A Comparison of Methods for Evaluating Ventilation Cooling Potential
Building Program Based Climate Analysis for Early Design Decisions

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Abstract

One of the most widely discussed passive building design strategies is using natural ventilation for cooling. In addition to providing fresh air, which enhances occupant productivity and comfort, strategic implementation of natural ventilation in buildings reduces the energy needed for cooling. And this reduction in energy consumption significantly reduces carbon dioxide emissions. During the initial design phase, designers routinely use climate-file based analysis to evaluate the potential for comfort ventilation against other passive building strategies. Following this initial screening, it is customary to conduct detailed simulations to further develop design ideas. At this point, inconsistencies can arise between the early climate-file based analysis and later-stage simulations. Major differences arise from limitations of climate-file based analysis to account for influences of construction assemblies, building program, and occupant comfort preferences. This manuscript presents a building performance-based climate analysis method where quick, single-zone simulations are run in EnergyPlus. The ventilation cooling potential for a site and a building program is calculated using a series of Python scripts.

Introduction

Thermal comfort is one of the fundamental aspects of indoor environmental quality that is strongly related to occupant satisfaction and energy use in buildings (Schiavon et al 2014). In order to understand whether natural ventilation is a valid design strategy to enhance thermal comfort for a given building type and site, many building science textbooks for designers and architects promote an hourly climate-file based analysis that yields the number of comfort hours natural ventilation could add to a space over the course of the year using bioclimatic charts. These methods were first developed during the 1950s and were implemented into digital design tools such as Climate Consultant and Ecotect Weather Tool.

An important pioneer of thermal comfort representations was Victor Olgyay, who used the concept of an Effective Temperature (ET) as the basis of his comfort diagram, the 'Bioclimatic Chart' (Schiavon et al 2014). This chart assumes the criterion that the perimeter of the comfort zone outlines the conditions in which an average person will not experience the feeling of discomfort. It applies to moderate climate zones (Olgyay 1963). Givoni, the author of the 'Building Bioclimatic Chart', extended Olgyay's representation to the psychrometric chart and added rules about passive heating and cooling strategies (Figure 1). The Building Bioclimatic Chart, which is implemented in Climate Consultant, is a widely used climate-file based tool that uses two components: thermal comfort area and 'boundaries of climatic conditions within which various building design strategies and natural cooling systems can provide comfort' (Givoni 1992).

Climate Consultant allows users to upload standardized EPW format climate data, which are made available online by the US Department of Energy (Climate Consultant 6.0 Documentation), and visualizes all hours of the year on the Building Bioclimatic Chart where selected design strategies are shown (Figure 2). However, it does not allow users to control the level of air movements and does not include Standard 55's model for elevated air speed. The thermal comfort area reported in the Bioclimatic Chart is not consistent with ASHRAE 55 thermal comfort areas (Schiavon et al 2014). Furthermore,

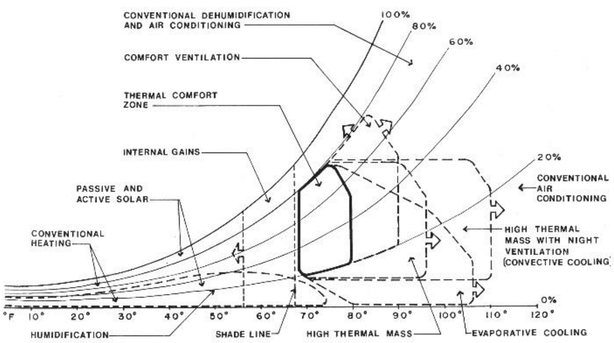

Figure 1:Summary of design strategies as a function of ambient conditions (climate). (From Pschrometric-Bioclimatic Chart, by Baruch Givoni and Murray Milne.)

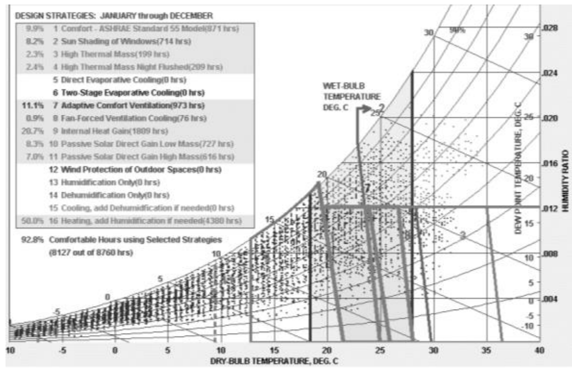

Figure 2:Climate Consultant is a simple to use, graphic-based computer program that helps users create more energy efficient, more sustainable buildings, each of which is uniquely suited to its particular spot on this planet (Milne 2009).

the underlying principle for Climate Consultant's comfort ventilation calculates for psychological sense of cooling which increases the rate of sweat evaporation, and clearly states that ventilation does not reduce the dry bulb temperature (Climate Consultant 6.0 Documentation). On the contrary, thermal simulation tools such as EnergyPlus and CoolVent allow detailed building analysis to predict zone temperatures and airflow rates in naturally ventilated buildings but do not calculate psychological cooling effects due to indoor air movements.

The application that provides a good alternative for cooling ventilation potential calculation is the CBE Thermal Comfort Tool for ASHRAE-55 (Figure 3). Designers can use it during the programming and schematic design phases to assess different thermal control strategies including natural ventilation and elevated air speed (Schiavon et al 2014). However, users can only calculate results for a single point in time by defining indoor air temperature, mean radiant temperature, prevailing mean outdoor temperature and air speed. This requires users to know indoor and outdoor conditions before conducting the analysis, and falls short to perform annual analysis in contrast to climate-file and simulation based methods.

Designers and their consultants interested in designing high performance buildings tend to start their conceptual design with a quick, climate-file based analysis. If the required knowhow is available on the team, they later switch to more detailed building simulation tools that can further evaluate the hourly indoor thermal comfort conditions for a particular building design. Based on the observations discussed above, this paper carefully reviews the assumptions underlying these two analysis steps, evaluates their consistency for a variety of building types and climates, and proposes an alternative workflow for design teams to use. The objective is to allow a design team to transition between an early climate-file based analysis to a detailed building design analysis without getting inconsistent results.

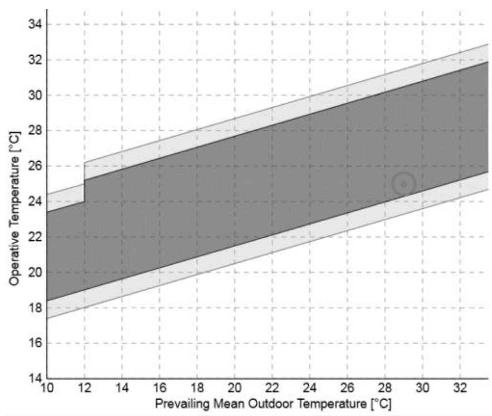

Figure 3: CBE Thermal Comfort Tool. For the ASHRAE Standard 55-2010 Adaptive Comfort model (de Dear and Brager 1998), the comfort zone is represented with indoor operative temperature as ordinate and prevailing mean outdoor temperature as abscissa.

Methodology

From a building physics standpoint, natural ventilation effects on comfort can be classified into two different phenomena: cooling ventilation by lowering operative temperature and cooling ventilation effected by moving air near an occupant inside a building.

Cooling ventilation by lowering operative temperature

This approach measures how much operative temperatures during overheated hours are reduced with cooling ventilation where indoor warmer air is replaced with outdoor cooler air. Air displacement calculation methods that naturally exchange inside air with outside air lead to comfort improvements if outside air is cooler than inside air. In the case of buoyancy driven ventilation, this temperature difference between inside and outside is required to initiate the air exchange in the first place. Once the temperature difference drops below 3 K the sensible cooling effect becomes quite small, even if air change rates as high as 5ACH can be maintained (CIBSI AM 10). Transient thermal simulation programs such as EnergyPlus consider temperature and air change rates. Effective reduction in overheating hours achieved by ventilation can be measured by comparing simulation results from low and high ventilation scenarios.

Cooling ventilation by the effect of moving air (physiological cooling)

Moving air has long been used to provide comfort in warm environments. Provision for indoor air movement was one of the wellsprings of traditional architectural design in warm regions, affecting building form, components, and equipment over millennia (Arens et al 2009). Climate-file based analysis methods calculate ventilation cooling potential by estimating indoor air movement for direct physiological cooling. Results are shown on psychrometric charts where temperature and humidity values of analysed hours are plotted.

In the case of Climate Consultant, this method accounts for hours where there is sufficient indoor air velocity and zone of effectiveness is defined by a minimum air velocity to effect comfort, usually at least 0.2 m/s (Climate Consultant 6.0 Documentation). The underlying assumption is that with effective daytime cross-ventilation the indoor air temperature tends to track the outdoor level along with higher indoor airspeed. Therefore, the temperature limit of comfort ventilation applicability is the comfort limit at the enhanced airspeed at any region or season (Givoni 1998). The quantitative effect of convective cooling was studied extensively by Givoni at the Institute for Desert Research of Ben Gurion University in Israel and at the University of California, Los Angeles (Givoni 1992).

There are two important limitations of this method that could cause errors on cooling ventilation predictions. Firstly, the comfort zone defined in Bioclimatic based analysis do not align with comfort zones defined in

ASHRAE Standards 55. Hence, when users switch to detailed studies using simulation tools and comfort standards, there is a high probability that the dynamic simulation results are inconsistent with design concepts developed during early stages. Secondly, extended comfort zones indicated with the various design strategies including cooling ventilation and thermal mass are shown in such a way that their applications improve comfort in all instances; the influence of strategies on each other when implemented at the same time is not well explained. A very good instance is the internal heat gain zone that is defined only by a balance point temperature below which heating is needed. This approach leaves out effect of internal heat gain during hours of high temperature where cooling strategy is required. Furthermore, ventilation heat loss, which results in effective temperature reduction, is not considered along with physiological cooling in the ventilation cooling strategy. Therefore, identifying comfort ventilation potential for building programs with different internal gains and envelope performances becomes challenging when using climate-file based analysis.

Integrated method for predicting ventilation cooling by reducing operative temperature and providing physiological cooling effect

This paper presents an integrated method where a simplified simulation is performed to calculate operative temperature for a generic well-ventilated single zone building and physiological cooling with allowable indoor airspeeds is considered to enhance base simulation results. The thermal zone, the simulation process and output results of the method are discussed in detail in the following subsections.

i. Climate box: best case thermal energy model

As a first step, it is assumed that a user selects a specific climate file (same as for Climate Consultant) along with a program type such as office, residential etc. Information for the latter such as envelope materials and construction, conditioning schedules, internal loads, and ventilation ware stored in a template library and applied to a single-zone EnergyPlus model (Figure 4). This model is supposed to represent a “climate box”, i.e. the abstraction of a building rather than an actual architectural design. The climate box is 10m by 10m open plan with 3m floor to ceiling height and 30% window to wall ratio. Operable

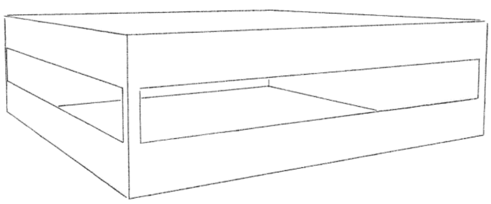

Figure 4: Single zone thermal zone is used to represent program based building simulation settings.

area ratio is 30% of opening area and discharge coefficient is 0.65 giving a net area of 1.8m2 for air exchange.

Ventilation Air Change Rate (ACH) of the zone is calculated using simple wind and stack equations implemented in Archsim based on EnergyPlus Input Output Reference (http://archsim.com/documentation-energy-modeling/natural-ventilation/). The upper setpoint is 33.5 ºC as the Adaptive Comfort Standard works if the mean monthly outdoor temperature is between 10 ºC and 33.5 ºC (ANSI/ASHRAE Standard 55-2010). The lower natural ventilation setting is adjusted to 23 ºC outdoor air temperature. Indoor air speed can not be more than 0.2 m/s for temperatures lower than 23 ºC (ANSI/ASHRAE Standard 55-2010). Physiological cooling of elevated air speed can be implemented for temperatures above 23 ºC where air speeds can go up to 0.8 m/s for office spaces and 1.2 m/s for less sedentary activity spaces such as residence (ANSI/ASHRAE Addendum g 2016).

In addition to calculated ventilation and physiological cooling, a constant infiltration rate of 0.6 ACH is considered based on the base reference given in PNNL-18898 document prepared for the U.S Department of Energy (PNNL-18898 2009). This infiltration rate is equivalent to 50 lit/sec and sufficient to provide required fresh air supply for a maximum of 5 people with 10 lit/sec/person base standard.

The climate box, being a small and very open space, is supposed to yield the maximum ventilation cooling potential for a given program type and climate. Cross ventilation based on wind and buoyancy ventilation are both supported. Further study is being conducted to optimize physical definition of the climate-box and possibilities of providing user control on building parameters such as occupancy schedules while maintaining the simplicity of the method.

ii. Base simulation

Two program types were developed for residences and offices as shows in Table 1. Construction systems and material choices for both residence and office differ based on the climate zone where the building is located. After comparing standards provided in *ASHRAE: Energy Standard for Buildings Except Low-Rise Residential Buildings* (ANSI/ASHRAE/IES Standard 90.1-2013) and building templates provided by US Department of Energy (DOE) prototypes, climate zones 8, 5 and 1 are selected to adequately represent climatic diversities from cold to hot.

Table 1: Residence and Office single zone thermal model settings for internal loads, conditioning and ventilation defined in simulation input files.

Settings	Residence	Office
Occupancy (no of people)	0.018 p/m2	0.062 p/m2
Equipment	5 W/m2	14 W/m2
Lighting set point	200 lx	500 lx
Electrical lighting load	1W/m2	8 W/m2
Heating set point	20 ºC	20 ºC
Ventilation	Buoyance, wind	Buoyance, wind

The DOE prototypes present different references for residence and office buildings distributed in different climatic zones mainly in the US. Furthermore, ASHRAE 90.1 defines construction types based on energy performance requirements and the standard presented for the different climate zones applies for all building types except low-rise residential building. The residential and office prototypes used in the proposed method have similar performance defined with U-values complying with ASHRAE 90.1.

Table 2: Building constructions for three different envelope performance options

Constructions	Cold	Average	Hot
External Facade	U-0.212	U-0.315	U-0.705
Glazing	Triple-Pane	Double-Pane	Double-Pane
Glass Coating	Low-E	Low-E	Low-E
Shading	Internal	External	External
Slab	Adiabatic	Adiabatic	Adiabatic
Ceiling/roof	Adiabatic	Adiabatic	Adiabatic

Among the four construction types in the ASHRAE Energy Standard; mass, metal buildings, steel structures and wood framed; envelope performance value of steel structure is used for the single zone model. The U-values range between 0.705 (climate zone 1) and 0.212 (climate zone 8).

For each of the functions, residence and office, six variants of single zone energy plus input files, IDFs are created. Envelope performance and thermal mass of the building highly influence the effectiveness of cooling ventilation. Consequently, the six variants presented are based on three different envelope performances, high (for cold climates), average (for temperate climates) and low (for hot climates) and two conditions of thermal mass, high and low mass. For high thermal mass conditions, additional 10 cm thermal mass with a volumetric heat capacity of 50 x 10^6 J/K is considered in the internal surface of the thermal zone.

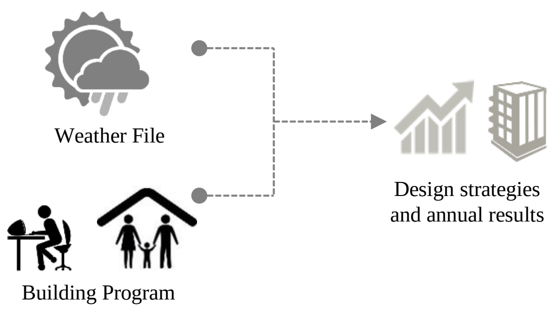

Figure 5: Users select the building program and upload weather file before running background simulation using EnergyPlus.

iii. Post Processing of simulation results

Simulated results are evaluated based on the ASHRAE 55's Adaptive Comfort Model and Elevated Air Speed standards to calculated number of hours that fall outside of the comfort limit (ANSI/ASHRAE/IES Standard 55-2010). In addition, indoor air humidity levels which are less than 20% and higher than 85% RH (relative humidity percentage) are counted towards hours of discomfort.

iv. User inputs and strategy selection

To achieve sufficient simplicity while guaranteeing consideration of critical building parameters, all the zone input settings are predefined for the climate box as discussed in the above section. The user is able to run all prototypes that are defined in the IDF simulation files by selecting the program and uploading EnergyPlus weather data for the project's location.

As mentioned above, there are two main categories of user inputs: building preferences and occupant preferences (Figure 6). Building preferences are given for envelope performance where three options are provided: cold, temperate and hot climates. Furthermore, these options can be used with base construction option for thermal mass or can be combined with high thermal mass option where additional construction layer is introduced to augment themal capcity of the zone.

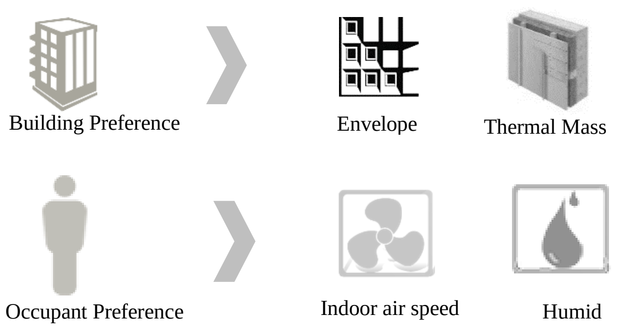

Figure 6: Designers can select building envelopes, thermal mass and indoor air speeds from provided options.

Occupant preferences are defined for physiological cooling effects with elevated air speed and indoor humidity levels. Under the Graphical Elevated Air Speed Method (ANSI/ASHRAE Standard 55-2010), the required air speed for light, primarily sedentary activities may not be higher than 0.8 m/s—although higher air speeds are acceptable when using the SET Method (ANSI/ASHRAE Standard 55-2010, Section 5.2.3.2). In contexts where occupants are engaged in non-sedentary activities, most commonly in residences, have a wider tolerance for higher elevated air speed of a 1.2 m/s maximum threshold.

v. Visualization of results

Once all the six simulations are completed for the selected program and climate data, the interface displays a temporal graph for the typology with the least number of overheated hours, giving a summary of selected envelope, thermal mass definition and indoor air speed. The number of overheated hours are shown in bold at the top-right corner of the chart. A comfort level rating highlighting the number with green, yellow or red marks the range from comfortable to very hot.

Analysis result for the chosen set of building parameters is shown in a comprehensive time-based chart (Figure 7). The main graph in the upper section of the interface displays operative temperatures of all hours in dark dotted marks. Outdoor dry bulb temperature is shown in a light grey colour shade at the background to give a good sense of outdoor condition in contrast to the indoor operative temperatures. The grey band going across all hours represents the adaptive comfort range as defined by the ASHRAE standard 55's adaptive comfort model. The comfort band clearly shows when in the year thermal comfort is achieved with natural ventilation and when it is too hot. The two horizontal bands in the lower part of the graph summarize comfortable hours and relative humidity levels as shown in Figure 7.

Results

The authors have closely studied the cooling ventilation calculation methods used by climate-file based bioclimatic charts and simulation based calculations to predict potential of natural ventilation in a particular climate to achieve thermal comfort.

Hours of discomfort calculations are based on the extended Adaptive Comfort Model (CBE Thermal Comfort Tool) where physiological cooling effect with elevated air speed is incorporated to the Adaptive Comfort Model (see Figure 3). In addition, the authors have accounted discomfort in naturally ventilated zone caused due to high humidity where indoor air relative humidity is higher than 85%.

Figure 8 compares Climate Consultant's report on overheated hours and calculated results using the proposed method for 20 different climates. Results from Climate Consultant, best residence and office scenarios consider high thermal mass strategy and cooling ventilation. The locations are selected mainly from the list of DOE's prototypes for different climates ranging from Climatic Zone 1 (hot) to Climatic Zone 8 (cold) as referenced in ASHRAE's construction standards. A few more climates including Kuwait and Mumbai are added to represent wider variety of climatic conditions.

Climate consultant considers the effect of comfort ventilation where by indoor air is completely replaced with outdoor temperature hence indoor air temperature follows outdoor air temperature. The underlying logic behind this climate-based analysis assumes that 100% heat and mass transfer has taken place between indoor air and incoming outdoor air. In addition, it accounts for Physiological cooling effect by evaluating wind speed from weather data and translating it into indoor air speed according to the guidelines given in ASHRAE Fundamentals 2005 (Climate Consultant Documentation: Natural Ventilation Cooling). This results in a perceived temperature reduction of 2.5 ^{o}C for air velocity of 0.82 m/s and 3.7 ^{o}C for air velocity of 1.60 m/s (Climate Consultant 6.0 Documentation). As a result, climate consultant's comfort prediction during warm to hot seasons is calculated mainly based on outdoor conditions of air temperature, humidity and wind speed. Effects of internal gain and solar gain are only accounted during hours of low temperatures.

Climate Consultant considers thermal mass as a cooling design strategy independent from the comfort ventilation. Maximum and minimum dry bulb temperatures above and below comfort thresholds are used to evaluate each hour of each day rather than diurnal cycles. As a result, comparison of proposed method and climate consultant shows that the latter tends to estimate higher number of discomfort hours from overheating than simulated thermal zones with thermal mass (See Figure 8).

The evaluation shown in Figure 9 clearly indicated that making functional distinctions is crucial when predicting potential of ventilation cooling. In addition, it is very

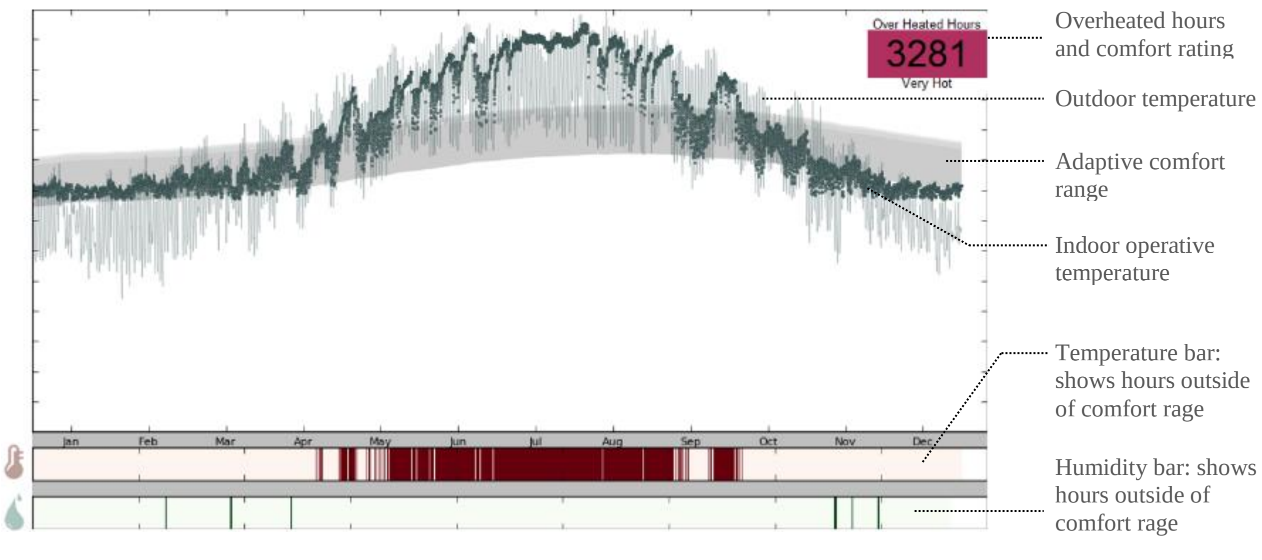

Figure 7: Analysis for a residence in Kuwait shows that active cooling is necessary from April to September. Indoor humidity levels remain below 80% almost all year round.

critical to analyse occupied hours of the respective programs to estimate hours of discomfort. In all prototypes, the goal is to provide maximum ventilation cooling as discussed in the methodology section. One limitation of Climate Consultant is the absence of occupancy schedule definition except the general filtering to select months, dates and hours of the year. At the current stage of the study presented in this paper, residence and office prototypes are considered. Other programs including retails and manufacturing spaces will be studied in future work.

Limitation of natural ventilation cooling in different climates can be because of high humidity or high temperature. About 100% of discomfort in the climates of Kuwait, Riyadh and Phoenix is due to high temperature, which is above the adaptive comfort maximum threshold while in Miami, Mumbai and Houston discomfort is due to a combination of high humidity and temperature (See Figure 10).

The distinction between high temperature and high humidity is important in selecting natural ventilation strategies and other complementary active systems when necessary. If the main cause of discomfort is high outdoor temperature the goal of design will be to lower operative temperatures. On the other hand, if the main cause of discomfort is high air humidity the strategy will be to increase physiological cooling by enhancing air movement.

Designing naturally ventilated buildings with thermal mass reduces overheated hours significantly. A comparison of residence prototypes with high and low thermal mass for the selected 20 cities is shown in Figure 11. This allows for daytime ventilation when outdoor temperature is below adaptive comfort's upper threshold. Moreover, when the condition for daytime ventilation is not met, night ventilation will be used to cool thermal mass to a lower temperature during the previous night. With this mode of ventilation, daytime ventilation will not be allowed and the space will be kept in comfort temperature during the day by radiation and convection from the cooled thermal mass.

When acceptable comfort cannot be met with only natural ventilation and thermal mass, a hybrid system shall be considered by integrating mechanical cooling and ventilation. The proposed method gives annual building performance analysis for a given climate by indicating times in the year where conditions are above acceptable maximum thresholds (Figures 12 to 15). Two separate bars report overheated hours and high humidity hours. This in turn can be used to predict the need for active cooling and ventilation to provide comfortable environment.

Figure 12 illustrates analysis with the proposed method for high thermal mass residence prototypes for Kuwait and Miami. Discomfort hours in naturally ventilated space in Kuwait are due to overheating in May through August. In comparison, number of discomfort hours in Miami is a fifth of that of Kuwait and is due to both overheating and high humidity.

Discussion

The method proposed in this manuscript has the benefit of comparing strategies by enhancing indoor air movement, improving envelope properties and adding thermal mass Furthermore, it shows the number of hours when selected strategies such as thermal mass would add to the comfort hours. In the case of climate-file based analysis using building bioclimatic charts the application of all strategies is considered to increase comfort hours in all climates. Nevertheless, simulation based analysis clearly shows that strategies such as improving envelope performance and adding thermal mass do not necessarily contribute to comfort hours in some climates. Hence, the proposed method for an early design aims to guide designers towards reliable decisions by resolving inconsistencies during a design process.

Comparing the six prototypes for residence and office for both occupied and all hours shows that the effectiveness of strategies differs among different climates. The prototypes are combinations of high and low thermal mass for envelope performances of Climate Zones 1(hot), 5(average) and 8(cold) as defined by ASHRAE 90.1 Energy Standard for Buildings. Figure 16 illustrates that designing high performance envelopes with lower U-values in hot climates such as Kuwait, Riyadh, Mumbai, Houston and Phoenix will increase hours of discomfort. However, adding thermal mass in these warm to hot climates will significantly increase comfort hours.

As discussed in the methodology section, using a single zone model for evaluating potential of natural ventilation for cooling by lowering operative temperature as well as providing physiological cooling effect is made possible. This approach allows to account for building envelope properties and internal loads from occupancy, equipment and lighting in contrast to other climate-file based early design tools.

The single zone model used for the proposed method is compared with the energy model of DOE's middle-sized commercial prototype building in Phoenix. The simulations are done using EnergyPlus engine and Archsim, which is a Grasshopper plugin in the 3D CAD working environment called Rhinoceros (https://www.rhino3d.com, http://www.grasshopper3d.com/group/archsim-energy-modeling). The validation analysis has shown that the whole building simulation result is consistent with the proposed method.

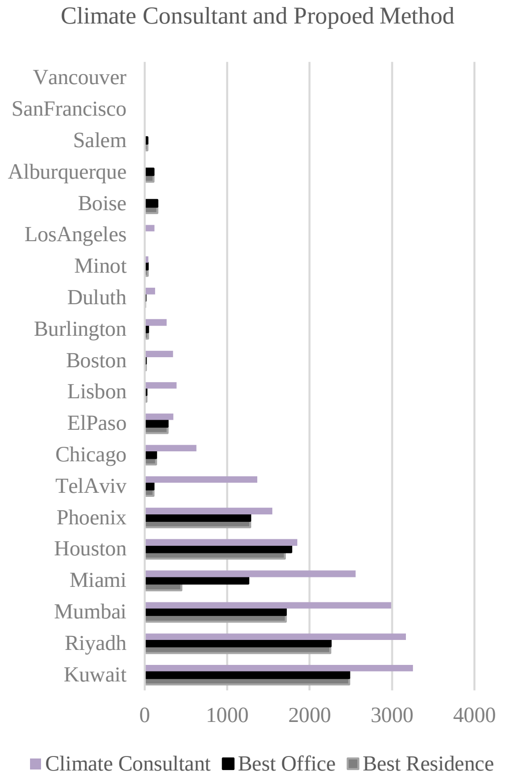

Figure 8:Hours of discomfort due to overheating calculated for all hours of residence and office

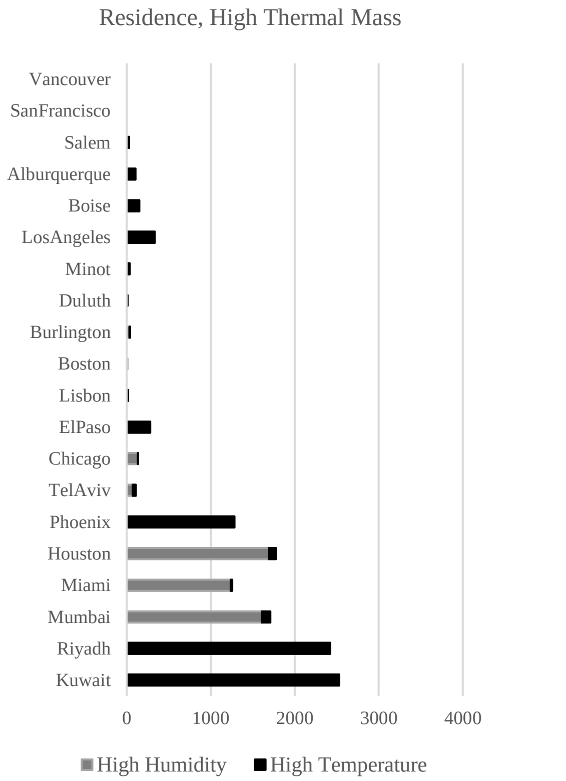

Figure 10: Residence Prototype with average envelope performance and high thermal mass, calculated hours of discomfort.

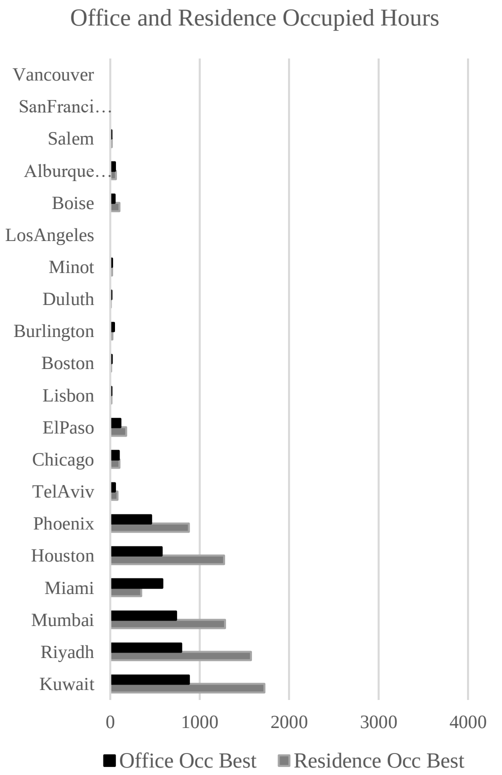

Figure 9: Hours of discomfort due to overheating calculated for occupied hours, for residences and offices

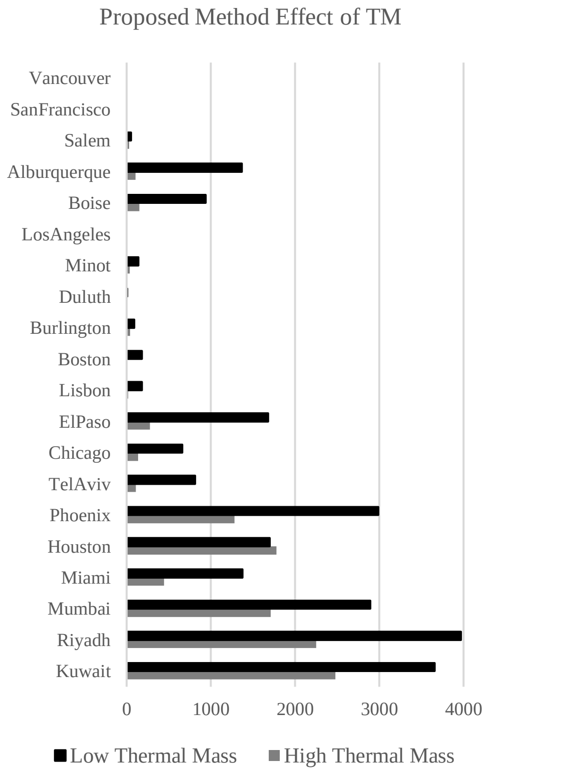

Figure 11: Hours of discomfort due to overheating calculated for residence for all hours to study the effect of thermal mass

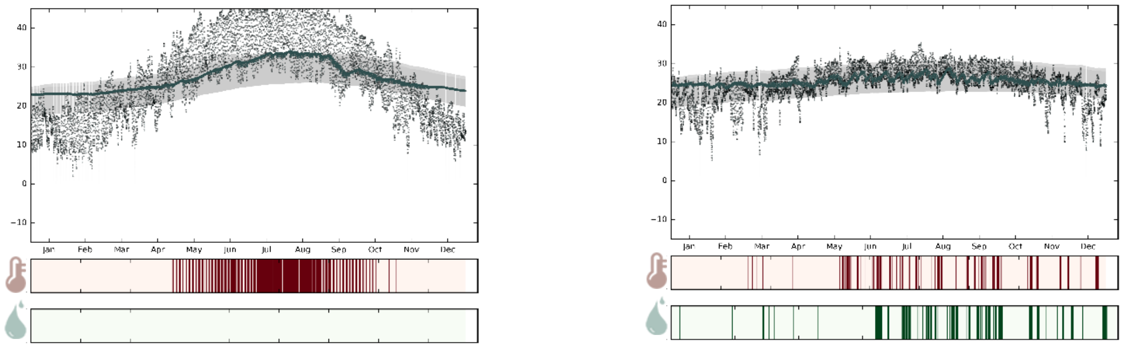

Figure 12: Kuwait (left) and Miami (right) prototypes with high thermal mass

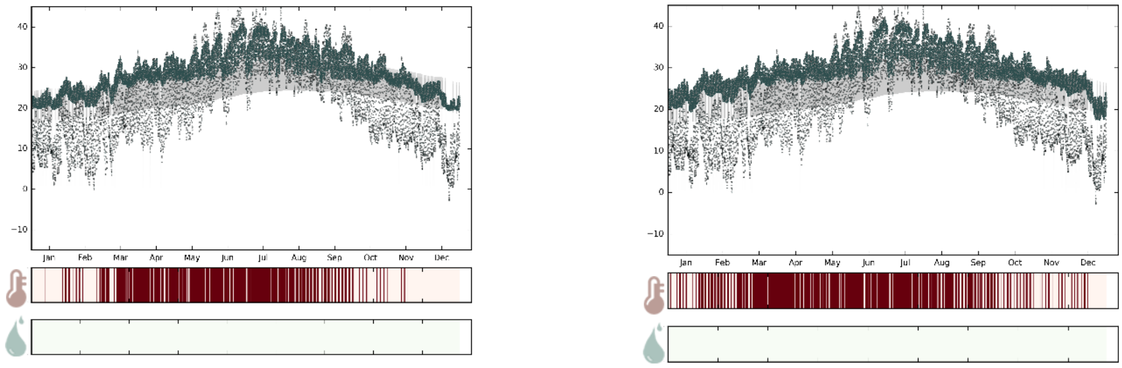

Figure13: Phoenix, residence (left) and office (right) with low thermal mass

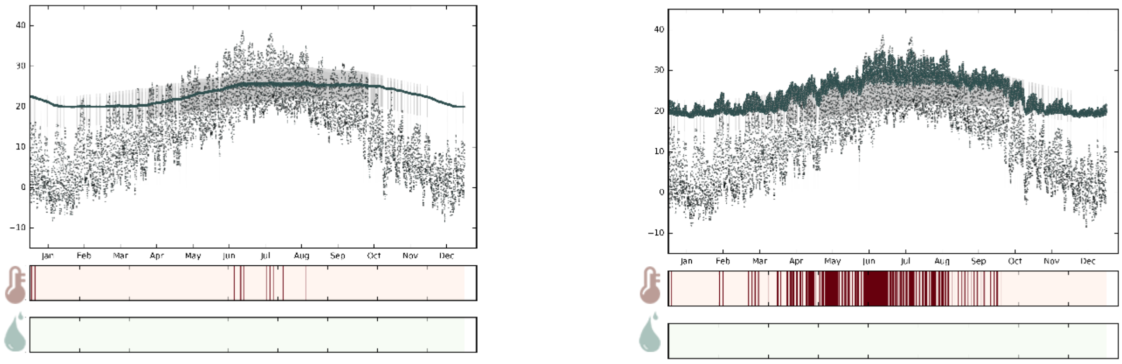

Figure 14: Albuquerque, with high thermal mass (left) and with low thermal mass (right)

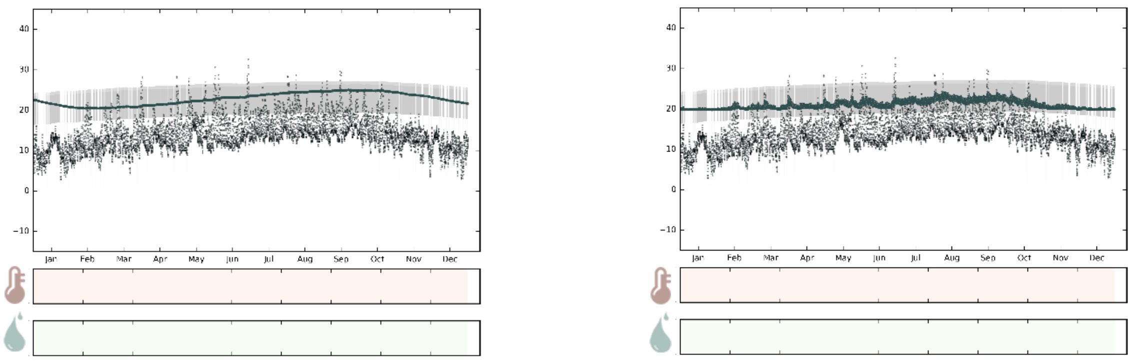

Figure 15: San Francisco, with high thermal mass (left) and with low thermal mass (right)

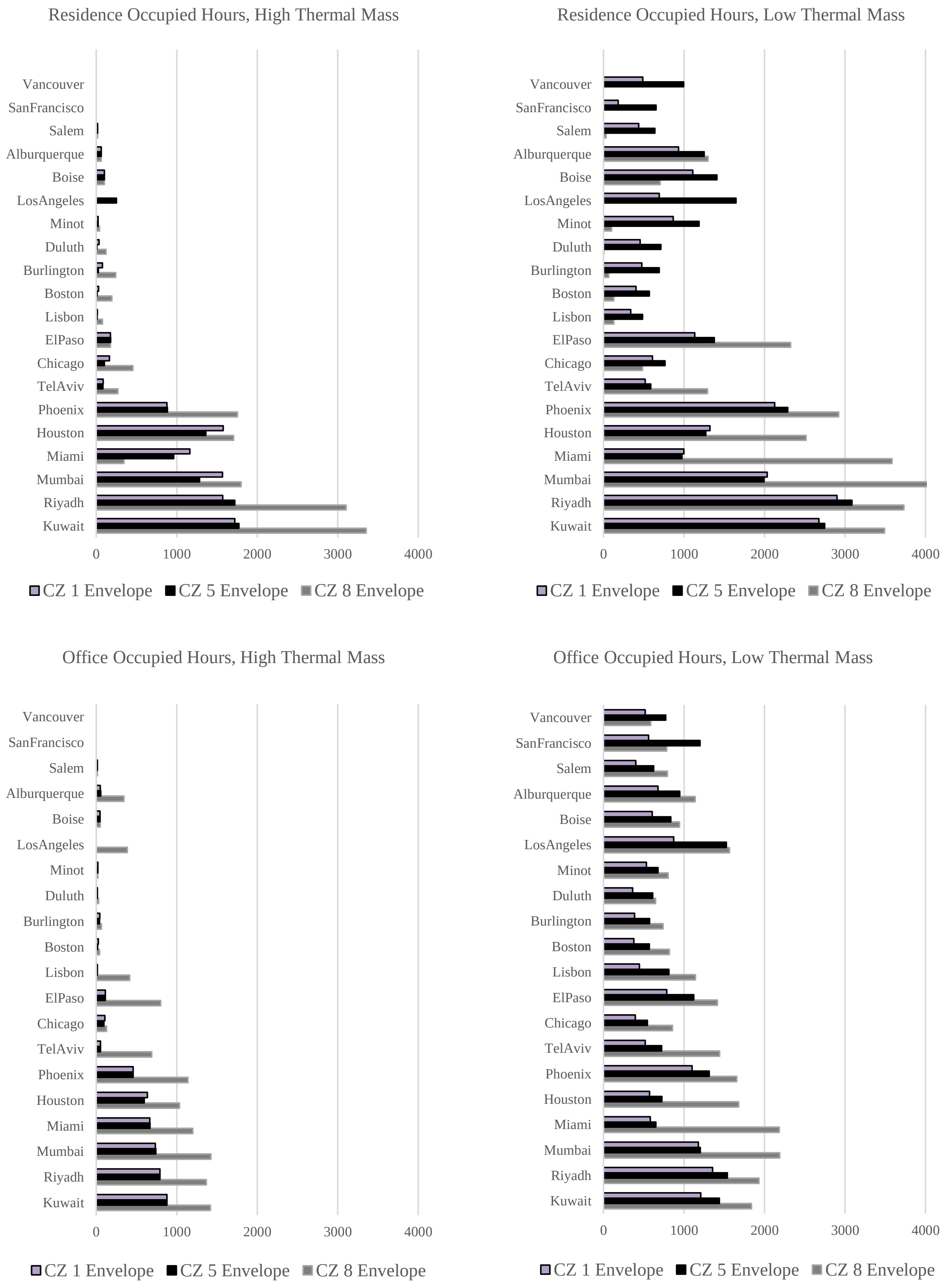

Figure 16: Hours of discomfort due to overheating and high humidity calculated for occupied hours for different envelope performances

Conclusion

The different natural ventilation cooling potential methods currently used during the different phases of a design process of buildings can lead to inconsistent results, especially in cooling and heating dominated climates. This may lead to confusion among design team members and uncertainties whether natural ventilation is actually an option for a particular project. Going forward, the method promoted in this paper is important for steadfast design concept development by giving feedback on the best strategies where natural ventilation will be most effective. Temporal visualizations of comfort indicators inform when in the year selected strategies have achieved thermal comfort. Finally, the capability to analyse different occupancy schedules or all hours of the year helps to customize and optimize design strategies based on intended programs of the project.

Acknowledgement

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