NATURAL VENTILATION IN A WARMING CLIMATE: AN EVALUATION OF COMPUTATIONAL SIMULATION METHODS AND METRICS

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ABSTRACT

With wider concerns around increasing global temperatures, it is imperative to look at how we quantify (simulation methods employed) and evaluate (thermal comfort metrics utilized) natural ventilation schemes especially in warmer climates. This study focuses on three apartment typologies, at different heights and orientations, to assess how design alterations affect annual thermal comfort hours. We utilize four modeling methodologies that start from simplified zone airflow to detailed airflow network coupled with external pressure coefficients and internal wind speeds derived from a CFD simulation. We use three thermal comfort metrics: predicted mean vote, adaptive thermal comfort and 26ºC operational temperature threshold. On the metrics front, we find that the operative temperature thresholds predict fewer annual discomfort hours, drawing attention to the importance of the metrics. On the modelling front, our results reveal that the most granular modeling approach is the most successful at identifying additional cooling hours in the cross-ventilation scheme.

Keywords: natural ventilation, airflow analysis, thermal discomfort, hot climates, design sensitivity

1 INTRODUCTION

Shifting climatic conditions have presented various new regions in the world with the challenge of having to cool their indoor environments to keep residents comfortable. Combined with higher income levels in some parts of the world, global energy demand for space cooling is expected to more than triple by 2050 (OECD/IEA, 2018). However, not everybody is expected to have access to air conditioning to stay healthy. Exasperated by rising population and urban growth rates, the Global South is particularly vulnerable to increasing temperatures and the phenomena of energy poverty. Current estimates show that only 8% of the 2.8 billion people living in the hottest regions of the world have access to air-conditioning (Mastrucci et al., 2019). In this light, the lack of essential indoor cooling can be seen as an increasingly prominent threat to health and wellbeing, a challenge that design must rise to address.

When climatic conditions allow, natural ventilation can offset cooling energy consumption as well as the associated carbon dioxide emissions and energy costs, becoming a powerful tool to reduce space overheating (Cardinale et al., 2003). Unlocking natural ventilation potential in warmer climates is particularly challenging as it requires careful design implementations that are effective in the narrow temporal windows of opportunity that exist throughout the year. The assessment of natural ventilation schemes in residential building typologies has focused on the influence of fundamental design parameters affecting air movement which include local site features, the building massing, facade design as well as internal space divisions (Aynsley, 2007). With reference to floor plan typologies, extensive research has investigated wind-driven flow schemes, where the identification of opening configurations that promoted cross-ventilation schemes have shown to be especially efficient in offsetting discomfort hours (Allocca et al., 2003; Shirzadi et al., 2018; van Hooff et al., 2017). In addition to studying the impact of design parameters, studies have also quantified natural ventilation potential across varying climatic conditions in high rise construction which is particularly relevant to the densification we are witnessing in cities today (Chen et al., 2017; Tong et al., 2017). However, the fundamental challenge rests in not only assessing overall overheating hours across climatic differences and spaces, but also in quantifying the spatiotemporal impact of subtle design variations on indoor thermal conditions.

Assessment workflows centered on evaluating annual natural ventilation hours, have varied in spatial and temporal resolution. EnergyPlus (U.S. Department of Energy, 2020) employs an airflow network (AFN) solver that provides the capability of simulating multizone wind-driven air flows based on the AIRnet model (Walton, 1989). This workflow is a simplification in comparison to Computational Fluid Dynamics (CFD)-based simulations that calculate context-specific pressure coefficients which can be used to more accurately evaluate predicted energy savings and thermal comfort conditions. The applicability of these methods should be largely informed by the density of the urban environment and the climate of interest, as larger deviations could be witnessed when utilizing the simplified models (Cheung & Liu, 2011; Dogan & Kastner, 2021). Moreover, when informing design strategies and comparing alternatives, the metrics used to evaluate comfort differ substantially. The evolution of studies centered on adaptive self-regulation in thermal comfort models, have identified air velocity as critical in evaluating naturally ventilated spaces, especially in climates that depend on higher flow rates (Kumar et al., 2016; Nematchoua et al., 2018).

This paper presents a natural ventilation case study of an apartment unit with three configurable design variations in five different climate zones in the Global South region. It provides an insight into the impact of design changes in altering discomfort hours while assessing the differences between different airflow assessment metrics. An order of magnitude analysis is established between the different modeling approaches when assessing different geometrical configurations. The combined results reflect on the modeling methods most sensitive to design alterations and the need to further examine the assessment metrics we use to inform design decisions.

2 METHODOLOGY

To understand the variations across assessment methodologies, four workflows were implemented. These are further detailed below along with the context parameters and building properties.

2.1 Climate Zones

The analysis focused on evaluating apartment design variations in five different cities, spanning different climates in the Global South. The intention was to capture a gradient of conditions from tropical and dry climates (A and B) to a more temperate climate (C) under the Köppen-Geiger climate zone classification.

2.2 Apartment Design Configurations

Three design schemes were considered with varying degrees of complexity. The first configuration is a simple single-sided ventilation scheme that looks at three zones in a living quarter/apartment typology; a bedroom, a living room and a service/dining zone. The second design alternative investigates the effect of a double-heighted living room space, with no other design changes. Finally, the last scheme builds upon the second alternative and additionally considers the effect of opening interior doors and thus explores a cross ventilation scheme across the apartment unit. In this configuration, both the bedroom and living room door are opened allowing for cross flow from either side of the apartment. The aggregate window-to-wall ratio was kept at 30% across all design variations.

Table 1: Climate Zones Investigated

Climate Zone Classification (Köppen-Geiger)	**A- Tropical** Aw- Tropical Savanna	**A- Tropical** Aw- Tropical Savanna	**B- dry** Bwh- Tropical and Subtropical Desert	**B- dry** Bwh- Tropical and Subtropical Desert	**C- temperate** C- sa- dry-summer subtropical
City	Bangkok, Thailand	Mumbai, India	Karachi, Pakistan	Cairo, Egypt	Casablanca, Morocco

Figure 1 illustrates the three discussed typologies, for which each was simulated across 4 different orientations (N, S, E, W) at three different heights from the ground (low-0m, mid-15m and high-30m). The developed schemes were parametrically modeled within Grasshopper, the visual programming interface of Rhino3D, a CAD software (McNeel 2016). An automated workflow was developed using the parametric model to procedurally link the different simulation engines and extract downstream discomfort hours across methods and metrics.

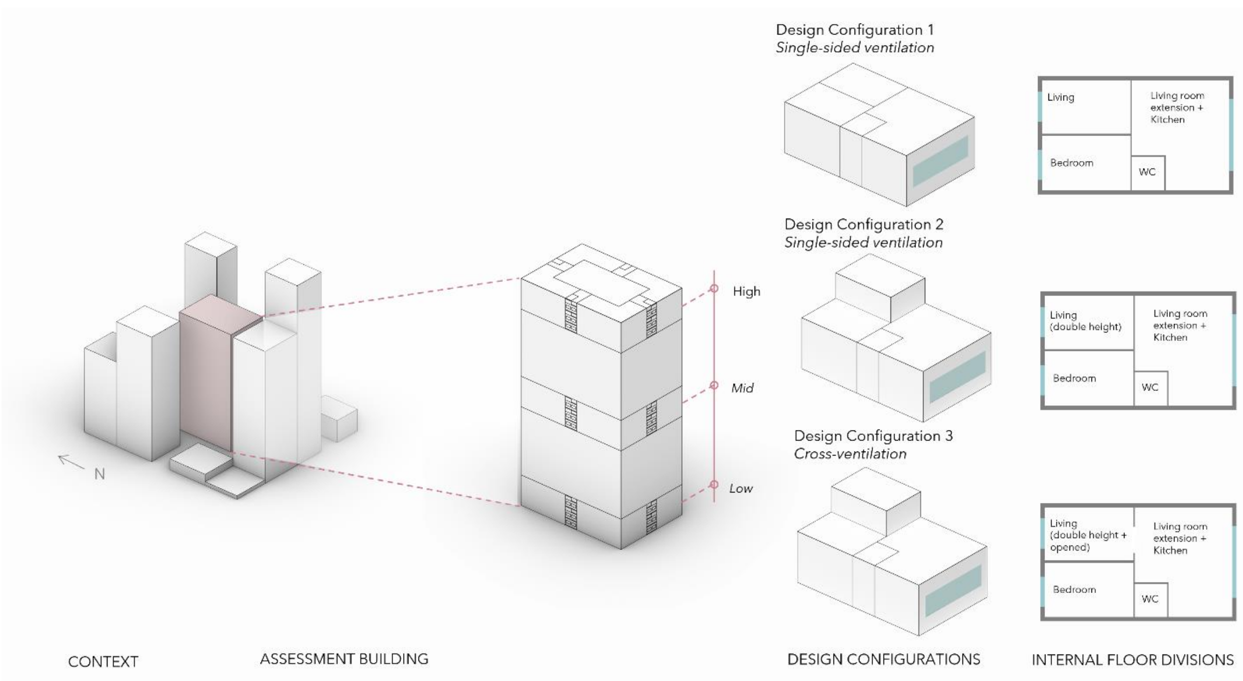


Figure 1: Apartment Set-up Design Configurations

2.3 Assessment Methods

The evaluation of natural ventilation potential and its impact on indoor thermal comfort was carried out using an integrated workflow that combines and synthesizes results of independent thermal and computational fluid dynamics simulations. These are carried out respectively using ClimateStudio (Solemma, 2020) and Eddy3D (Kastner & Dogan, 2022) which are environmental performance analysis interfaces within Grasshopper for EnergyPlus and Radiance engines for the first and OpenFOAM engine for the latter. Figure 2 summarizes the various assessment methods and metrics investigated across design configurations and climates. Four progressively more refined methods of assessment were investigated to capture the method resolution sensitivity to design alterations. The description below details the models and simplifications used in each.

2.3.1 Method 1: Simple Zone Airflow Model

The first method represents the simplest analysis scenario which is based on EnergyPlus's Simple Zone Airflow Objects. This approach only considers single-sided ventilation and approximates the context using an urban terrain type. This presents a simple model that serves as a reference to compare against more complex airflow network-based models.

Each apartment unit model consists of three thermal zones for the bedroom, living room and service spaces. To capture the difference in how each space is used throughout the day for typical use, custom occupancy schedules were defined as detailed in Table 2. The thermal properties selected were consistent across the different zones and defined based on an average of typical construction types in the investigated climates, summarized in Table 3.

Table 2: Settings for occupancy schedules and internal loads

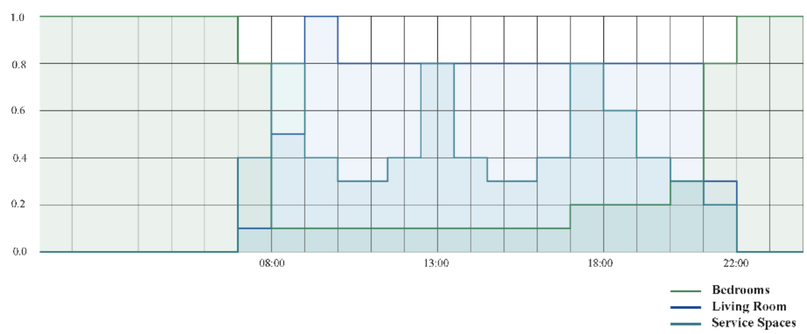
Zones	**Occupancy Schedule**
Bedroom 10pm- 8am	
Living Room 8am-11pm	
Service Spaces (kitchen, circulation, dining area) 7am-10pm	

Table 3: Thermal Envelope Properties

Construction Type	**Assembly Properties**
Walls	U-value= 0.2 W/m2k
Roof	U-value= 0.2 W/m2k
Windows	U-value = 3.16 W/m2k SHGC=0.31 Tvis = 0.743 Discharge coefficient = 0.65

2.3.2 Method 2: AFN + EnergyPlus Pressure Coefficients

The EnergyPlus Airflow Network (AFN) method is implemented, and which, in contrast to the baseline simple model that evaluates each zone in isolation, captures the airflow between zones. This method consists of nodes that are linked by airflow components, where the node variable is an array of pressure coefficients and the linkage represents the flow rate. The pressure coefficients at the inlets are estimated internally using the method developed by Swami and Chandra (1988). No CFD airflow analysis is conducted in this alternative.

2.3.3 Method 3: CFD: External Pressure Coefficients

This method introduces pressure coefficients derived from eight CFD simulations across the cardinal directions. The simulations quantify the outdoor airflow surrounding the building under study and its surrounding immediate context buildings, as well as the indoor airflow of the apartment units under a fully open windows condition during natural ventilation hours and closed otherwise. Industry standards for CFD modeling for urban wind applications were used to define the appropriate simulation model and parameters (EU-RTD, 2007; City of London and RWDI, 2019). The OpenFOAM solver, through Eddy3D grasshopper plugin, was used to solve the steady-state Reynolds-averaged Navier-Stokes equations (RANS) with a realizable k-epsilon turbulence model. A cylindrical domain spanning horizontally 15 times the height of the tallest building and vertically 6 times was used. The minimum meshing size is defined as 3 meters in the region of interest, with further refinement to about 0.3m closer to the ground, buildings and corners. Immediate context buildings were modelled and combined with an effective terrain roughness of 2 to represent flow in urban centers. Residuals falling below five orders of magnitude were used as the convergence threshold for the simulations. For each window in the apartment unit, across typologies, heights and orientations, eight normalized pressure coefficient values are extracted and used as inputs to the EnergyPlus simulation.

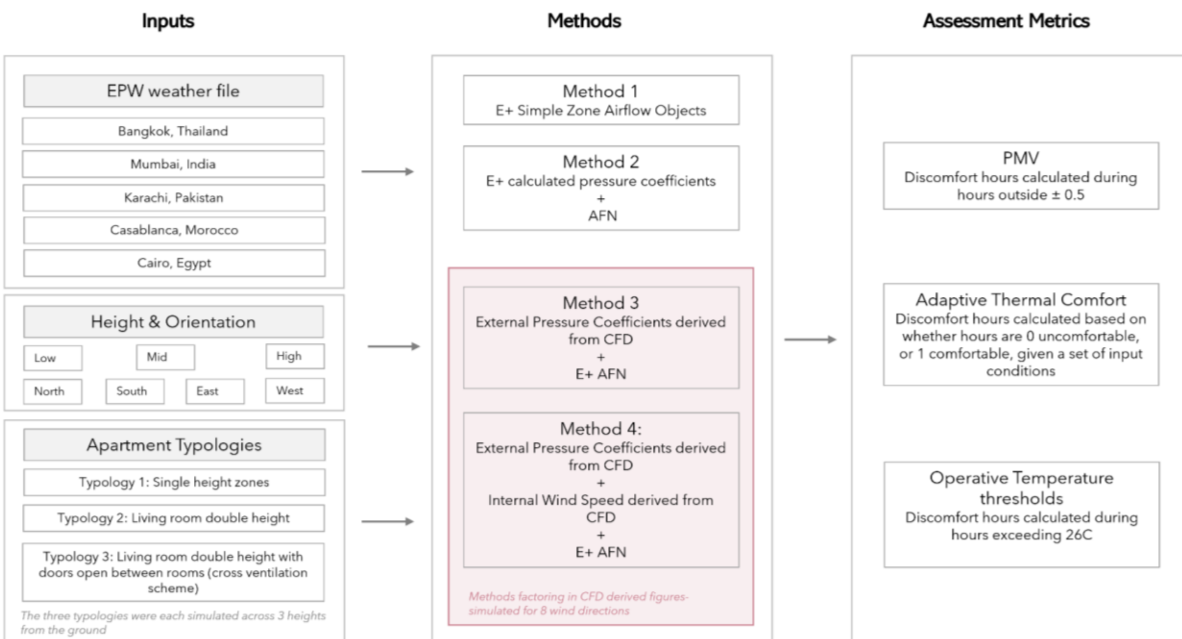


Figure 2: Summary of assessment methods and metrics used to simulate different design conditions

2.3.4 Method 4: CFD: External + Internal Analysis

Using the resolved flow of the eight simulations described in 2.2.3, analysis points on a 1 meter-grid across a 1.7m high horizontal slice were used as probes to measure internal wind speeds inside the various apartment typologies, heights and orientations. For each hour of the year and for each climate, the normalized wind factor of the closest simulated wind direction was scaled to the corresponding hourly wind speed. This generates a list of 8760 wind speed values' list for each point and climate. The variation of wind speeds within each zone is limited with larger variations happening close to wall corners. Because we do not expect spaces too close to walls to be usable, we use the hourly average wind speed within each zone for downstream comfort calculations, while excluding points within the closest 0.5 meters of the zone boundaries. The calculated average wind speed is then used as an input to the three comfort models estimated, and replaces the constant internal 0.1m wind speed assumption for natural ventilation potential hours only.

2.4 Metrics of Assessment

In the work presented, we utilize the two common comfort metrics: predicted mean vote (PMV) and the adaptive comfort model, which are typically used to assess indoor thermal comfort conditions and adopt the thresholds defined in their respective frameworks. Additionally, we record an additional measure of comfort that captures temperature exceedances in the space above a specific operational temperature threshold (26°C). The key thermal comfort models are summarized below:

- **PMV (Predicted Mean Vote):** PMV is an index that aims to predict the mean value of votes of a group of occupants on a seven-point thermal sensation scale. This metric is calculated based on 4 measurable quantities; air velocity, air temperature, mean radiant temperature and relative humidity as well as two inputs defining clothing and metabolism rate (Ole Fanger, 1970). In the experiment set-up, discomfort hours are regarded as those that fall between the -0.5- 0.5 thermal range sensation as prescribed by ASHRAE 55 (ASHRAE, 2020).
- **Adaptive Comfort Model:** Developed specifically to capture wider comfort conditions with the use of natural ventilation, this comfort model expands on the narrow comfort ranges set by the PMV model (de Dear & Brager, 2002). This model goes beyond the heat balance model, to additionally consider the psychological dimension of adaptation, which is particularly relevant to contexts where people's varying environmental set-ups or diverse thermal experiences may alter their satisfaction with thermal environments (Parkinson et al., 2020).
- **Operative Temperature Threshold:** This additional measure looks at a static temperature threshold, such that exceedance hours can be calculated to evaluate discomfort. We employed a fixed temperature of 26°C as prescribed under the Chartered Institution of Building Services Engineers overheating guide to specifically assess overheating in homes (CIBSE, 2017).

3 RESULTS

3.1 Metrics and Methods

Figure 4 shows the average discomfort hours during occupancy across the three assessment metrics (PMV, Adaptive Comfort and Operative Temperature threshold) against the four methods that were used for modeling internal conditions. The size of each pie chart corresponds ot the overall number of discomfort hours. The color scheme further divides these hours by season of occurrence. The first observation we see is that the metric that captures the highest number of annual discomfort hours is the PMV and the metric capturing the lowest is the Operative temperature threshold. In reference to climatic differences, the PMV metric shows the largest sensitivity in capturing increasing discomfort hours across the hotter climates to the more temperate ones (the visual uses the same ordering established by the climate zone classifications). One explanation for this is the wider indoor comfort bands established under the adaptive comfort model that are directly linked to average outdoor temperatures. In most cases, we see Casablanca and Cairo having the least discomfort hours and Bangkok and Mumbai having the highest.

Looking at the analysis methods, the simple zone airflow method consistently captures the largest discomfort hours across all set-ups. The adaptive comfort metric shows the smallest deviations across the different methods utilized. Method 1 differs substantially in comparison to Methods 2-4, which show a smaller deviation range. The PMV metric shows the largest difference between Method 3 and Method 4, where internal wind speeds are utilized. Across all climates, discomfort hours under Method 4 are 8.1% lower than Method 3, using the PMV metric. Originally developed for the assessment of indoor environments where wind speeds are controlled and generally low, the PMV metric shows higher sensitivity to larger wind speeds. This is translated in the form of a reduction in discomfort hours during winter where higher wind speeds have a bigger impact on discomfort.

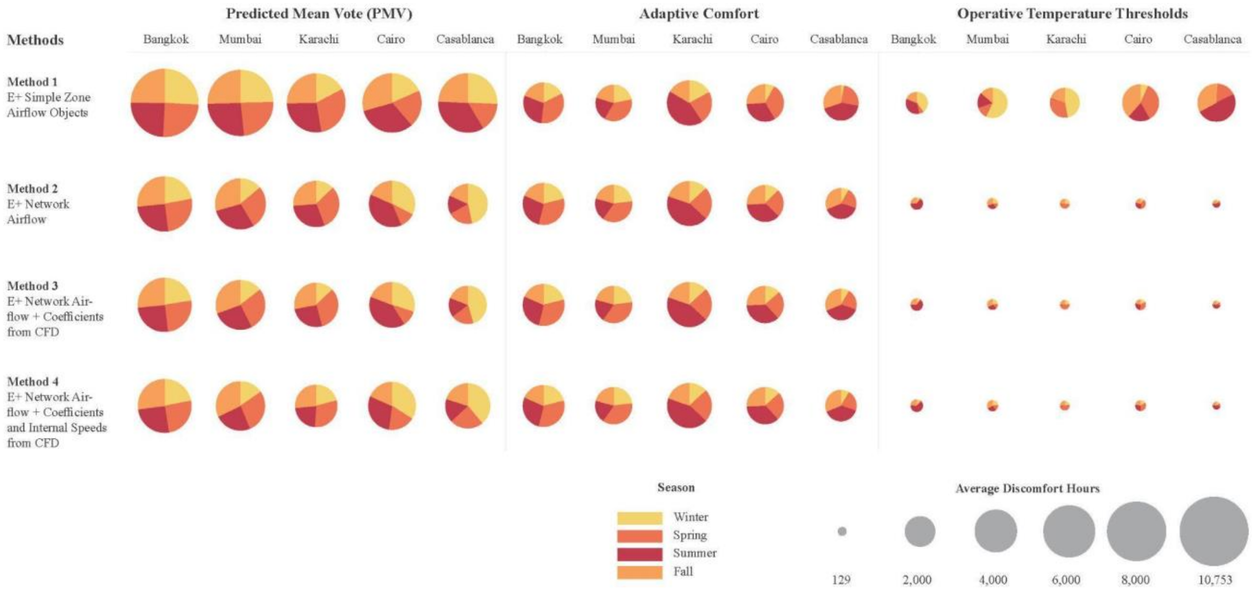


Figure 3: Method and Metric comparison showing average annual discomfort hours across climates

3.2 Design Sensitivity

To investigate the results further, we look at the metric variations across the different design configurations. Below is a summary of the discomfort hours captured by the different metrics, when specifically looking at the method with the highest resolution (Method 4).

3.2.1 Floor Height

The metric showing the largest variations across the different floor heights is the adaptive comfort; the highest floors have the lowest discomfort hours, while the lower floors have the highest. This trend flips in the PMV metric. A possible explanation for this is that the adaptive comfort is less sensitive to temperature and radiation exposure because it follows outdoor temperatures, hence with higher floors the increasing wind speeds have a higher impact on reducing discomfort. With PMV we see that radiation has more influence with higher floors, that ultimately leads to warmer temperatures and higher discomfort hours. We confirm this trend by looking at winter where we find that in higher floors the discomfort hours are reduced because an increase in radiation exposure helps to passively warm the building. To show the difference when internal wind speeds are simulated in Method 4, Figure 5 shows the magnitude of the deviation between the constant assumed wind speed of 0.1m/s and the simulated values in terms of occupied hours across spaces and heights.

3.2.2 Apartment Zone Configuration

The biggest change between the design variations can be seen under the PMV metric. When height is kept constant and radiation is consistent, we see that the cross-ventilation scheme shows a reduction in discomfort hours with the introduction of wind flow. This can be specifically observed in summer months across all climates. It is important to note that these observations are most evident under Method 4, meaning that the effects of the cross-ventilation scheme are best captured under the set-up which includes the internal CFD simulation. In addition to this, Method 3 also shows a reduction in discomfort hours when compared to Method 2, meaning that the introduction of actual CFD pressure coefficients also helps to capture the cross-ventilation effect. Table 4 below shows the percentage decrease in discomfort hours between these two methods during summer months in the cross-ventilation scheme under the PMV metric. The adaptive comfort and operative temperature metrics show smaller variations across the different design configurations.

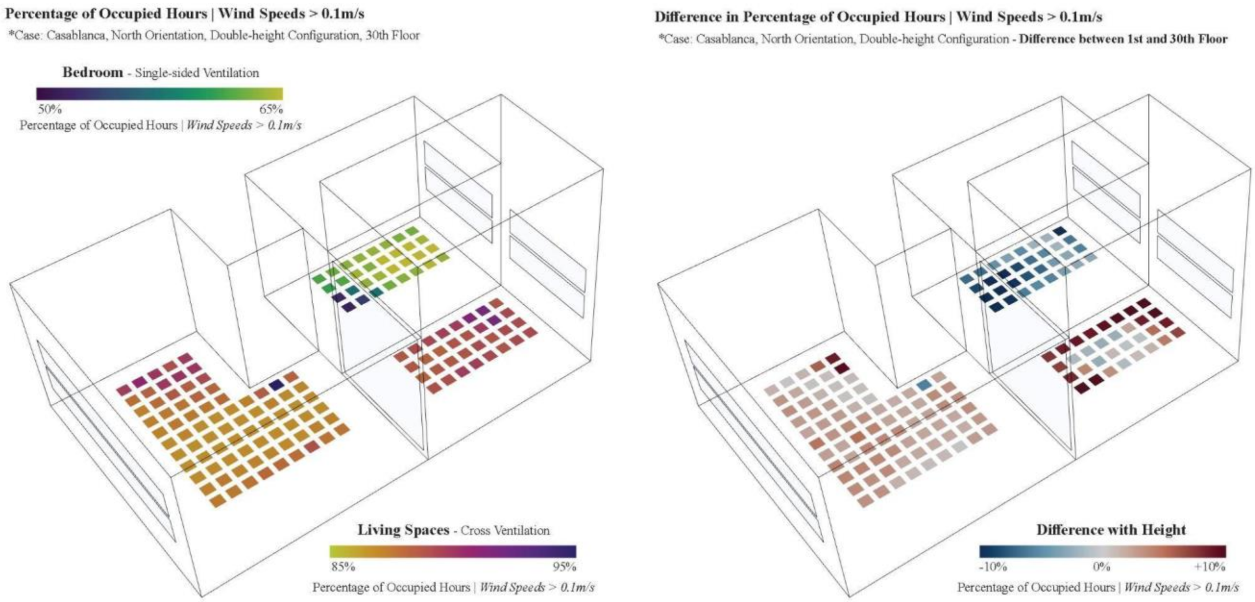


Figure 4: Deviation between simulated internal wind speeds and constant assumption of 0.1m/s

Table 4: % Decrease in discomfort hours between Method 2 and 3 during summer months in the cross-ventilation scheme under the PMV metric

Climate	% Decrease in discomfort hours
Bangkok	8%
Mumbai	16%
Karachi	22%
Cairo	2%
Casablanca	0.5%

3.2.3 Orientations

In both the discomfort hours captured under the Adaptive comfort model and the PMV metric, we see differences across different orientations. This is largely due to varying degrees of solar and wind exposure in our site setup. For instance, the South facade is not exposed as it is obstructed by contextual buildings, hence the apartment unit having this exposure does not exhibit higher levels of discomfort as would be expected. Due to the same underlying reason, the East and West show higher levels of discomfort due to their exposed set-up. While results are specific to the simulated urban context, it represents a diversity of exposure conditions that provide the means to evaluate the simulation methods and metrics' sensitivity to contextual variations and orientations. Figure 5 shows the summary of all design configurations (height, orientations and apartment design) with reference to the evaluation metrics across seasons. We note that the design strategy with the biggest impact on discomfort hours is the orientation.

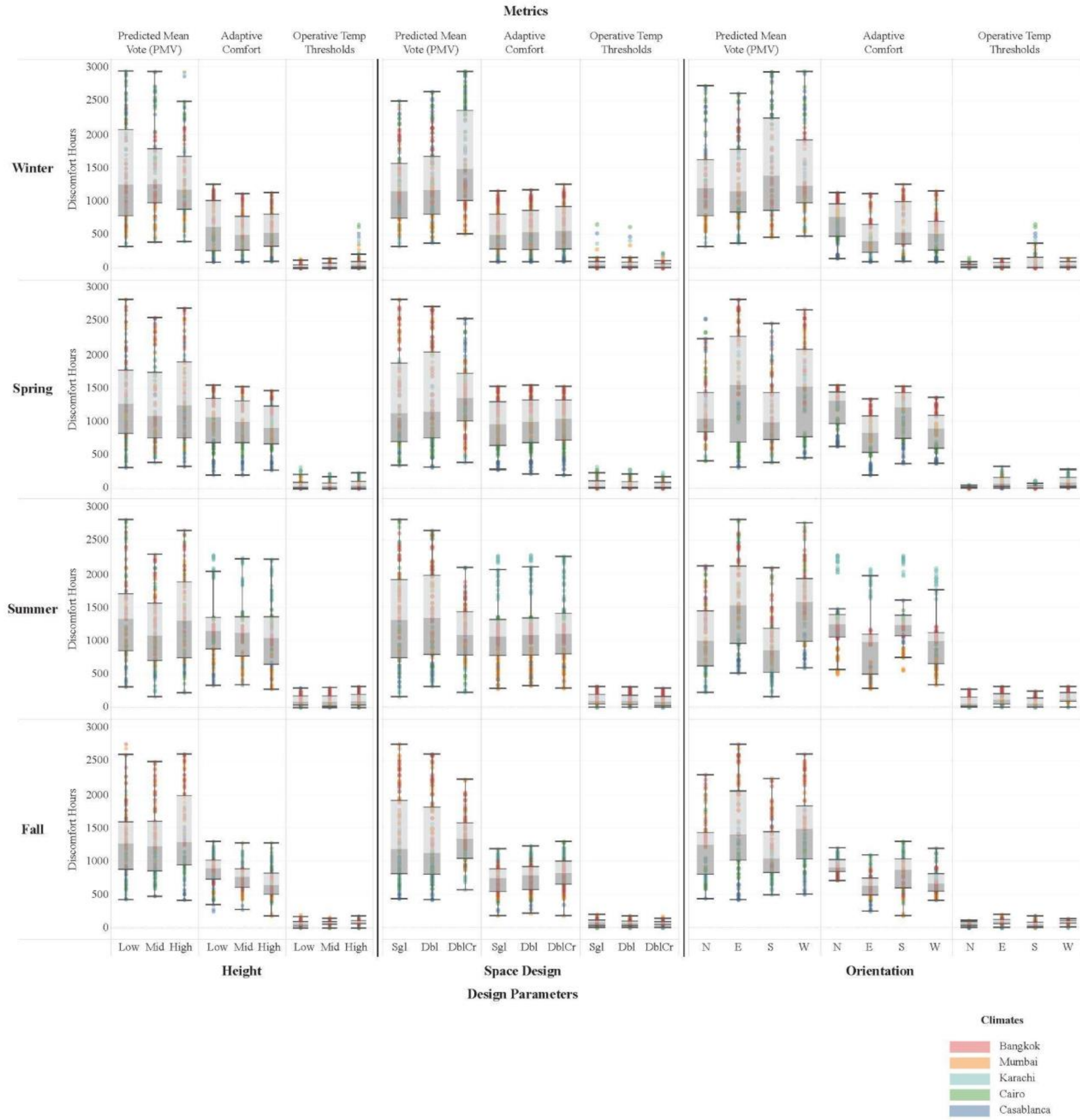


Figure 5: Metric comparison showing annual discomfort hours across different design configurations

4 DISCUSSION

A shift towards increasingly detailed models is evident in the analysis of indoor thermal discomfort. With the obvious barriers being additional computational time and complexity, it is key to understand when more granular modeling methodologies and metrics would need to be employed to effectively evaluate differences between intricate design set-ups. In other words, when is increasing model complexity by including CFD simulations more justifiable? In line with recent literature on warmer climates, the results have indicated that a large variation in annual discomfort hours is seen when CFD calculations are introduced in the AFN simulation (Dogan & Kastner, 2021). We find that in instances where cross-ventilation is being considered, a larger discrepancy can be seen between the method that includes internal wind speeds and the methods that assume a constant speed. In addition to this, in low-level configurations (near ground conditions) where more urban obstructions are present, having pressure coefficients that accurately represent the surrounding geometry makes a difference. In reference to the simpler modeling methodologies, we note that Method 1 has consistently over-estimated the discomfort hours due to the lack of wind-flow integration and hence an underestimation of natural ventilation cooling potential. It is also important to note that the study evaluates the effects of wind-driven single-sided and cross ventilation and that the AFN method may not be suited for the investigation of buoyancy schemes.

While we also examined seasonal performances across climates, an expanded set of studies would need to additionally consider annual humidity level fluctuations and tolerances within these climate zones. A more intricate study could investigate the relationship between the humidity profiles during natural ventilation hours and the resultant comfort levels captured under the different metrics. In such an application, PMV may be better suited as it factors in humidity levels into its assessment of comfort. Moreover, the wide disparity between the thermal evaluation metrics signals towards the need to further investigate the application of the metrics and arrive at a consensus on the specific use-cases and trade-offs between each one.

5 CONCLUSION

The results of the study show that additional model complexity is justified in the investigated climate zones, especially in cross-ventilation schemes, to more accurately represent the cooling potential of wind-driven natural ventilation. While a higher modeling resolution does not always translate to a larger fidelity, in the absence of real measurements, it is considered in this study to be the most suitable assumption. We find that the simplest modeling method (Method 1) with no air flow accounting continuously overestimates discomfort hours in comparison to Method 4 with internal CFD and air flow coefficients. Method 1 also shows the largest deviations across different thermal comfort metrics. Method 4 shows the biggest sensitivity in the cross-ventilation design scheme where the average decrease of discomfort hours across all climates with the introduction of internal CFD is 8.1% using the PMV metric. The T-operative assessment shows significantly less discomfort hours in comparison to the PMV and Adaptive comfort. One explanation is the static nature of this measure since it only accounts for temperatures and not any other parameters. With reference to the design alterations, the design change contributing to the largest differences in discomfort hours is the orientation. This is followed by the introduction of the cross ventilation scheme vs single sided ventilation. The results emphasize the need to match both the modeling and method of evaluation to the design configurations being investigated, in order to avoid misrepresenting a strategy’s potential to alleviate discomfort hours.

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