

Dynamic Microclimate Modelling for Urban China: Assessing Pedestrian Comfort, Air Quality and Building Ventilation Potential

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ABSTRACT: *It is common practice to use hourly dynamic thermal modelling for building design, yet climate responsive urban design, is often based on predominant wind directions analysed for particular ‘typical’ days or times. Such a snapshot view does not reflect how often these conditions occur and whether design changes based on single instances are warranted. This paper explores the efficacy of using an annual dynamic approach, by extending and comparing results from a previous study of district massing on local microclimate. These dynamic annual analyses were undertaken using a new cloud-based microclimate analysis tool that employs open source software for Computational Fluid Dynamics (CFD) and post-processing of results. This tool allows for complex hourly analyses of solar radiation, wind and comfort distribution to be conducted within a commonly used 3-D modelling software environment. Following the previous study, this paper compares the resulting urban form across three major issues: pedestrian comfort, air quality and building cross-ventilation potential. Pedestrian comfort assessment includes thermal comfort, using the Universal Thermal Climate Index (UTCI) and wind comfort, using the Dutch standard NEN 8100. Air quality is approximated by air age distribution. Building ventilation potential is assessed by mapping pressure differentials at points on opposing building faces.*

KEYWORDS: *Pedestrian comfort maps, CFD-based microclimate, Air quality, Natural ventilation potential, Urban physics*

1. INTRODUCTION

Buildings are commonly modelled using dynamic hourly thermal software, yet a more limited approach is used in climate evaluation for urban design. The computational intensity required often results in a simplification of the wind regime; limiting analysis to particular dates and times, e.g. summer or winter solstices, at mid-day. This “snapshot view,” helps designers generalize about design improvements in response to wind or solar access, but does not reflect the frequency with which these conditions occur or whether decisions based on these instances achieve the desired improvement at other times of the year.

This paper explores the efficacy of using an annual dynamic simulation approach, by extending and comparing results from a previous study of urban district massing based on local microclimate [1,2]. The first phase of the study assessed five “super-block” housing developments in Wuhan, China for pedestrian comfort, air quality and building ventilation potential. The second phase redesigned the neighborhood using Transit-Oriented Design (TOD) guidelines for China [3] and compared it to an existing, comparable density super-block scheme, Fudidonghu (Fudi). In this study, we compare the resulting TOD scheme and the original Fudi design across three major issues: pedestrian comfort, air quality, and building cross-ventilation potential.

Pedestrian comfort assessment includes thermal comfort, using the Universal Thermal Climate Index (UTCI) [4] and wind comfort, using the Dutch standard NEN 8100 [5]. Air quality is approximated by age of air distribution and building ventilation potential is assessed by measuring pressure differentials at points on opposing building faces.

These analyses use a new, original, cloud-based microclimate analysis tool that employs open source software OpenFOAM [6] for the Computational Fluid Dynamics (CFD) and ParaView [7] for data analysis and visualization. This tool allows for complex hourly dynamic analyses of solar radiation, wind, and comfort distribution to be conducted within SketchUp [8]. Analyses can be undertaken for as many or as few hours of the day and days of the year as required and results can be mapped back onto the 3-D model. This approach allows one to probe microclimate behavior at specific times of year as well as explore varying seasonal patterns, all within the context of the 3-D geometry.

Typical Chinese super-block development has poor walkability, transit support and street life, along with high energy use and auto dependence. TOD guidelines address these issues, but may reduce building ventilation potential at lower levels due to greater site coverage and block perimeter buildings.

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The project's hypotheses are 1) On an annual basis, TOD development can be designed to equal super-block wind performance; 2) Dynamic annual wind and comfort modeling improves performance feedback time and quality for urban design, as compared to simpler CFD methods.

2. METHODOLOGY

We assessed Super-block and TOD schemes of equivalent density on an annual basis. Figure 31 shows overview of the massing layout.

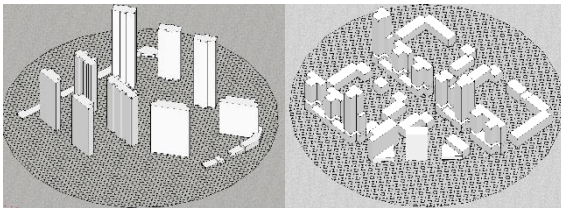


Figure 1: Superblock Massing (L) and TOD Massing (R)

All analyses share a common analysis grid on which the final results are mapped. For this study, the grid used was 400m in diameter and comprised of 5000 individual points. To encourage walkability, the analyses used times of day that spaces are most likely to be occupied; nominally between 8 AM to 10 PM.

The annual radiation analysis looks at distribution of radiation on site, accounting for direct and diffuse shortwave radiation, longwave radiation and overshadowing from buildings.

The CFD analysis used OpenFOAM. The wind inlet boundary condition used was the default Atmospheric Boundary Layer condition in OpenFOAM (D.M. Hargreaves and N.G. Wright). The solver used for simulation was SimpleFoam with a k-epsilon turbulence model. The domain size was generated automatically based on standard practice; with domain width 10 times the height of the tallest building, and domain height 5 times the height of the tallest building. The domain was octagonal to account for the eight wind directions. This approach has the advantage of having to mesh the domain only once for all wind directions at the cost of slightly larger meshes, resulting in a total of up to 20 million cells - predominantly hexahedral - for both cases in this study, with a ground boundary layer refinement. Annual hourly weather data used was obtained from the EnergyPlus website as an EPW file [9].

We then combined the results of these analyses to generate comfort indicators for each point in the mesh for each annual hour occupied. The overall methodology for this study was:

- Run dynamic microclimate analysis and extract age of air and comfort maps for particular dates to compare with previous "snapshot" studies

- For each scheme, generate seasonal statistics and graphical maps for pedestrian comfort, age of air, and façade ventilation potential
- For one of the TOD massing 'courtyards,' quantify the impact of typical passive design measures on occupant comfort
- Analyze results to find strategic ways to improve the TOD design for wind performance
- Evaluate the results to test the hypotheses in a subsequent paper

3. RESULTS AND DISCUSSION

The results for occupant comfort, air quality and natural ventilation potential, along with comparative review with the previous results, are discussed in subsections 3.1 to 3.6.

3.1 Comparison with previous results

The initial study undertook age of air and comfort analyses for specific dates and times. The key differences between the parameters for the previous study and the current analysis are shown in Table 1.

Table 1: Difference between standard and dynamic analysis

STANDARD ANALYSIS	DYNAMIC ANALYSIS
NE & SE directions only, fixed initial wind speed 2.6 m/s	All wind directions & speeds in hourly weather file
Typical summer day (June 22) and winter day (Jan 20), Single hour, 12 noon	365 days a year Hours, 8 AM to 10 PM
PMV comfort for Summer, 30°C (86°F) Winter, 5°C (41°F)	UTCI comfort for local wind speeds from CFD and hourly weather file

The comparison between age of air results from the previous and current study are shown in Figure 2 to Figure 5.

The age air results are not a like for like comparison as the initial study combined a wind speed and direction and date that didn't necessarily occur concurrently in the weather data set used. However, both sets of analyses indicate that the Fudi superblock massing tends to have a greater rate of air change (lower air age) than the TOD massing.

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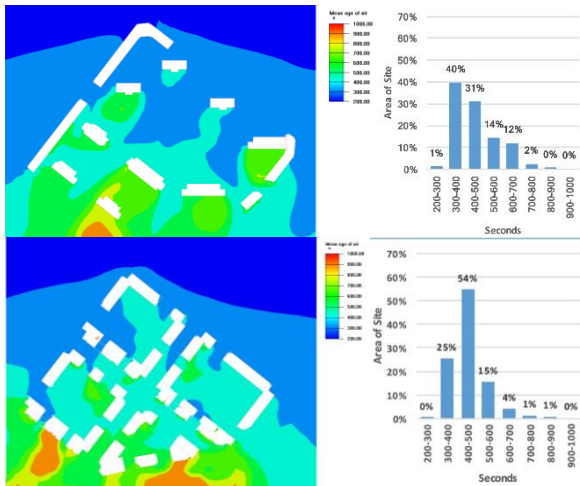


Figure 2: NNE Age of Air Snapshot (original study)

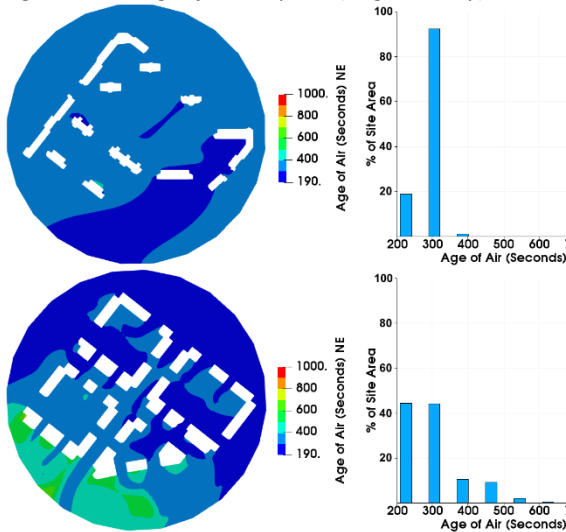


Figure 3: NNE Age of Air Snapshot (extract)

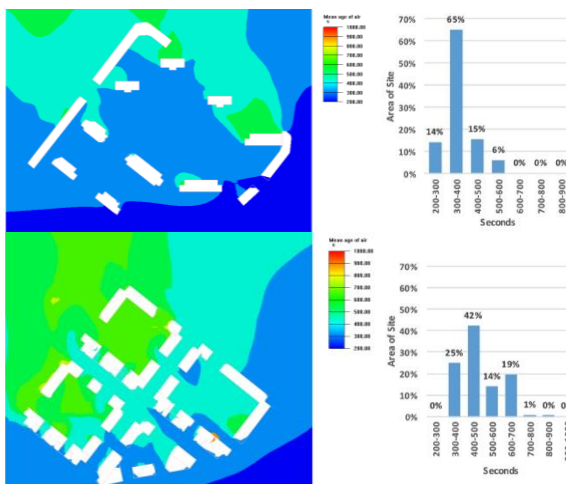


Figure 4: SE Age of Air Snapshot (original study)

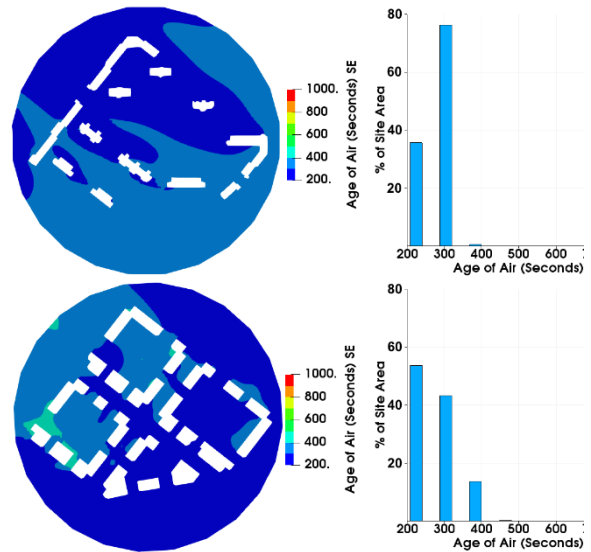


Figure 5: SE Age of Air Snapshot Comparison

The comfort results also do not directly correlate with each other because, in addition to the issues described above, they use different metrics (PMV in the previous study vs UTCI in this simulation). Both sets of results concur on the fact that a majority of the site experiences discomfort on both dates; cold discomfort on Jan 20th and warm discomfort on June 22nd.

3.2 Wind comfort distribution

The wind comfort calculation references the Dutch standard NEN-8100, which evaluates how often the wind speed exceeds 5m/s throughout the year and its impact on different activity levels in external spaces. An overview of the standard is shown in Figure 6.

% Hours/Year Wind Speed > 5m/s	Sitting	Standing	Strolling	Grade
<2.5%	Good	Good	Good	A
2.5% - 5%	Moderate	Good	Good	B
5% - 10%	Poor	Moderate	Good	C
10% - 20%	Poor	Poor	Moderate	D
>20%	Poor	Poor	Poor	E

Figure 6: NEN8100 Wind Comfort Criteria

Overall, the wind speeds on site are quite low and the results outlined in Figure 7 indicate that wind speeds greater than 5 m/s occur for less than 2.5% of the year, rendering all areas of the site suitable for all levels of activity.

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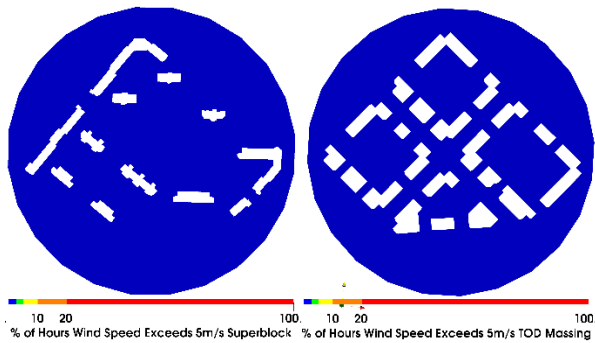


Figure 7: Annual Wind Comfort Comparison

3.3 Thermal comfort distribution

UTCI is a comfort index that models in detail, the thermal exchange between the human body and its environment through combining environmental variables (local air speed, temperature, relative humidity, radiant gain/loss) and physiological variables (clothing and activity levels) to provide an indication of the perception of the thermal environment by occupants. The standard comfort range for UTCI is from 9 to 26.

A value below 9 indicates cold discomfort and above 26 indicates warm discomfort.

The results in Figure 8 and Figure 9 provide an overview of how often the UTCI occurs within the comfort range (9-26) in each season. Overall, the TOD massing experiences marginally higher comfort levels (see legend). However, both massing types show a similar pattern of distribution annually, where Spring is the most comfortable season and Winter is the least.

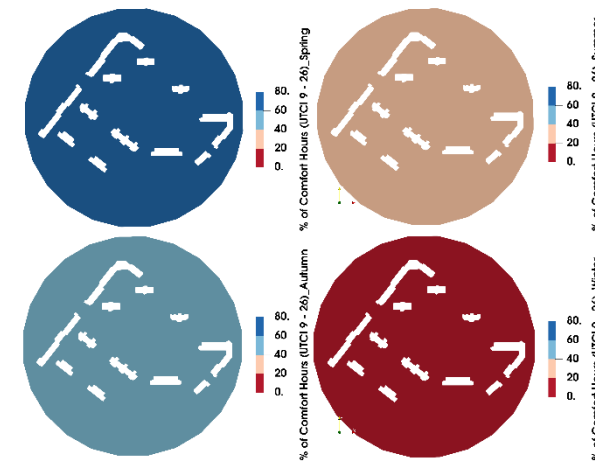


Figure 8: Fudi Superblock Seasonal Comfort Comparison

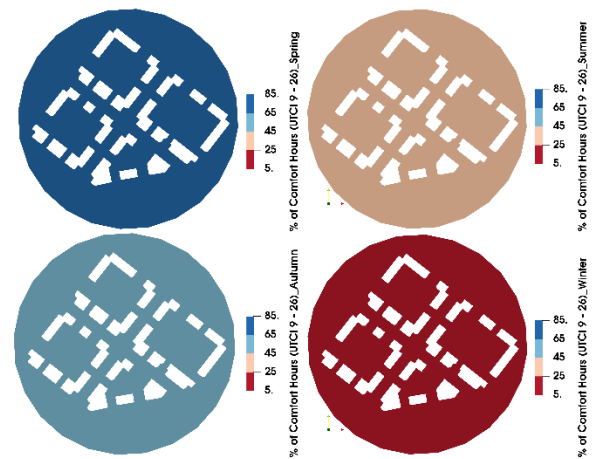


Figure 9: TOD Seasonal Comfort Comparison

Since the results in Figure 8 and Figure 9 don't show the distribution and variation in comfort levels within the site, Figure 10 shows the difference in results for both schemes in Spring. The histogram for the Fudi massing is stacked towards the left of the chart; i.e. majority of the site area experiences relatively fewer hours with UTCI in the comfort range (9-26). The marginally improved comfort observed for the TOD massing likely relates to greater overshadowing from surrounding buildings.

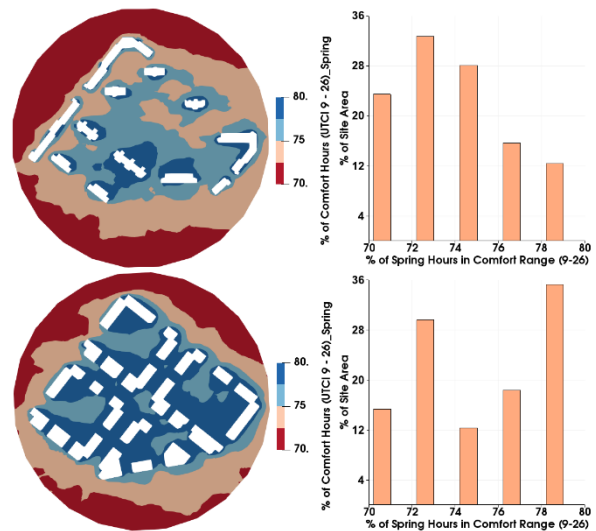


Figure 10: Spring Comfort Comparison

3.4 Age of air distribution

Typically, age of air is a metric used for indoor spaces to indicate air quality; i.e. how often air is replaced with fresh air from outside. The upper limit is 5 minutes or 300 seconds. This approach does not directly translate to outdoor spaces and at best, serves as a comparison of how long it takes air at any point to be displaced from the time it enters the domain.

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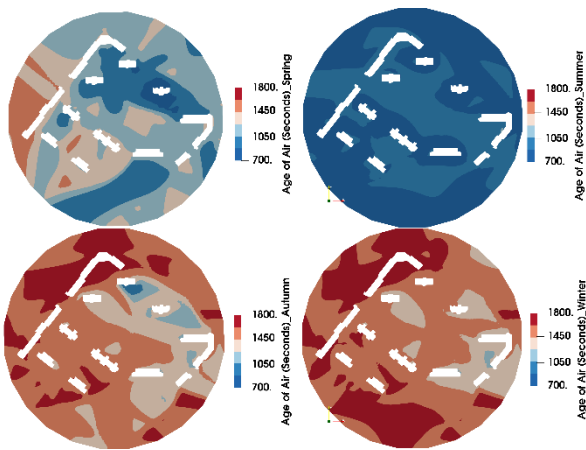


Figure 11: Fudi Superblock Median Age of Air by Season

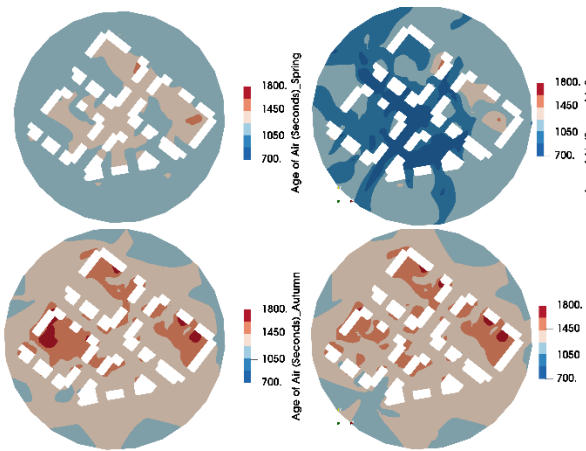


Figure 12: TOD Median Age of Air by Season

This study looks at wind speed and direction for each occupied hour of the year, making the age of air indicative of local wind patterns.

Overall, the results in Figure 11 and Figure 12 indicate that age of air is lowest in summer and highest in autumn and winter. This has positive implications for thermal comfort as this is closely correlated with air speed. Spring shows the greatest variation within the site, but overall the superblock massing has lower age of air; i.e. better air circulation, for at least part of the site, as compared to TOD, which includes a few 'dead' spots in all seasons, including summer.

Figure 13 shows the comparative age of air results for both massing types in Spring. The Fudi superblock experiences a wider range of age of air with roughly 5% of the western part of the site showing very low air change. While the overall age of air in the TOD massing is higher, on average the air change rate is in the range of 18-20 minutes.

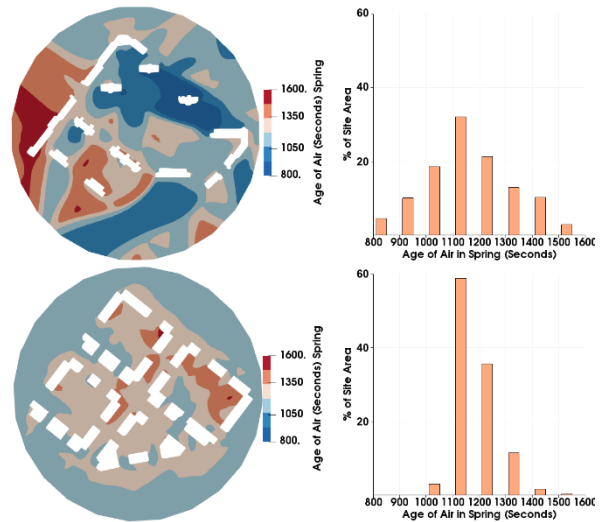


Figure 13: Spring Age of Air Comparison

3.5 Natural ventilation potential

Chinese ventilation standards for double-sided through ventilation of housing call for a minimum pressure difference between opposite openings of 1.5 pa [10]. The pressure differential was mapped at a distance of 0.5m from the wall surface across 24 hours to include night cooling. Mapped results in Figure 14 show the percentage of hours that the pressure differential exceeds the 1.5 pa minimum threshold for ventilation potential. The TOD massing shows greater variation in ventilation potential but also improved performance relative to the Fudi superblock massing, at least in the taller buildings. The low rise buildings within the TOD massing tend to show an equivalent or worse performance compared to the Fudi superblock. Figure 15 shows a histogram that plots the proportion of surface area that exceeds the 1.5pa differential against the proportion of hours.

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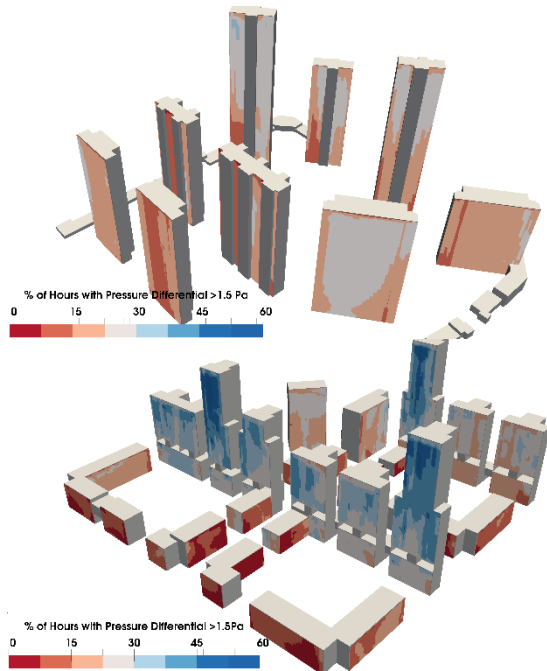


Figure 14: Natural Ventilation Potential Comparison

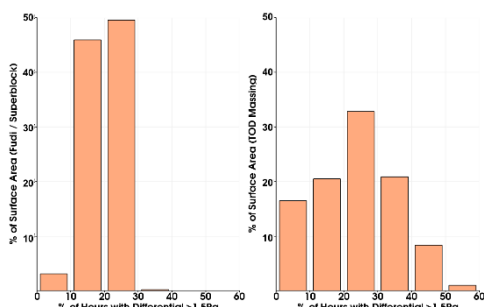


Figure 15: Natural Ventilation Potential Histogram

3.6 Impact of passive design measures

Results for the TOD massing indicated that a majority of the site experienced warm discomfort for >50% of hours in summer. One of the benefits of undertaking an annual assessment is that it allows us to quantify the impact of design interventions.

A point in one of the courtyards in the TOD massing was evaluated for comfort without any interventions and then, including design interventions, such as adding vegetation and physical shading, as shown in Figure 16.

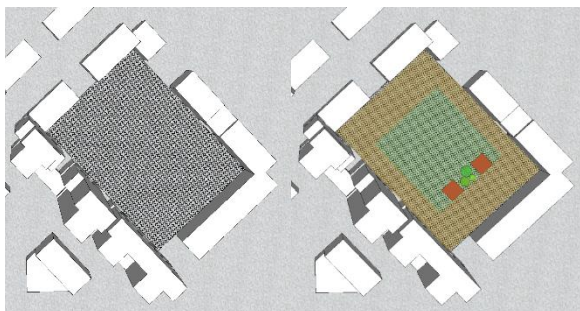


Figure 16: Unshaded Baseline (L) and Shading Inclusion (R)

The maps resulting from this evaluation are shown in Figure 17 and point A within this map was further analyzed to determine the change in distribution of comfort occurrence at this point throughout summer.

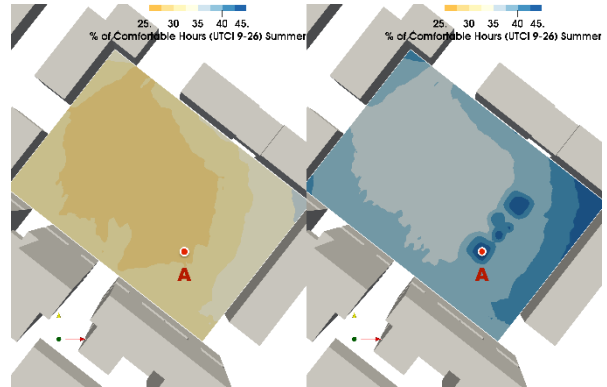


Figure 17: TOD Massing – Impact of Design Measures

Figure 18 shows the comfort distribution at point A across the summer months as a heat map; with the x-axis showing the time of year and the y-axis, the time of day. The areas that show up in dark orange are UTCI>26 and as a result, are outside of the comfort range. The most noticeable improvements in comfort occur in early June and late August and September.

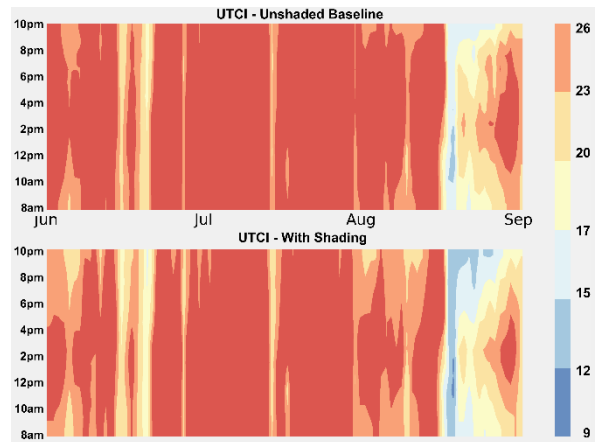


Figure 18: Heat Map of Summer UTCI for Point A

Overall, there are 179 more hours that fall within the comfort range, an improvement of 14% or the equivalent of 11 additional days where it's comfortable for every hour of the day.

4. CONCLUSION

The methods used so far mostly look statistically at the site as a whole. The final example in 3.6 is an exception, aimed at clarifying the level of granularity this approach affords. Further developments of the methodology can extend this approach to improve comfort in primary pedestrian areas, such as sidewalks and building entrances, in addition to gathering places and seasonal activity areas.

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The results in 3.6 indicate that even basic passive design measures can noticeably improve comfort levels in Wuhan during the warmer months. Covered outdoor circulation, such as arcades along the streets, plus street trees for shading would improve pedestrian comfort locally where people walk most. Locating summer public outdoor spaces in breezeways under buildings or on the north side of tall buildings offers further refinement for warmer months.

Winter is almost always uncomfortable in this climate and the passive measures available include local wind blockage and increased exposure to radiation. The latter suggest a tension between solar access for buildings and outdoor sun for open spaces. Solar exposure for buildings, as required by Chinese codes, is expressed in the TOD guidelines by locating tall buildings to the southern edge of blocks; overshadowing much of the open space in winter. This indicates that there is a need to include specific winter outdoor spaces with access to sunlight. These might also benefit from deciduous trees to provide some shade in summer.

One way to improve air circulation might be to stagger the heights of the buildings even more, to create a greater variation in pressure distribution and as a result, increase air movement.

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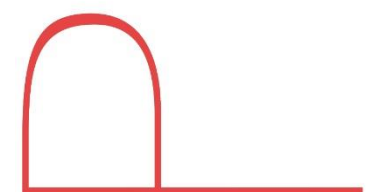
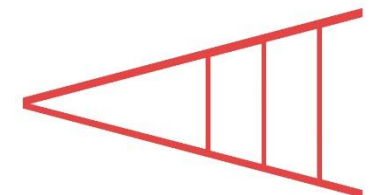
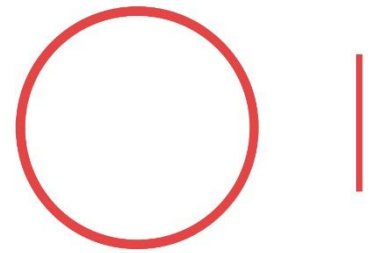
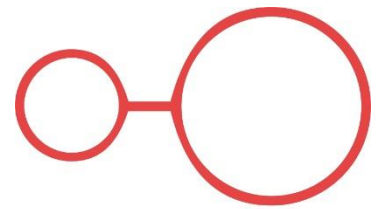
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