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Design to Thrive



Urban Wind Patterns in High-Rise Residential Super-Blocks: assessing pedestrian comfort, air quality and building ventilation potential

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Abstract: This paper reports phase 1 results from a project to develop design guidance for urban wind fields. Phase one assesses “super-block” developments; Phase 2 redesigns neighborhoods using Transit-Oriented Design (TOD) guidelines for China and draws comparisons. The project addresses urban form for three major criteria: pedestrian comfort, air quality, and building ventilation potential. Five super-block developments in Wuhan, China, were studied, each with 500-700 m (1650–2300 ft) blocks and 100-140 m (330–460 ft) “towers-in-a-park.” Computational Fluid Dynamics (CFD) software was used to model velocity, PMV comfort, pressure and air age patterns for summer and winter conditions. Air quality is approximated by air age distribution. Building ventilation potential is assessed by pressure differentials at multiple points across building sections. 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. We hypothesized that the super-block tower pattern would perform well on all three criteria. Results show differently: 1) Building ventilation potential is below Chinese standard for a high fraction of building facade areas, 2) Air age, poorer than expected, and 3) Pedestrian comfort, highly varied.

Keywords: Pedestrian comfort, air quality, natural ventilation potential, urban form, China

Introduction

The purpose of this research is to develop design guidance on urban wind fields for a range of climates. Existing wind field research typically, though not always, focuses on one or two variables or strategies in abstract and idealized environments, characterized by repetitive and simplified urban forms, free of culture, using science-based methods to produce portable knowledge that informs the “building blocks” of urban form (Grimmond & Oke, 1999; Zhang, et al, 2005; etc.). This works well to isolate performance variables. Often studies are interested in pedestrian comfort, pollution or building ventilation, but not all three. In real urban design situations, sites are unique and building form, less repetitive. Real cities are composed of complex and differentiated forms set in local cultures with local development regulation and economics. Therefore, the project takes real sites as its subject and examines three criteria.

We selected a rapidly growing Chinese context in Wuhan where the typical new construction for housing districts is “super-blocks,” with large tracts of 500-700 m (1650–2300 ft) 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” (Le Corbusier, 1933). 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 of are more affluent, drive many more annual kilometers, and use much more energy than those in traditional neighborhoods (Calthorpe, et al, 2012).

In contrast, Peter Calthorpe, et al, (2012) 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 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. 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.

Methods

Our hypothesis for the larger project, to be fully evaluated in Phase 2, 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 larger project is in six parts; the first two are covered herein: 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.

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 three summer "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, Hubei Province, China. 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 (see Fig. 2) are Fudidonghu (Fudi), Quingshan, Ten Mile, Wuhan Business Center (WHBC), and Wu Tong Yuan (WTY).

These were assessed for the following site characteristics, with results shown in Table 1: 1) *Gross Floor Area Ratio* (FAR), also called “Plot Ratio”, as total built floor area of all floors divided by site area; 2) *Net Floor Area Ratio*, as total built floor area of all floors divided by site area, with areas of internal roads subtracted; 3) *Gross Open Space %*, as area unbuilt, including internal roads, divided by site area; 4) *Gross Site Cover %*, as building footprint area divided by site area, including internal roads; 5) *Net Site Cover %*, as building footprint area divided by site area, where internal roads are subtracted. Buildings were traced in CAD from site plans. 3-D models were built in Ansys AirPak (Fluent, 2007) with heights estimated by

typical Chinese floor-to-floor dimensions of 3 m (10 ft). 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 (MOHURD, 2013). 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.

TABLE 1 Site metrics of Wuhan superblock developments

	Fudi	Quishan	Ten Mile	WHBC	WTY
Gross FAR	3.03	3.64	4.10	2.94	5.43
Net FAR	3.22	4.38	7.34	4.35	6.61
Gross Open Space %	88%	86%	88%	86%	84%
Gross Site Cover %	12%	14%	12%	14%	16%
Net Site Cover %	13%	17%	21%	21%	20%

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. Turbulence flow regime used was RNG *k-e* turbulence model. Boundary layer thickness was set at 300 m (984 ft) at 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 air age, air speed, velocity vectors.

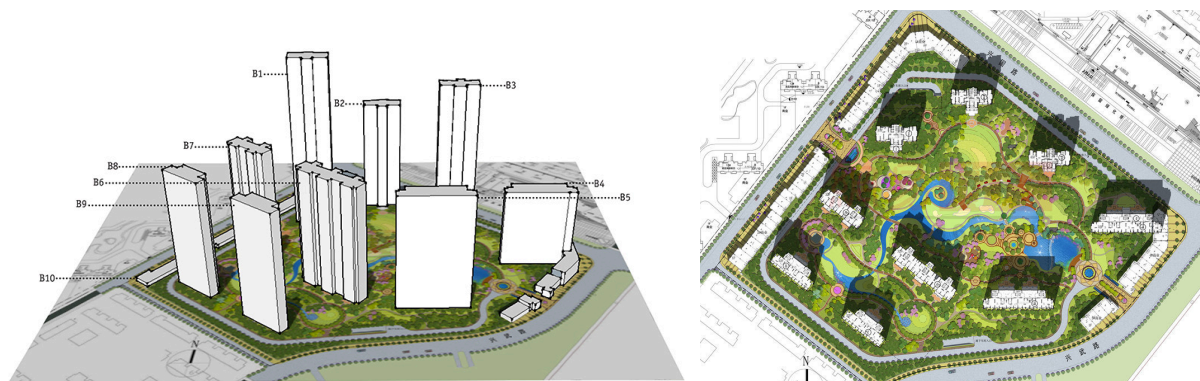


FIGURE 1 CAD model and plan of original Fudidonghu super-block in Wuhan

Results

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

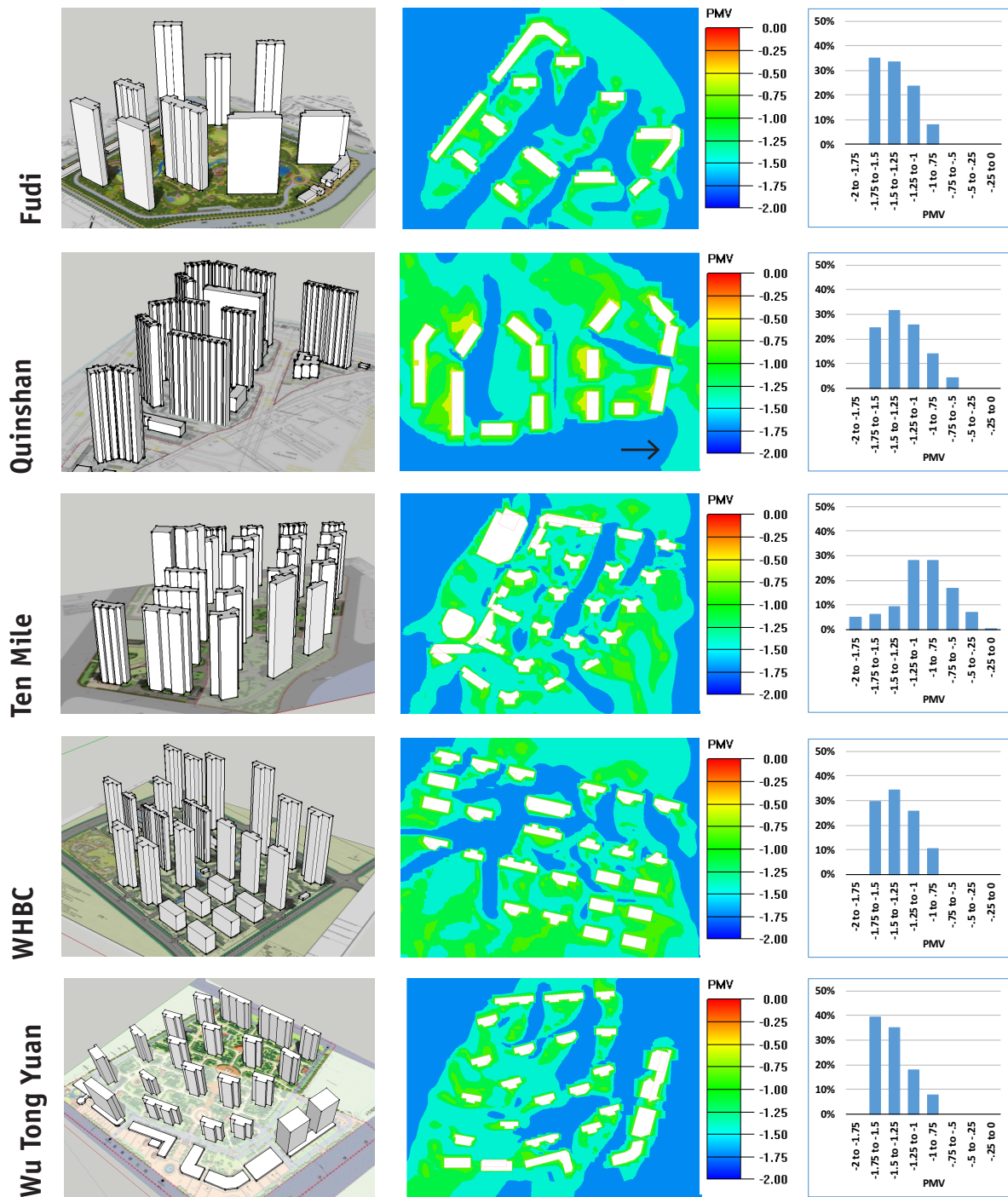


FIGURE 2 Predicted mean vote (PMV) in five super-block neighborhoods with NNE wind
(See Table 2 for statistics)

at intervals on the PMV scale. Output was an indexed eight-color raster format, which isolated contour zones to specific single-color bands, shown in Table 3. The specific site areas within bounding streets were excerpted graphically and analyzed by color range in Photoshop® using the histogram function to count pixels and determine the percentage of site area outdoors within each PMV band. Due to space limits, Figure 2 shows results for the NNE direction only. The distribution percentages are graphed. Comparative PMV statistical analysis is shown in Table 3.

TABLE 2 Statistics for pedestrian comfort near the ground from two directions in five superblocks, PMV score (NNE is winter, SE is summer condition)

	Mean		Median		Variance		Std Dev		1st Quart		4th 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	-1.3	1.87	0.08	0	0.28	0.04	-1.5	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	0.4	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

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. Results are shown graphically in Figure 3, which, due to space limits, shows results for the NNE direction only. Results of comparative statistical analysis are shown in Table 3. 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 (Ramponi, et al, 2015). The results do not represent the age 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].” (Fluent, 2007). Because the distances are much greater than for an indoor room, mean air age values are longer than for indoors. Air age is therefore an imperfect freshness indicator.

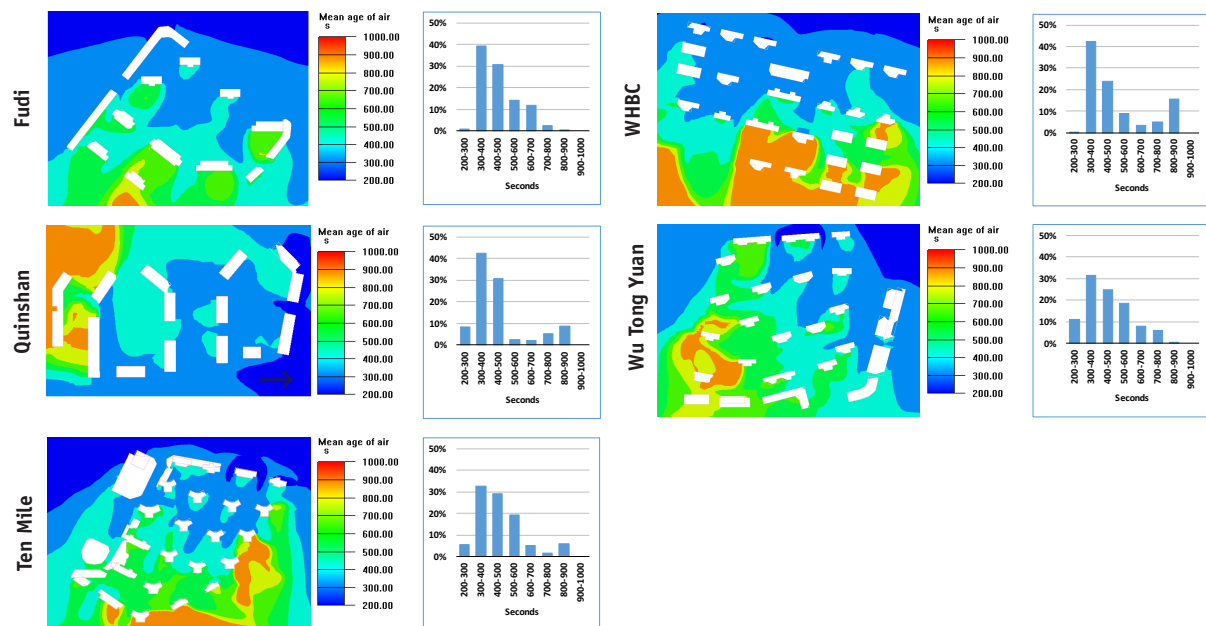


FIGURE 3 Predicted mean air age in five super-block neighborhoods for NNE wind direction (See Figure 2 for 3-D illustrations of each site. See Table 3 for statistics)

TABLE 3 Statistics for air age near the ground from two wind directions in five superblocks, seconds

	Mean		Median		Variance		Std Dev		1st Quart		4th 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
Quishan	448	431	398	416	27222	19902	165	141	339	311	479	540	140	229
Ten Mile	466	492	440	448	20816	24342	144	156	359	376	539	562	180	186
WHBC	502	369	502	356	33618	7290	183	85	359	317	595	396	236	79
WTY	451	511	431	455	18467	35365	136	188	345	358	543	646	198	288

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 export of a grid of data points for each building face. The vertical grid was in 2 m (6.6 ft) 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 was grouped and analyzed within vertical facade zones of 33 m height (108 ft). For example, a 100 m (328 ft) 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.

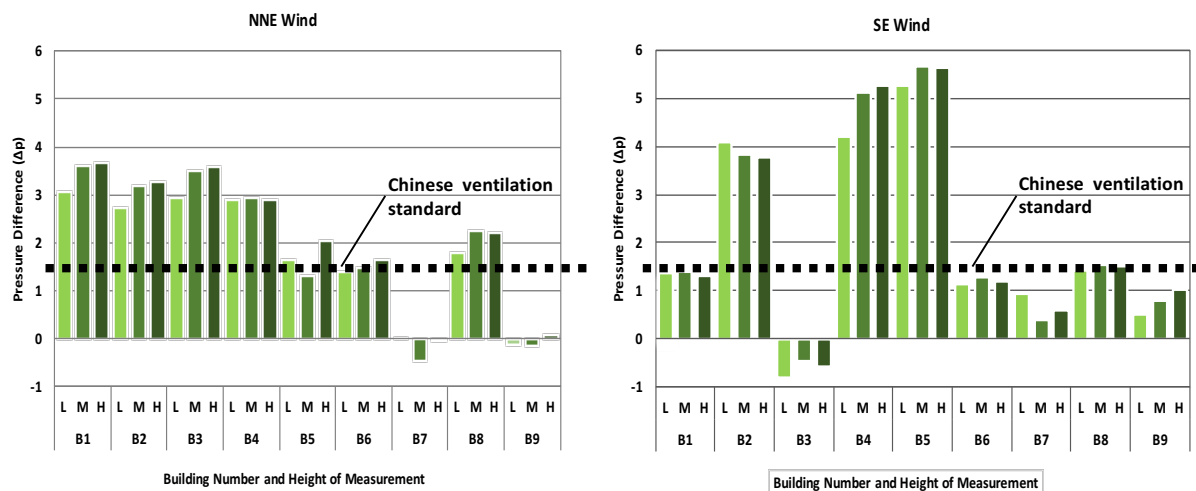


FIGURE 4 Wind-driven pressure differences between facades in Fudi superblock buildings
(See Table 4 for statistics)

Figure 4 shows results for the Fudi site from two wind directions. Table 4 gives the percentage of buildings with pressure difference less than the 1.5 Pa Chinese standard.

TABLE 4 Percentage of buildings *not meeting* Chinese natural ventilation standard of $\Delta p > 1.5$ Pa

Site	Height	NNE	SE	Site	Height	NNE	SE	Site	Height	NNE	SE
Fudi	L	33	67	Ten Mile	L	71	46	WHBC	L	57	57
	M	44	56		M	75	54		M	35	35
	H	22	56		H	75	50		H	47	41
	Ave	33	60		Ave	74	50		T	0	17
Qingshan	L	56	78	WTY	L	72	67		Ave	35	43
	M	44	67		M	67	61				
	H	33	67		H	56	67				
	Ave	44	71		Ave	65	65				

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

Analysis of Results

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 2) range from –0.85 (*slightly cool*) in WHBC to –1.42 (*cool*) at WTY. Median comfort conditions are generally 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 2) show a tight range from +1.84 (*warm*) at Ten Mile and WHBC to +1.89 (*warm*) at Fudi. 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 for outdoor hot climates.

Air Quality

Median site air ages with NNE wind show a relatively small range from 398 to 502 seconds (s), with Qinshan having the freshest air. From the SE, median air ages range from 356 to 455 s, with Fudi and WHBC both having the lowest air age. The results show that a combination of density, wind direction, building type and building layout appear to have an influence on air age. The densest scheme, Ten Mile, at FAR 7.34, has a lower median air age than WHBC, with FAR of 4.35. Ten Mile uses tall point blocks, whereas WHBC is configured in rows of more slab-like towers. For such an aligned arrangement, wind direction makes a big difference in air age. In WHBC, NNE wind, which is perpendicular to the slab facades, gives an average air age of 502 s, while the SE wind, arriving at an angle to the building faces, drops air age to 369s. It is, rather obviously, important to consider multiple primary wind directions in a city where each of the hottest three months has a different predominant direction (SE, SW, and NNE).

Building Ventilation

Pressure difference analysis showed some surprising results, including large differences based on wind direction. Summer analysis is mandated from the SE, yet, three of the five sites performed better with a NNE wind. When wind is from NNE, the best overall performance is in Fudi, where 33% of building façade areas do not meet the standard. In some cases, such as Ten Mile, 74% fall short. According to the SE wind analysis, WHBC is best at 43% not meeting the ventilation criteria, while 71% of Quinshan's units fail. The ventilation effectiveness is below anticipated, and we believe the methods used were rigorous, so the poor results suggest questioning either the CFD accuracy or the ventilation standard itself.

Results showed that higher floors (H) of tall buildings do not always get better ventilation. Although wind pressures may be higher, pressures are higher on both sides of buildings, so pressure difference is not always greater than on lower (L) floors. Flow disturbances in a complex arrangement change the wind directions, such as with downwash. The mid-height (M) sections sometimes have poorer ventilation potential than the lower (L)

floors, such as at Ten Mile. We expected greater difference between low and high floors, but the range in many cases is relatively small (11% for SE in Fudi, 10% for SE in WHBC, etc.).

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. Figure 5 shows our site design following TOD rules with the same floor space as Fudi. The superblock is subdivided into four blocks with street-facing buildings and internal courts and each housing unit provided with sun and through-ventilation.

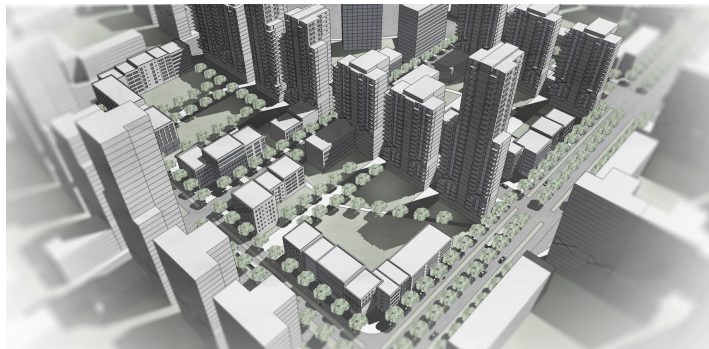


FIGURE 5. Fudi site redesign using TOD guidelines for “Tower Residential Zone.” Floor area = 200,000 m²

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Conclusions

In analysing five Wuhan superblock schemes, we established the range of comparative performance against which new TOD or other designs can be assessed and reported in a future paper. Based on the PMV’s weak distinctions for hot conditions and the tight range found, we are left with an ambiguous result for relative pedestrian comfort based on PMV and will investigate other metrics and analysis tools. Air age as an indicator of air quality gives us a basis for TOD comparisons, with temperance warranted as previously discussed. Despite some questions about accuracy, including our surprise at how many buildings do not meet the Chinese ventilation criteria, the ventilation potential results should also serve as a comparative base for urban design. Towers and slab types were promoted in the 20th century as good for providing light and air. If pedestrian-, urban- and energy-friendly TOD can provide equal or better light and air at similar density, then it will be another positive argument for its emergence as a model for rapidly expanding cities in China and elsewhere.

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