \cdot s^{-1}]$  at height z, U<sub>ref,corr</sub> is the corrected wind speed at height z<sub>ref</sub>, z<sub>d</sub> is the zero-plane displacement height [m], and z<sub>0</sub> is the roughness length [m]. At microscale, inside the urban canopy layer, where turbulent fluxes occur at a height z lower than displacement height z<sub>d</sub>, the log-law is not valid and turbulent models should be applied. The k-epsilon  $(k-\epsilon)$  model is the most common model in CFD analyses for simulating the mean flow characteristics for turbulent flow conditions. It belongs to the Reynolds-averaged Navier Stokes (RANS) models that represent an optimal compromise between accuracy and efficiency for microclimate studies in urban environments (Javanroodi et al., 2022).

# 2.4 Wind Flow at Building Local Scale

Natural ventilation in buildings is driven by pressure differences on building façades by two forces: the stack (or buoyancy) effect and the wind-driven effect. This work focuses on the latter, while in future works, buoyancy will be considered in a multi-zones airflow model to assess ventilation loads in buildings. Wind generates positive pressure and negative pressure on windward and leeward façades, respectively. The surface pressure (Ps, Pv) can be calculated according to Eq.4 or Eq.5 (Fig. 2), respectively, with Cp and zd methodology, where  $\rho$  is air density [kg·m<sup>-3</sup>], V<sub>z</sub> (power law) and  $U_z$  (log-law) are the adjusted wind speed [m·s<sup>-1</sup>] and C<sub>P</sub> is the pressure coefficient [-]. It is a nondimensional coefficient estimated according to i) real scale measurements, ii) wind tunnel tests, iii) CFD and iv) parametric models, among which there is Cpcalc+ software (Chiesa & Grosso, 2019), whose input data are listed in Table 2. Even if the power law application determines a vertical variation of wind velocity at the local urban scale, the C<sub>p</sub> allows the distribution of wind speed horizontally and vertically at the scale of interesting points on a building facade with respect to the windward and leeward façade dimensions; it also considers building geometry and orientation, urban density, and roughness characteristic of the surrounding environment. The algorithm used in Cpcalc+ is based on experimental wind tunnel tests results, considering different typical buildings and urban contexts (e.g., Fracastoro et al., 2001). Limitations of the software concern the scale of the application field (suitable at building scale, not at district-urban scale), and the application range of some parameters, especially the relative building height and the aspect ratios  $(0.5 \le FAR \le 4 \text{ and } 0.5 \le SAR \le 2).$ 

Table 2 – Input data required by *Cpcalc*+ software (https://iris.polito.it/handle/11583/2579969)

Climate data				
Wind speed	Wind direction			
Urban parameter				
Plan Area Density	Surroundings building height		Wind profile exponent	
Building Characteristic				
Frontal/Side Aspect Ratio (FAR/SAR)	Building dimension	Buildin azimutl	g Roof n slope	

# 2.5 Place-Based Tools and Plug-Ins for Wind Analysis at Urban Scale

In this paragraph, GIS-based tools and a plug-in to assess wind at urban scale are described.

SAGA GIS software presents some useful tools for wind correction at the mesoscale, to consider terrain influence on observed meteorological conditions. In the Climate and Weather section, the Wind Effect Correction tool allows the scaling factor of the wind effect in determining ABL conditions (e.g., precipitation, cloudiness) to be calibrated. In the Terrain analysis - Morphometry section, the Wind Effect tool classifies wind exposed and shades area through a dimensionless index, considering terrain elevation and specifying wind data; these tools were created for topo-climatic wind assessments. Existing methods to determine the aerodynamic parameters at urban scale can be grouped into three main classes: i) reference-based values from field observations, which provide a wide range of values whose application in complex and heterogenous urban areas has some limitations; ii) anemometric methods requiring experimental campaigns, applicable on a limited and non-replicable scale; iii) morphometric methods based on the relationships between aerodynamic parameters and roughness elements geometry, described through urban morphological parameters, already used both at mesoscale (Darmanto et al., 2017) and local scale (Badach et al., 2020). This work aims to present zd methodology (Fig. 2), determining  $z_d$  and  $z_0$  using the open-source QGIS plug-in Urban Multi-scale Environmental Predictor (UMEP), version 1.6.1 (Lindberg et al. 2016). Among the pre-processing tools, there are the Urban Morphology- Morphometric Calculator (Grid) and (Point), which only differ in the geometry of the calculation area. Both calculate five morphometric parameters (Table 3, Fig. 3) based on digital surface models (DSM) to calculate the two aerodynamic parameters according to six different methods (Table 4). The required input data are three separate raster files (geoTIFF) with the same pixel resolution: DSM, digital elevation model (DEM, only ground elevation), and roughness elements elevation, calculated with the QGIS Raster calculator tool, by subtracting the other two rasters (DSM-DEM).

	Cp method	z <sub>d</sub> method			
Software:	CpCalc+	QGIS UMEP plug-in			
Input data:	Wind speed (U <sub>ref</sub> ) from a re	ference height $(z_{ref})$ of the weather station			
Uref adjustment – wind incident angle (0)	Eq. 1) $U_{ref,corr} = 0$	$V_{rr} = U_{ref} \cdot \cos(\theta)$ $\left. \begin{array}{c} \theta \text{ wind incident angle normal to} \\ \theta \text{ the windward building facade} \end{array} \right.$			
	Power law wind profile	Log law wind profile Turbulent wind profile			
Uref adjustment – terrain and object roughness correction:	$ \begin{array}{l} \textbf{Eq. 2)} & V_Z = U_{ref,corr} \cdot (\frac{z_{UBLref}}{z_{ref}})^{v_{ref}} \cdot (\frac{z}{z_{UBL_z}})^{v_z} & \text{v} \\ \text{data} \\ \text{- Mesoscale} \end{array} \right  \text{- Tabular} \\ \begin{array}{l} \text{- Hence} \\ \text{- Mesoscale} \end{array} $	$ \begin{array}{ll} \textbf{Eq. 3)} \\ U_Z = & U_{ref.corr} \cdot \left[ \frac{\ln{(\frac{Z-Z_d}{Z_0})}}{\ln{(\frac{Z_{ref}-Z_d}{Z_0})}} \right] \text{Z}_d \right] \cdot \text{GIS plug-in} & \textit{Uz from correlations} \\ of CFD results \end{array} $			
	vertical distribution for each z <sub>n</sub>	vertical distribution for each z <sub>n</sub>			
		horizontal distribution for each grid cell			
Pressure coefficient (Cp) calculation:	vertical and horizontal distribution on building facades (from Cpcalc+)				
Surface pressure :	Eq. 4) $Ps [Pa] = \frac{1}{2} \cdot \rho \cdot V_z^2 \cdot Cp$	Eq. 5) $P_{\mathcal{V}}\left[Pa\right] = \frac{1}{2} \cdot \rho \cdot U_x^2$			
Limits of the methodology:	<ul> <li>Roughness correction at mesoscale (wide scale)</li> <li>Roughness correction from tabular data (wide range values)</li> <li>Application range of some parameters based on experimental tests (0,5 sFAR s4 and 0,5 sSAR s2, building height)</li> <li>Building scale application not suitable for district scale</li> </ul>	Results accuracy strongly affected by the radius of calculation area and size of grid cells (no unified standard for selecting area)     Horizontal distribution of wind speed variation only for heights greater than Zd (above canopy layer)			

Fig. 2 – Comparison between the Cp and  $z_d$  methodologies for the assessment of surface pressure generated by the wind flow



Fig. 3 – Plan area index  $(\lambda p)$  within its range (0-1) for a squared cell grid, considering building heights in a selected area

The main setting concerns the extension of the calculation area that will be considered to determine the morphological and aerodynamic parameters, indicating the radius length from the selected point or the centroid of each grid cell. There are no unified standards for the size of calculation area, though it greatly affects the accuracy of results (Lv et al., 2022). In addition, it is possible to specify the wind direction (in degrees, from north - clockwise). The five morphometric parameters calculated in UMEP correspond to some of the most frequently used urban parameters in the urban planning research field; Table 3 reports their definitions. The morphological and aerodynamic parameters can vary according to the analyzed wind direction, allowing more precise results of zd and zo, considering the variability of the roughness surfaces (Oke, 2004).

Table 3 – Urban parameters defined in QGIS-UMEP tool

Urban parameter	Unit	Formula
Plan Area Index	[-]	$\lambda_p = (\sum_{i=1}^n Api) / A_T$
Frontal Area Index	[-]	$\lambda_f = (\sum_{i=1}^n Afi) / A_T$
Mean Height	[m]	$z_H = \left(\sum_{i=1}^n Hi\right)/n$
Maximum Height	[m]	$Z_{Hmax} = Max (H_i)$
Height variability	[m]	$z_{Hstd} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (Hi - Z_H)^2}$

The UMEP tool calculates the aerodynamic roughness parameters ( $z_d$ ,  $z_0$ ) by applying six different morphometric methods (Kent et al., 2017). For each method, Table 4 reports urban parameters used in the calculation: plan area density ( $\lambda_p$ ), frontal area ratio( $\lambda_i$ ), average ( $z_H$ ) and maximum ( $z_{Hmax}$ ) buildings height and height variability ( $z_{Hstd}$ ). In this work, the Kanda method was used (Kanda et al., 2013), as it is more suitable in dense, city-center districts, due to the importance of considering roughness elements' height heterogeneity. The flow chart in Fig. 4 summarizes the  $z_d$  methodology used to determine the aerodynamic parameters and the proper wind profile with the QGIS UMEP plug-in.



Fig.4 – Flow chart of the  $z_d$  methodology based on QGIS-UMEP tools

Table 4 - Morphometric methods included in the UMEP plug-in

Method	Urban Parameter				
	$\lambda_P$	$\lambda_{\rm f}$	Ζн	ZHmax	ZHstd
Rule of thumb			х		
Raupach		Х	х		
Bottema	Х	Х	х		
Macdonald	х	Х	х		
Millward-Hopkins	Х	Х	х		х
Kanda	х	Х	Х	х	Х

# Application of the UMEP Tool at District Scale in Turin

The place-based methodology was applied to a central district in the city of Turin (Italy). For an indepth analysis of case study zone (200 m x 200 m) selection criteria and characteristics, refer to (Mutani et al., 2021). The local monthly prevalent wind is from North-NorthEast and West-SouthWest, with a mean velocity of 1.4 m/s. Table 5 shows main the urban parameters calculated in QGIS to describe the case study area.

Table 5 – Morphological and roughness characteristic of the area

Urban parameter	Unit	Study area
Built Coverage Ratio (BCR)	[-]	0.33
Plan Area Density (PAD)	[-]	1.66
Volume Area Ratio (VAR)	[-]	0.30
Surrounding buildings' height	[m]	19.5
Height of boundary layer (ZUBL)	[m]	450
Wind speed profile exponent ( $\nu$ )	[-]	0.4
Short urban canyon (L/H)	[m]	≤ 3
Long urban canyon (L/H)	[m]	> 5

For the UMEP tool application, a grid vector polygon was created, with a 5-m-squared grid, and results were assigned to grid cells and related buildings. Three raster files were created, starting from a 1-m resolution surface elevation dataset (DSM). From the centroid of each cell of the grid, a 300m radius study area was set, obtaining, for each cell, 12 different results of morphological and aerodynamic parameters, for 12 wind directions.

### 4. Results and Discussion

The UMEP tool results are the anisotropic and isotropic output: the first gives values for each wind direction, the second reports mean values of all wind directions. Fig. 5 shows the isotropic results of the displacement height zd for the case study zone. The anisotropic results of zd consider the two prevalent wind directions (N-NE, Fig.6a and W-SW, Fig.6b). Results were assessed at the building scale. According to building heights (z) and floor numbers, for each floor, the wind speed was adjusted applying the log law (if  $z > z_d$ ) or the turbulent motion equation (if  $z \leq z_d$ ). Buildings were classified into those with logarithmic and turbulent wind profile, or only turbulent profile (red and blue points, in Fig. 6a-b, respectively). Figs. 6a-6b show that the buildings for which the log law is valid are those located in urban canyons oriented parallel to the prevailing wind direction. In this work, the wind speed above zd was calculated applying the log law equation (Eq.3, in Fig.2), while below z<sub>d</sub>, it was calculated based on correlations

found from the CFD model results (Javanroodi et al., 2022). Reference was made to a case study with similar urban morphological characteristics (Table 5); linear and exponential correlations were determined for short and long canyons (Fig. 7).

A block of buildings (red rectangle, Fig. 6a) well exposed to the N-NE wind, was selected to assess the surface pressure generated by the wind on the windward façade of buildings, comparing results of the two different methodologies (Fig. 2). Wind speed was corrected applying the power law (*Cp method*) and log law ( $z_d$  *method*), at three representative heights for each building in the block (first floor- $z_1$ , average floor- $z_2$ , top floor- $z_3$ ) and 30 points on windward block façade (i.e., 1-30).



Fig. 5 – Isotropic result of the displacement height z<sub>d</sub> [m].





Fig. 6 a,b – Anisotropic result of displacement height  $z_{\rm d},$  for wind direction N-NE (a) and W-SW (b)



Fig. 7 – Correlations for long (blue) and short (orange) canyons

To horizontally distribute the wind speed along the windward façade,  $C_p$  was calculated with the *Cpcalc+;* in the *z<sub>d</sub> method,* a value of *z<sub>d</sub>* and *z<sub>0</sub>* was determined for each cell of the grid, obtaining a different wind velocity for each cell spatially distributed in front of the façades. Considering the three heights of building, Fig. 8 shows results of the surface pressure P<sub>s</sub> and P<sub>v</sub>, calculated with *Cp*-*method* and *z<sub>d</sub>-method*, respectively.



Fig. 8 – Surface pressure calculated with the cp method (Ps, dotted lines) and the zd method (Pv, continuous line)

It can be noticed that, for the height z3 (blue line), above  $z_d$ , results of  $z_d$ -method are more precise than the *cp*-method one when describing variations that occur on façades and that are mainly due to the wind wakes generated from surrounding buildings. The main limit of the *cp*-method concerns its range of application, since the analyzed block exceeds the aspect ratio range (FAR>4). For heights ( $z_1$ ,  $z_2$ ), below  $z_d$ , surface pressures are very low in both methods, due to the reduced wind speed inside the canyon (Fig. 8).

## 5. Conclusion and Further Development

This study aims to determine the variation in wind speed at local scale as a function of roughness elements and their effects on the urban context. The model's place-based approach, based on accessible databases and open-source software (QGIS), is applied at neighbourhood scale and it is adaptable to other contexts and urban scales. The methodology presented determines heights of boundary canopy layer  $(z_d, z_0)$  to apply the proper wind profile law, in relation to building heights. If compared to the Cp method, it can assess horizontal wind speed distribution along building façades, and to calculate surface pressure driving the air flow rate inside buildings. This aspect can be further investigated thanks to the flexibility of GIS place-based methodology. In fact, the novelty of this work lies in the possibility of adapting and integrating new or already existing software into QGIS, in the attempt to calculate the natural ventilation loads with a lumped model for all buildings at urban scale. A recent upgrade of the CpCalc+ algorithm in a Python script (Chiesa & Grosso, 2019), constitutes an interesting opportunity for methodology implementation. Therefore, different scenarios can be investigated, including exploiting the GIS tool to retrieve all input data at urban scale necessary for Cp calculations, or directly integrating the CpCalc+ algorithm into a dedicated QGIS plug-in. A simplified parametric model to evaluate wind flows around buildings at urban scale is essential for supporting urban planning in increasing buildings' energy performance and liveability of urban environments.

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