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Study on Urban Wind Patterns for Developments in Wuhan China

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Abstract. This paper reports a project with the purpose to develop design guidance on urban wind fields for the Chinese city. The project assesses “super-block” developments in Wuhan China at first, then redesigns a super-block using Transit-Oriented Development (TOD) guidelines and draws wind performance comparisons. The project addresses wind Patterns for three major criteria: pedestrian comfort, air quality, and building ventilation potential. Computational Fluid Dynamics (CFD) software was used to model velocity, PMV comfort, pressure and air age patterns for summer and winter conditions. Super-blocks with isolated towers have poor urban quality on many measures, while residents drive more and use much more energy than in traditional housing. TOD guidelines solve these problems but no discussion of urban wind patterns, air pollution, pedestrian comfort, or building ventilation which have been found important during the period of Corona Virus Disease 2019 (COVID-19) in Wuhan China. Our target was to generate TOD urban form that equaled or exceeded super-block wind performance. Results were inconclusive for pedestrian comfort and other indices and modeling are needed. Other parameters depend significantly on orientation and wind direction. Therefore, sometimes TOD was better than towers and sometimes not. The general method of the project is in six parts: 1) Assess five existing super-block designs for wind performance and characterize three performance metrics; 2) Draw conclusions about performance. Select one site for redesign; 3) Using TOD guidelines, design a new neighborhood at the same density on the selected site; 4) Evaluate wind performance of the new design; 5) Select wind design strategies to improve performance and redesign the TOD neighborhood; 6) Compare wind performance of TOD neighborhood and super-block. The study indicates the value of wind field analysis for improving urban designs for multi-building sites or for development rules. We were generally able to make performance improvements for development schemes, even during the special period.

1. Introduction

The purpose of this research is to develop design guidance on urban wind fields for a range of climates. We selected the rapidly growing Chinese city of Wuhan, where the typical new construction for



housing districts is “super-blocks,” with large tracts of 500-700m (1650–2300ft) across, few internal roads, low street connectivity, and tall buildings spaced widely apart to meet the Chinese sunlight and overshadowing requirements. This approach follows the 20th century Modernist tenets of “towers in a park” [1]. In contrast to previous Chinese urban patterns, the Super-block type shifts from mixed use to single use, from street-oriented and courtyard types to slabs with setbacks, from small interconnected blocks on narrow streets to hierarchical wide auto-dominated streets, from a dependence on walking, bicycles, and public transit to car-dominance and underground parking. Residents are more affluent, drive many more annual kilometers, and use much more energy than those in traditional neighborhoods [2].

In contrast, Calthorpe have proposed guidelines for “Transit-Oriented Development” (TOD) on small blocks as a model that supports mixed mode transportation, reduces energy use and personal expense for housing, cars and fuel, and improves the quality of life by making shopping, school and work more convenient to home. However, in reviewing the TOD small block guidelines we found no discussion of urban climate, wind patterns, air pollution, pedestrian comfort, or building ventilation which been found important during the period of Corona Virus Disease 2019 (COVID-19) in Wuhan China. Variations in the suggested building form for different climates seem absent, preferring a standard spacing angle, rather than solar access angle adjustments by latitude as found in Chinese codes.

2. Methods

Our hypothesis for the project is that the more compact and enclosed TOD development will perform rather poorly on wind criteria, as compared to super-blocks at equivalent density. The general method of the project is in six parts: 1) Assess five existing super-block designs for wind performance and characterize three performance metrics; 2) Draw conclusions about performance. Select one site for redesign; 3) Using TOD guidelines, design a new neighborhood at the same density on the selected site; 4) Evaluate wind performance of the new design; 5) Select wind design strategies to improve performance and redesign the TOD neighborhood; 6) Compare wind performance of TOD neighborhood and super-block.

2.1 Assessing existing sites

Lying in a sub-tropical monsoon climate, in IECC warm-humid zone 3B (similar to Memphis, Tennessee, USA), the four seasons in Wuhan are clearly marked. Winter in Wuhan is cool with significant wind-chill from river winds and high humidity. With its reputation as one of China's four summers "furnace cities," summer is hot and humid, continuing for about 130 days with mean high temperatures of 30–34°C (86–93°F) and summer design temperatures of 34–38°C (93–100°F).

We examine common contemporary development patterns in rapidly developing Wuhan City, five sites and their existing or proposed development patterns were evaluated for their wind field patterns and assessed for: 1) Pedestrian comfort (based on PMV); 2) Air quality (based on air age); 3) Cross-ventilation potential of buildings (based on pressure differences on facades). The five sites (Table 1-2, Figure 1) are Fudidonghu (Fudi), Quinshan, Ten Mile, Wuhan Business Center (WHBC), and Wu Tong Yuan (WTY).

Table 1. Site metrics of Wuhan super-block developments

	Fudi	Quishan	Ten Mile	WHBC	WTY
Floor Area Ratio	3.22	4.38	7.34	4.35	6.61
Open Space %	87%	86%	88%	86%	84%
Site Cover %	13%	17%	21%	21%	20%

3-D models were built in Ansys AirPak [3] with heights estimated by typical Chinese floor-to-floor dimensions of 3m (10ft). CFD analysis in AirPak was conducted for two wind directions: North-Northeast (NNE), which is the most common direction for 10 months, from August to May, and Southeast (SE), the most common direction in June and the required direction for summer analysis by government standard [4]. Initial airport wind speed used was 2.6 m/s (5.8 mph), a rate representative of afternoon winds, slightly higher than the daily average, but more likely to be coincident with high afternoon temperatures. For comparison, the same speed was used for both directions. This airport speed was reduced by AirPak to 1.3 m/s (2.9 mph), accounting for urban terrain. The same procedures were used to analyze the TOD proposals.

Table 2. Statistics for pedestrian comfort near the ground from two directions in five super-blocks, PMV score (NNE is winter, SE is summer condition)

Site	Mean		Median		Variance		Std Dev		1 st Quart		4 th Quart		IQR	
	NNE	SE	NNE	SE	NNE	SE	NNE	SE	NNE	SE	NNE	SE	NNE	SE
Fudi	-1.36	1.85	-1.36	1.89	0.06	0	0.24	0.05	-1.57	1.82	-1.18	1.95	0.39	0.13
Quishan	-1.27	1.87	-1.30	1.87	0.08	0	0.28	0.04	-1.50	1.81	-1.07	1.94	0.43	0.13
Ten Mile	-1.01	1.82	-0.98	1.84	0.14	0.01	0.37	0.11	-1.21	1.75	-0.76	1.92	0.45	0.16
WHBC	-1.33	1.82	-0.85	1.84	0.06	0.01	0.24	0.11	-1.54	1.75	-1.14	1.92	0.40	0.16
WTY	-1.39	1.84	-1.42	1.85	0.05	0.01	0.23	0.09	-1.59	1.78	-1.24	1.93	0.35	0.15

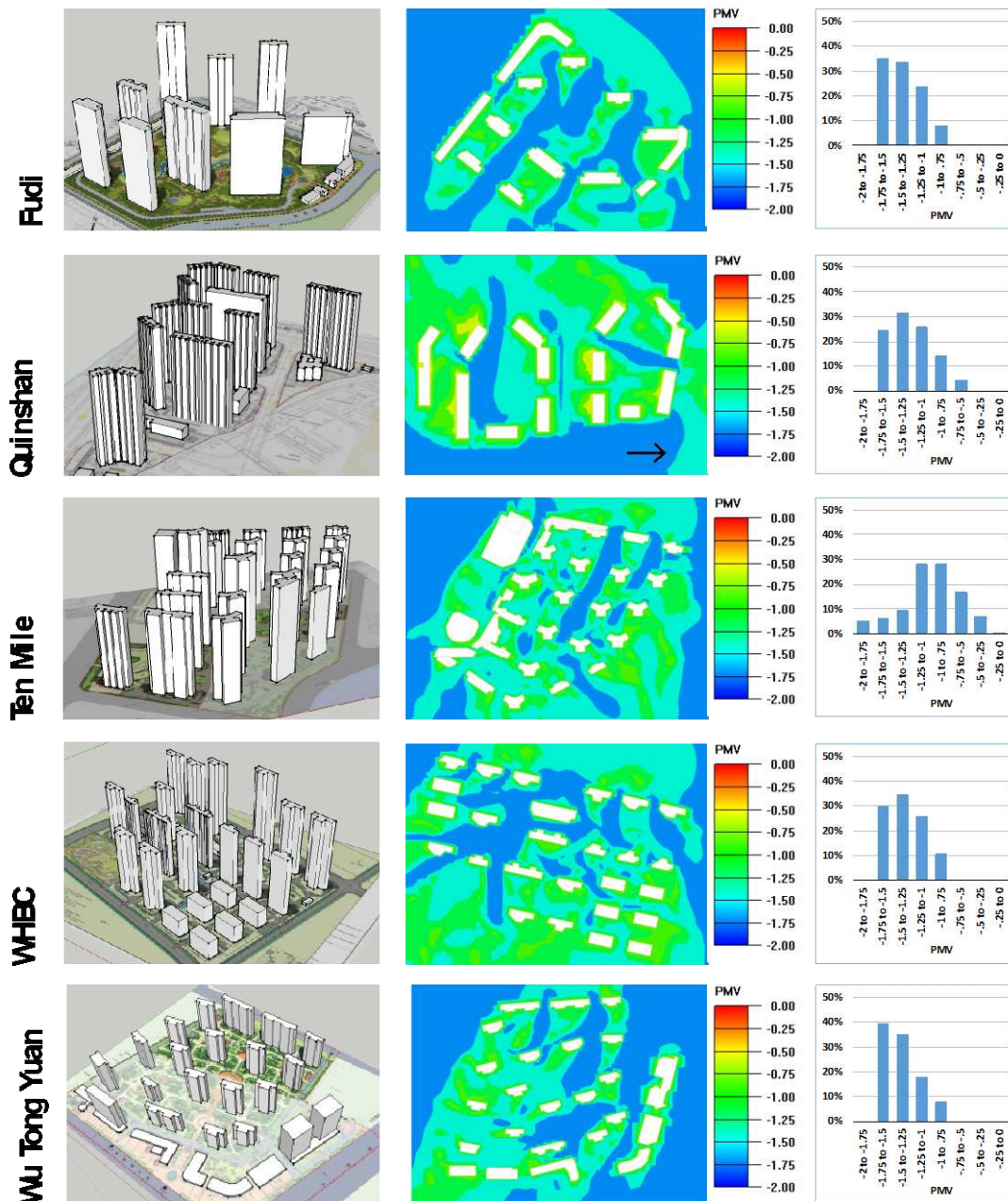


Figure 1. Predicted mean vote (PMV) in five super-blocks with NNE wind

Basic set-up parameters included modeling, of climate conditions for Wuhan (31 N, 114 E) on a typical summer (June 22) and winter (Jan 20) day, including solar loading for 12 noon, radiant effects between buildings, IAQ, and air flows for velocity and pressure. The turbulence flow regime used was the RNG k- ϵ turbulence model. The boundary layer thickness was set at 300 m (984 ft) at the meteorological station and 450 m (1476 ft) in Wuhan city with “urban” as the surrounding terrain type. The surrounding flow field context in AirPak, called the “room,” was defined at 300 m (984 ft), 3 times the tallest building height, with upwind dimensions at least two times the height and

downwind, at least six times. For visual analysis, CFD contour plots were printed at the same scale with the same intervals for all sites for visual comparison of the air age, air speed, velocity vectors.

2.2 Site redesign

The project objective is to determine whether or not TOD could meet the wind-related performance of the super-block schemes. The TOD “High-rise Residential” zone has a maximum FAR = 3.5 and 20 stories, while the “Tower Residential” zone allows up to FAR = 4.0 and 33 stories. All of the super-blocks except Fudi have net FARs over 3.5 and towers of 33 or more stories. For this reason, we chose the Fudi site for redesign to TOD standards. (Table 3, Figure 2-4)

Table 3. Site metrics of Wuhan super-block (Fudi) and TOD developments

	Fudi	TOD1,High Rise	TOD2,Towers
Floor Area Ratio	3.22	3.5	4.0
Open Space %	87%	64%	76%
Site Cover %	13%	36%	24%
Floor Area ,m²	200,000	180,000	200,000

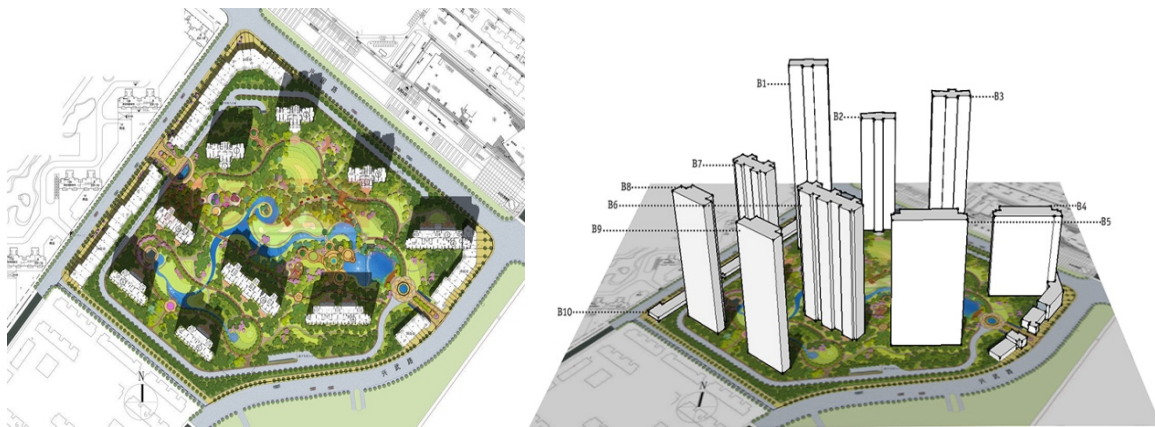


Figure 2. Plan of original Fudi super-block



Figure 3. Fudi site redesign version 1

using TOD guidelines for “High Rise Residential Zone”

Floor area = 180,000 m², FAR = 3.5

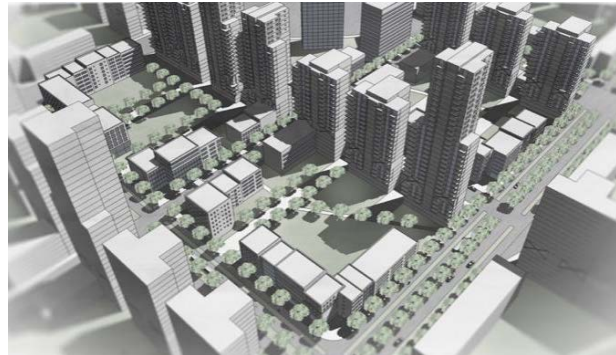


Figure 4. Fudi site redesign, version 2

using TOD guidelines for “Tower Residential Zone”

Floor area = 200,000 m², FAR = 4.0 max

TOD concepts ask designers to create small blocks of 100–200m per side, with 200–700 dwellings, interconnected by a grid of streets. By fostering, a more inter-connected, better-distributed road network, traffic and pollution are reduced significantly, and greater pedestrian walk ability and street frontage is achieved within the newly created blocks. Our first step was to sub-divide the Fudi super-block of 6000 square meters, having a perimeter of nearly 1000 meters, was subdivided following TOD suggestions into four separate, smaller blocks, using a street profile of 20 meters defined in TOD guidelines as a “local street,” made up of two lanes of traffic, a lane for street parking, bike lanes and pedestrian sidewalks. The original, base development had a total occupied floor area of 200,000 square meters (2.51 million ft²). The project was first designed to TOD’s “Mid-Rise Residential” category (FAR 3.5 max.) and later, expanded to study the “High-Rise residential” guidelines (FAR 4.0 max.). Building heights and placement were determined according to three major factors: solar access, street frontage, and site coverage requirements.

The first factor was solar access using rules already in place in the Chinese building code. Solar access codes require all apartments to receive a minimum of 2 hours of direct sunlight every day. This rule did not leave many options for tall building placement, essentially the only viable configuration meant placing tall buildings on the south side of city blocks so that the shadows cast fell mostly on open land in the middle of the block and not on the façade of neighboring buildings in the block. Buildings placed on the North sides of city blocks were limited in height by the width of the road they fronted, meaning that the width of the road set the height of the building. The “local street” type chosen limits buildings placed on the North side of the block to about 20-25m, since their shadows would fall just before the façade of the building across the street. Solar access played a major role in the external shape of the scheme and was probably the hardest requirement to meet. The second major factor was the street frontage. TOD requires all East-West Streets to be 70% minimum fronted by buildings, and streets running North-South Require 60% minimum street frontage. This limited building placement and how high buildings would rise given the allotted FAR. The final factor was a

site coverage limit of 40%, meaning we could utilize up to 40% of the site as building footprint, the other 60% remaining open space, of which 30% minimum green space is required with a maximum of 10% surface parking. In sum, FAR limited built area, while street frontage, solar access and site coverage requirements largely dictated the shape and organization that the development took.

To easily compare the TOD scheme to the original Fudi super-block design, we matched the original site's built floor area of 200,000 m². The initial model had an FAR of 3.5, the maximum FAR for TOD "Mid-rise Residential," which generated about 180,000 m² (1.94 million ft²). This required redesign to the next level of density, "High-rise Residential," which allows 200,000 m² with a max FAR of 4.0. Once the proposal matched the density of the original site, we began applying several climatic design strategies to the updated TOD model, this time infusing design strategies for air quality, air permeability and air circulation at the urban scale.

3. Urban Wind Design Strategies

Intersection Plazas. Research shows that opening up intersections increases the movement of air and replenishment of old air with new. We applied this to the model by essentially creating a more open public square by setting buildings back at intersections.

Building Podium Gaps. Tall buildings act as tremendous barriers to air movement. By adding a two-story separation between the towers and their 6-story base, wind movement through blocks increases significantly.

Improved Building Passages. We separated continuous buildings into smaller, isolated structures and perforated the long facades with two-story pass-throughs between the streets and the block courts. This increases overall block porosity, something the initial TOD model was lacking.

Networked Green space. The initial TOD model did not try to efficiently link green space and our CFD models reflected this. By aligning mid-block building gaps, more direct links between green spaces were created. These gaps are expected to foster greater ease of air movement between blocks.

Figure 3, 4 shows our site design following TOD rules with the same floor space as Fudi. The super-block is subdivided into four blocks with street-facing buildings and internal courts. Each housing unit is provided with sun and through-ventilation.

4. Results

4.1 Pedestrian Comfort

PMV (predicted mean vote) was calculated in AirPak for pedestrians, assuming moderate walking (MET = 2.4) and summer conditions of 30°C (86 °F) with CLO = 0.57, and winter conditions of 5°C (41 °F) with CLO = 1.12. We generated contour maps from the CFD software at intervals on the PMV scale. Output was an indexed eight-color raster format, which isolated contour zones to specific single-color bands. The specific site areas within bounding streets were excerpted graphically and analyzed by the color range in Photoshop® using the histogram function to count pixels and determine the

percentage of site area outdoors within each PMV band. The distribution percentages were graphed. A comparative PMV statistical analysis is shown in Table 4. Graphics are omitted due to space limits.

Table 4. Statistics for Pedestrian Comfort near the ground from two directions in Fudi super-block development and TOD redesigns, PMV score, (NNE is winter, SE is summer condition)

	Mean		Median		Variance		Std Dev		1 st Quart		4 th Quart		IQR	
	NNE	SE	NNE	SE	NNE	SE	NNE	SE	NNE	SE	NNE	SE	NNE	SE
Fudi	-1.36	1.85	-1.36	1.89	0.06	0	0.24	0.05	-1.57	1.82	-1.18	1.95	0.39	0.13
TOD 1,High-Rise	-1.31	1.87	-1.33	1.87	0.06	0	0.25	0.04	-1.51	1.81	-1.11	1.94	0.40	0.13
TOD 2,Towers	-1.28	1.89	-1.31	1.88	0.06	0	0.24	0.05	-1.46	1.82	-1.09	1.95	0.37	0.13

4.2 Air Quality

Contour plots for air age were output in post-processing with contour bands set for a range of time in seconds. The same analysis method described above for PMV was used to determine the percentage distribution on the site in each time band. The results are shown graphically in Figure 5. The results of comparative statistical analysis are shown in Table 5. A common standard for indoor air age as an indicator of air quality is a maximum of 300 seconds (5 minutes). For outdoor air, there is no similar standard, but healthy air can likely be present at longer ages than indoors, assuming the city is being supplied with fresh air, as the ratio of air volume per person is much greater outdoors. In general, air age can be used as a relative indicator for outdoor air quality [5]. The results do not represent the aging air at a particular point, that is, how long that local volume of air has been in one place. Rather, it measures “the average lifetime of air at a particular location in the [site] relative to the time when it first entered the [analysis boundary]. It gives an indication of the air freshness.” [3]. Because the distances are greater than for an indoor room, mean air age values are longer than for indoors. Air age is therefore an imperfect freshness indicator.

Table 5. Statistics for air age near the ground from two wind directions in Fudi super-block development and TOD redesigns, seconds, (NNE is winter, SE is summer condition)

Site	Mean		Median		Variance		Std Dev		1 st Quart		4 th Quart		IQR	
	NNE	SE	NNE	SE	NNE	SE	NNE	SE	NNE	SE	NNE	SE	NNE	SE
Fudi	455	363	431	356	13183	5107	115	71	361	317	526	394	166	77
TOD 1,High-Rise	446	449	435	445	9759	7576	99	88	373	380	488	506	114	126
TOD 2,Towers	453	488	446	461	7472	11301	86	106	399	401	492	563	92	161

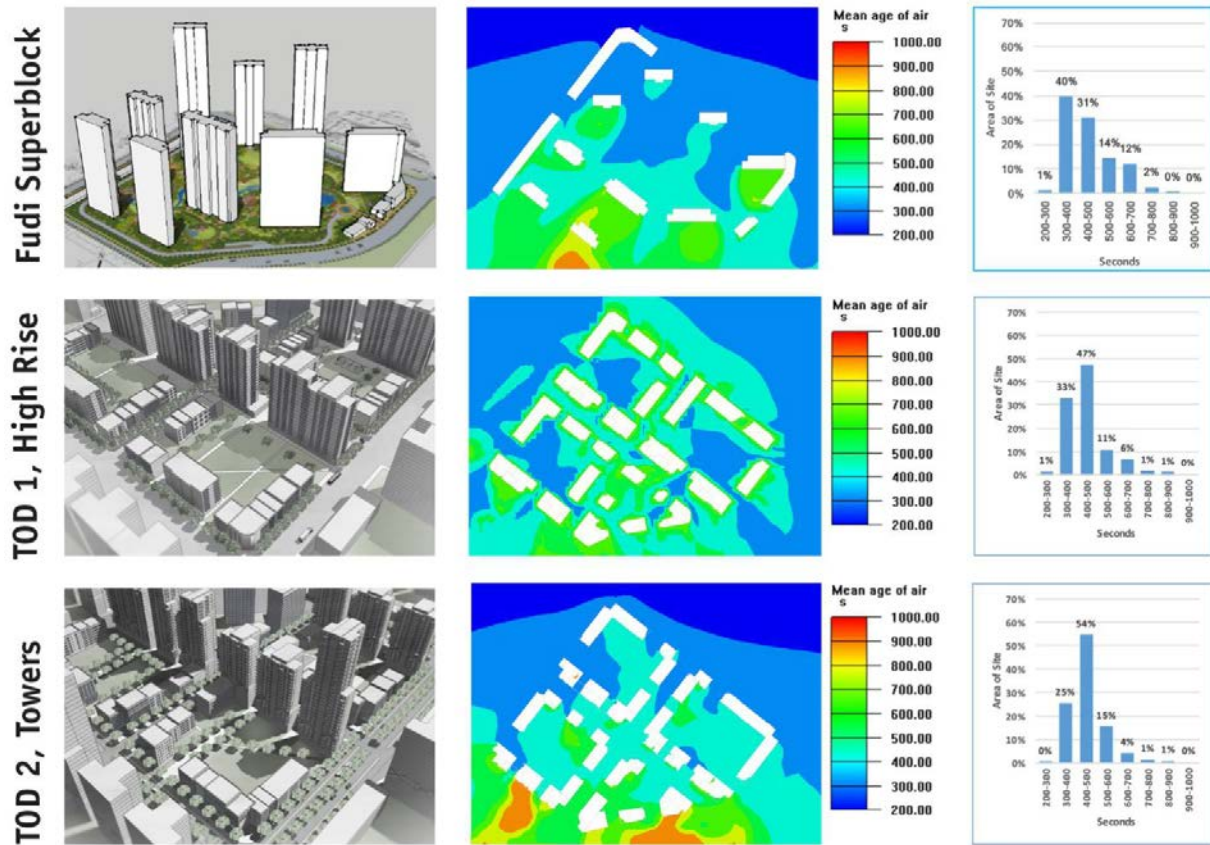


Figure 5. Predicted mean air age in five super-block neighborhoods for NNE wind direction

4.3 Ventilation Potential

Most Chinese residential buildings are one unit thick to promote cross-ventilation through the home. To assess cross-ventilation potential for buildings, we examined wind pressures at points on opposite building faces and calculated pressure differences between point pairs. The CFD software allows for the export of a grid of data points for each building face. The vertical grid was in 2m (6.6ft) increments and the horizontal grid, at least ten points per face, as required under Chinese standards for ventilation potential assessment. After the pressure differences were calculated, data were grouped and analyzed within vertical facade zones of 33m height (108ft). For example, a 100m (328ft) tower has Low (L), Middle (M) and High (H) zones. Shorter buildings have one or two zones and very tall towers have an additional Tower (T) zone (Figure 6-7).

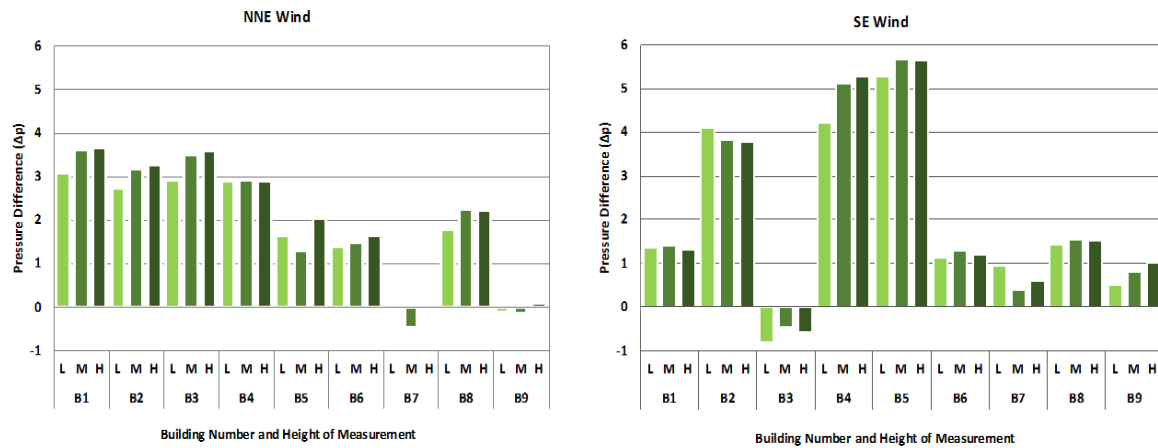


Figure 6. Wind-driven pressure differences between facades in Fudi super-block buildings

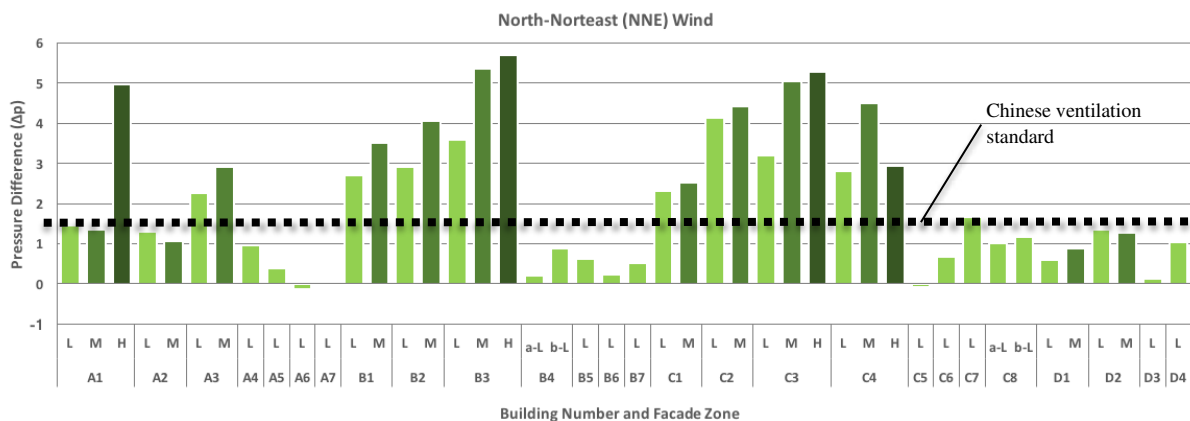


Figure 7. Wind-driven pressure differences between facades in TOD2-Towers buildings

5. Results and discussions

5.1 Pedestrian Comfort PMV

Winter conditions used in this analysis were 5°C (41°F), 70% RH, 300 W/m² global horizontal radiation in January. With a 1.3 m/s wind, a baseline PMV in an open field can be expected as −1.4 (slightly cool) or −0.6 (slightly cool) with no wind. Being in the direct sun without wind moves the PMV to neutral. Winter median PMVs (the NNE direction in Table 4) range from −1.31 in TOD2 to −1.36 (both slightly cool) in Fudi. Median comfort conditions are better than the baseline PMV, as expected in a more sheltered environment.

Summer conditions used were 30°C (86°F) for June, 70% RH, and 540 W/m² radiation. Under these conditions, baseline PMV in an open field can be expected to be about +2.5 (hot) in June with 1.3 m/s wind and +2.6 (hot) without wind, according to the PMV formula. The authors note that this very slight improvement with a breeze does not align with our lived experience under such warm-humid conditions. Being in the sun raises the PMV to 3.0 (very hot). Summer median PMV (the SE direction in Table 4) shows a tight range from +1.87 (warm) to +1.89 (warm) between the schemes.

Median comfort conditions are generally better than the baseline PMV, due to shading and radiant effects from buildings, one presumes, as increased wind speed makes little difference in the PMV improvement. For example, doubling the wind speed from 1.3 to 2.6 m/s (2.9 to 5.8 mph) surprisingly improves PMV by only 0.1, suggesting a somewhat limited utility of PMV for outdoor hot climates.

5.2 Air Quality

Median site air ages with NNE wind show a relatively small range among the three schemes from 431 to 446 seconds (s), with the original Fudi superblocks having a slight 3% advantage (Table 3). From the SE, median air ages range from 356 to 461 s, with Fudi again having the lowest air age, this time by a more significant 23%. This can be understood as due to the geometric difference between Fudi's parallel slabs that show blockage in the NNE direction and relative openness in the SE direction, as compared to the TOD schemes that arrange buildings around courts with perimeter buildings fronting all streets. The SE graphics are omitted due to space limits. Given the dominance of the NNE prevailing direction in Wuhan, the TOD schemes fair surprisingly well in comparison, with only a 3% difference in air age between directions.

5.3 Building Ventilation

The study examines ventilation potential from two wind directions in the low-velocity context of Wuhan. Results from Table 6 show that for these directions, the median façade zone of the TOD schemes as designed does not equal the original Fudi super-blocks by this metric. The TOD schemes are dominated by lower façade zones and the median zone is a lower zone. In the super-blocks, the median zone is a middle zone.

Looking more closely, low level facade zones (L) are twice as likely to fail the Chinese 1.5 Pa pressure difference criteria in the TOD schemes than in the super-block scheme. This was expected, as the TOD designs have much more floor area concentrated in shorter block perimeter buildings with multiple orientations. However, middle (M) and high (H) façade zones show TOD more comparable or even exceeding the super-block facades. In Table 6, lower percentages (of failure) are better. The modeling indicates the TOD2 scheme performs significantly better in mid and high zones. Between TOD1 and TOD2, 20,000 m² was added, along with several additional design moves intended to improve ventilation. Indeed, in almost all the conditions shown, the TOD2 scheme with greater FAR also showed improved ventilation potential.

Table 6. Percentage of buildings not meeting Chinese natural ventilation standard of $\Delta p > 1.5$ Pa

<u>Site</u>	Height	NNE	SE
Fudi	L	33	67
	M	44	56
	H	22	56
	Med Δp	2.21	1.36
TOD1,High Rise	L	64	86
	M	36	73
	H	/	/

TOD2,Towers	Med Δp	1.37	0.88
	L	68	75
	M	33	50
	H	0	25
	Med Δp	1.41	1.15

L=Low facade zone (0-33m); M=Medium(33-67m); H=High(67-100m); T=Tall(100-140m)

6. Conclusions

During the period of Corona Virus Disease 2019 (COVID-19) in Wuhan, we found it is very important that air flow patterns make better surround buildings. The study indicates the value of wind field analysis for improving urban designs for multi-building sites or for development rules. We were generally able to make performance improvements between TOD1 and TOD2 schemes, even with the addition of significant volume. The hypothesis that the TOD designs could meet or exceed the wind performance of the original super-block design was not conclusively confirmed nor disproved.

1. For the pedestrian comfort, the study is inconclusive on the hypothesis. The PMV index used in AirPak is clearly not really sufficient for a study of outdoor comfort. A metric such as the Universal Thermal Climate Index (UTCI) is more sensitive to outdoor variables, especially wind speed and radiation in a hot condition.
2. For air quality as suggested by the air age metric, under the conditions tested, the hypothesis is False for the SE wind direction and True for the NNE direction, as we consider a 3% difference insignificant and likely within the accuracy of the simulation.
3. For ventilation potential, the hypothesis is False for lower facade zones; True for middle and high zones.

The technique of calculating pressure difference across façade points or zones as an indicator of ventilation potential seems to have significant design feedback potential in three ways:

1. To identify zones where pressure difference needs improvement by design changes.
2. To identify zones or buildings where alternates to cross-ventilation, such as stack-ventilation or fan-forced ventilation constitute better strategies.
3. To help design ventilation apertures in the later stages of the design process. One possibility is larger windows or larger operable areas in zones with lower pressure difference and smaller openings in areas of high pressure difference.

Given the rather cumbersome and computationally intensive nature of the CFD tool used on desktop computers, we will seek alternate tools and methods that allow quicker feedback to the design process, in addition to the better metrics, such as UTCI and the ability to analyze for multiple wind directions, ideally with the help of cloud-based computation.

Acknowledgment

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