SIMULATING THE FUTURE MICROCLIMATE TO IDENTIFY VULNERABLE BUILDING INTERIOR CONDITIONS

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ABSTRACT
The purpose of this study is to identify indoor environment conditions that influence occupant thermal and visual comforts. Building simulations can predict indoor environmental quality (IEQ), which has a significant impact on building occupants. To evaluate IEQ, simulation input data must accurately account for factors affecting future building operations, such as building design, interior layout, and the near built environment, or microclimate. This study investigates the impact of future microclimate conditions on a “typical” single-occupant office’s indoor environment. Results indicate simply including microclimate in simulation can indicate thermal comfort, but may not provide an accurate picture of visual comfort.

INTRODUCTION
The purpose of this study is to identify indoor environment conditions that influence occupant thermal and visual comforts. The indoor environment is shown to have a significant impact on building occupants (Clements-Croome & Baizhan, 2000; Feige, Wallbaum, Janser, & Windlinger, 2013; Frontczak & Wargocki, 2011; Lee & Brand, 2005). Air contaminants may cause an imbalance in the body. This leads to long-term illnesses by weakening the body’s ability to defend against external changes (Bluyssen, Janssen, van den Brink, & de Kluijzenaar, 2011). Inadequate lighting conditions for screen-based work may lead to difficulty focusing and headaches (Osterhaus, 2005). Noise interruptions can disrupt office communication (Lercher, 1996). High temperatures can increase CO2 levels, which impact human blood flow to the brain, making it difficult for occupants to concentrate on their work (Wyon, 2013). Good indoor environmental quality is a result of buildings that are designed to meet the purpose and needs of the building occupants (Atmaca, Kaynakli, & Yigit, 2007). The indoor environment is a product of the dynamic, complex interactions between climate, urban morphology, and building design. Urban morphology describes both the building and urban properties that define the near built environment, or microclimate. Because of the interrelated nature of these elements, we cannot examine them individually. Instead, any examinations must be done in whole if we want to get a holistic prediction of the future indoor environment.

Building simulations are frequently used to design buildings and evaluate future building operating conditions because they account for these dynamic interrelationships over time. Further, simulations provide information essential to support the building’s purpose, such as predicting energy demand, indoor environment quality, and occupant comfort (Crawley, Hand, Kummert, & Griffith, 2008). However, simulation results are most valuable when they accurately account for the factors affecting future building operating conditions. Factors include physical building characteristics; use patterns; solar radiation; conduction through surfaces; internal gains from occupants, lights, and equipment; infiltration; heating, ventilating, air-conditioning, and refrigeration system operation; thermal inertia of internal mass (furniture and equipment); and microclimate conditions (Frankel & Turner, 2008). Accurate future building operating condition predications can lead to better building designs that serve the purpose and needs of building occupants.

To simulate the interacting factors affecting building operating conditions, two core tools are frequently used: whole-building energy simulation (BES) and computational fluid dynamics (CFD). BES programs obtain space-averaged indoor environmental conditions, cooling/heating loads, and energy consumption on an hourly basis for a period, such as a reference year. CFD programs make detailed predictions of interior conditions, including the distributions of air velocity, temperature, relative humidity, and contaminant concentration. Together, BES and CFD provide complementary information to predict the indoor environment, in terms of thermal and visual comfort, more accurately.

It is common practice in BES to rely on stand-alone building configurations. However, it is well known the urban microclimate strongly affects a building’s operation. Buildings in an urban context experience higher ambient temperatures due to urban heat island effects, different wind flow patterns caused by building placement and form, and increased solar radiation because of high-albedo materials on neighboring surfaces. Therefore, a microclimate model is needed to adapt climate weather data from a
stand-alone meteorological station to realistic site-specific air temperatures. Microclimate models work by simulating the effect of the urban morphology-climate interaction. Interactions include the exchange of energy between building and ground surfaces, airflow around the building based on wind, and the sensible heat flux from building and ground surfaces as a whole.

Future conditions are challenging to predict, and it is even more challenging to predict operating conditions for a building that does not yet exist – for example, a building being designed in a new development where no other structures yet exist. On the other hand, the trend towards more accurate simulation has led to research identifying probable operating circumstances (Burian, McPherson, Brown, Streit, & Turin, 2003). For instance, urban planning describes the context in which individual buildings are constructed, such as building form, building height-to-width ratios, and street orientation (Erell, 2008); (Elmualim, Valle, & Kwauk, 2012). Climate design strategies can provide an understanding of building design as it relates to envelope design, façade materials, and climate mitigation strategies, such as reflective glazed facades and high albedo materials, to radiate, conduct, and convect the climate to produce desired result of building performance (Emmanuel & Fernando, 2007; EPA, 2013; Moonen, Defraeye, Dorer, Blocken, & Carmeliet, 2012; Schuette, DeBaillie, & Ahl, 2014). Further, the tasks occupants perform in the building inform the furniture, equipment, and interior environment conditions required to carry out day-to-day business operations as well as the building systems needed to achieve those operating conditions (Leach, Lobato, Hirsch, Pless, & Torcellini, 2010). This continuing research has enabled more accurate predications than previously available.

This study examines a single-occupant office for the impact of the future microclimate. The goal is to develop an approach to building simulation that more accurately predicts the future indoor environment. First, the future building operating conditions are investigated and identified as an outcome of microclimate interactions. Second, the resulting indoor environment conditions, as an artifact of building design, are evaluated for their effects on human thermal and visual comforts.

**SIMULATION METHODOLOGY**

To assess the indoor environment, this investigation follows a five-step process, outlined in Figure 1:

1. Canyon morphology is defined for a site location in the Near West Side area of Chicago.
2. Microclimate conditions are predicted by combining canyon morphology and future regional weather data in a microclimate model.
3. A single-occupant office is defined within a medium office building typology to serve as a test case.
4. Microclimate conditions, building typology, and the site are simulated using a whole-building energy simulation (BES) to produce time dependent data for an entire future year.
5. BES results are examined in detail using CFD simulation for times where the metrics are outside the comfort zones and have the greatest fluctuation between cases.

![Figure 1 Simulation process](image1)

Four cases are used to evaluate the impact of the future climate on indoor environment conditions. These four cases have been developed to study how inclusion or exclusion of canyon morphology, site information, and microclimate conditions into the simulation produce different predictions. Figure 2 displays the inputs for each case. Case A simulates a medium office building as if it were located in isolation – no microclimate conditions are created – to serve as the baseline for comparison. Case B simulates a medium office building as if it were located in the Near West Side community area. Microclimate conditions are generated, but the site is not included in the BES or CFD simulations. This allows for the evaluation of the microclimate weather effects. Case C, like case B, simulates a medium office building in the Near West Side community area. However, case C includes the surrounding site in the BES and CFD simulations to evaluate their impact on the single-occupant office. Case D is the same as case C except the glazing solar heat gain coefficient is reduced on the opposing building (building #2) to represent a common climate mitigation strategy for the area.

![Figure 2 Simulation Cases](image2)
Canyon morphology

The canyon morphology was identified through observation of the Near West Side community area. The input data are summarized in Table 1, and shown graphically in Figure 3.

Table 1 Building Morphology Data.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>VARIABLE</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building #1</td>
<td>Footprint area</td>
<td>1,661 m² (17,879 ft²)</td>
</tr>
<tr>
<td></td>
<td>Height (H)</td>
<td>11.89m (39 ft)</td>
</tr>
<tr>
<td></td>
<td>Aspect ratio</td>
<td>1.5</td>
</tr>
<tr>
<td>Glazing SHGC</td>
<td>Default</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Case D Blg 2</td>
<td>0.20</td>
</tr>
<tr>
<td>Street canyon</td>
<td>H/W ratio</td>
<td>3:5 or 0.6</td>
</tr>
<tr>
<td></td>
<td>Width (W)</td>
<td>20m (65.6 ft)</td>
</tr>
<tr>
<td></td>
<td>Orientation</td>
<td>East-West</td>
</tr>
<tr>
<td>Brick</td>
<td>Thickness</td>
<td>0.0686m</td>
</tr>
<tr>
<td></td>
<td>Conductivity</td>
<td>0.76 W/m•K</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>2080 kg/m³</td>
</tr>
<tr>
<td></td>
<td>Specific Heat</td>
<td>837 J/kg•K</td>
</tr>
<tr>
<td></td>
<td>Thermal Absorb</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>Albedo</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Visible absorb</td>
<td>0.65</td>
</tr>
</tbody>
</table>

1 Weighted average value for roadway & sidewalk concrete albedo at 95% and sparse vegetation at 5%.

The canyon morphology encompasses both site and building characteristics. Characteristics include street orientation, canyon dimensions, street and building material properties, moisture availability, and anthropogenic heat.

Microclimate conditions

The microclimate conditions are generated by combining the canyon morphology and regional weather for the specific location using the Canyon Air Temperature (CAT) model, created by Ereel and Williamson (2006). The regional weather data for this study uses the future typical meteorological year (FTMY) data for Chicago, Illinois, constructed using the method described by Patton (2013). This method evaluates typical meteorological year (TMY3) data (NREL, 2012) recorded at O’Hare International Airport for total sky cover, dry-bulb temperature, dewpoint temperature, relative humidity, absolute humidity, pressure, and wind speed. A regional climate model (Weather Research & Forecasting Model) was paired with a global climate model (Community Climate System Model) to generate a moderate climate change scenario for Chicago.

Building typology

The Department of Energy’s commercial medium office building typology (Deru et al., 2011) serves as the larger building structure in which a single-occupant office is defined. The single-occupant office is centrally located east to west and along the north wall on the second level. This location was identified, based on results from a previous study, as being the most affected by the surrounding microclimate (Kalvelage, Passe, & Dorneich, 2015). Figure 4 shows a schematic diagram of the single-occupant office.

The office is 3.25 meters (10.66 feet) in the east-west direction by 4.57 meters (15 feet) in the north-south direction with a ceiling height of 2.74 meters (9 feet). A 1.32m (4.33 feet) high fixed storefront window system spans the entire width of the north wall with a 1m (3.28 feet) sill height.

The internal mass consists of furniture and equipment for an office, all gathered from a previous ethnographic study of the office domain. The study, conducted by Kalvelage, Dorneich, and Passe (2015), identified “typical” office tasks and the furniture, equipment, and space layout required for those tasks. These requirements reveal two task areas within the single-occupant office. Area “L” is where the occupant performs a majority of individual tasks, such as taking phone calls and computer work. Area “M” is where group tasks occur, such as small meetings. The remaining components of building systems, operating schedules, and occupant information retain the default settings for the medium office typology.

Whole-building energy simulation (BES)

EnergyPlus (DOE, 2013) was used to conduct whole building energy simulations. (EnergyPlus passed the IEA BESTest (DOE, 2014).) Using microclimate conditions, building typology, and site information, the simulations evaluate thermal comfort and visual comfort. Thermal comfort was evaluated in terms of predicted mean vote (PMV), predicted percentage of
dissatisfied (PPD), and mean radiant temperature (MRT). The PMV is the average thermal sensation response from a larger number of subjects and is the most recognized thermal comfort model. PPD correlates to PMV. However, because comfort is subjective, there will be a distribution of satisfaction among a large group of people. This satisfaction or dissatisfaction is represented by PPD. MRT is related to the amount of radiant heat transferred from a surface and on the receiving material’s ability to absorb or emit heat. Visual comfort was evaluated for glare index and daylight autonomy. Glare index is the degree of discomfort glare. Daylight autonomy is represented as a percentage of annual daytime hours that, at a given point in a space, is above a specified illumination level. Additionally, the results were evaluated to identify time periods when the conditions were the most vulnerable – the metrics are outside the comfort zones and have the greatest fluctuation between cases.

**Computational fluid dynamics (CFD) simulation**

Using the time periods identified by the BES, Autodesk Simulation CFD (2015a) is used to conduct a detailed simulation of the indoor environment. (Simulate CFD has been validated against several known experimental results and empirical hand calculations (Autodesk Inc., 2015b).) Task area L is used as the basis for simulation because the occupant will spend a majority of their time at this location. The results are discussed in terms of thermal comfort (PMV, PPD, and velocity magnitude).

**SIMULATION RESULTS**

The results of the BES provide insight into building occupant thermal and visual comforts for a future simulation year. This study assumed the site and building characteristics remain unchanged during the year, and occupant preferences conform to the standard ranges for thermal and visual comfort.

**Thermal comfort**

Figures 5, 6, and 7 display thermal comfort results for PMV, PPD, and MRT, respectively. The circumference of each figure depicts the reference year from January 1 to December 31. The figures were constructed using the maximum and minimum values for each day. Cases B, C, and D were averaged because there was little variation between each case throughout the year. Case A is shown as a black line and Cases B/C/D are shown in color (PMV green, PPD blue, and MRT red). The gray band indicates the recommended range for the associated metric. The nighttime and weekend temperature setbacks create the peaks and valleys over the course of the year.

**Predicted Mean Vote (PMV)**

The PMV ranges from -3 (cold) to +3 (hot) with a recommended range of -0.5 to +0.5 (shown by the gray band). The BES PMV was never greater than +1, therefore, the chart ranges from -3 to +1. The PMV results (Figure 5) indicate case A is within the recommended range from June to November, and the value for cases B, C, and D is around -2, indicating the occupants are cool. Throughout the year, case B has a 0.01 higher or lower PMV than case D high or low. Case D has a 0.02 higher or lower PMV than case C high or low. From November to June, for all cases, the PMV is on the cold side of the recommended range. Around mid-April, a spike in the PMV occurs. The values change to the hot side of the recommended range.

**Predicted percentage of dissatisfied (PPD)**

The recommended PPD range is to have fewer than 20% of occupants dissatisfied. The BES PPD results (Figure 6) indicate Case A achieves fewer than 20% dissatisfied during the daytime hours. Cases B, C, and D are well below the recommended range from May to October having around 75% of occupants being dissatisfied during the daytime hours. However, the daytime PPD is within the recommended range October through May. Throughout the year, case B averages 1.1% fewer dissatisfied occupants than case D, and case D averages 0.23% fewer dissatisfied than case C. In all cases, April indicates there are very few days where the PPD is lower than 20%, even with the nighttime and weekend setbacks. May through September indicates the largest deviation in PPD with 64% more occupants, on average, being dissatisfied in cases B, C, and D than in case A.

**Mean radiant temperature (MRT)**

There are two recommended ranges for MRT: 20°C to 23°C (68°F to 73.4°F) for winter (heating months) and 22°C to 26°C (71.6°F to 78.8°F) for summer (cooling months). The MRT results (Figure 7) indicate case A follows the recommended ranges over the course of the year. Cases B, C, and D, however, stay on the low end of the ranges. Case B averages 0.09°C (0.16°F) warmer than case D, and case D averages 0.03°C (0.06°F) warmer than case C throughout the year. Again, around mid-April, a peak in the MRT occurs in all cases. Similarly, to PMV and PPD, the greatest deviation in MRT occurs June through September.

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**Figure 5. Predicted mean vote (PMV)**
Visual Comfort

Visual comfort results indicate that at no time during the year, did the glare index exceed comfort levels, and daylight autonomy remained relatively consistent. Figure 8 displays the BES yearly average illumination levels for the single-occupant office as they occur from the interior wall (south wall) to the exterior wall (north wall). The BES results for illumination levels were the same for cases A and B as well as for cases C and D throughout the year. Illumination levels are highest near the exterior wall and lowest near the interior wall. Cases A and C peak around 625 lux within one-half meter of the exterior wall. Cases C and D peak lower at 450 lux, however, the peak location for cases A and B is around 1.5 meters from the exterior wall placing the higher illumination level closer to the center of task area L.

CFD Results

Based on the thermal and visual comfort results from the BES, two specific times, April 18 at 3pm and June 24 at 4pm, were examined in detail using CFD. Case A was selected to examine April 18 as it represents the very basic information commonly used in building simulation. Case D was chosen for comparison using June 24 because this case deviated the most from case A in wall and window surface temperatures, transmitted solar radiation, air node temperature, and air node mass flow rate.

Predicted mean vote. The results of the CFD PMV are shown in Figure 9 for April case A and Figure 10 for June case D with PMV ranges of -1.5 to 1.5. The results for both April and June indicate a warmer PMV than the BES results. The concentration of equipment (task light, computer tower, computer monitor) increases the air temperature around the occupant, increasing the PMV. While the June results indicate a cool PMV for a majority of the office, the occupant in task area L appears to be within the recommended PMV range due to equipment.

Predicted percentage of dissatisfied. The CFD PPD results follow closely with the PMV results. The results are shown in Figure 11 for April case A and Figure 12 for June case D with a PPD range of 0% to 50%. For case A, while most of the office is under 20%, the warmer equipment and exterior wall increase the PPD for the occupant to around 25%. In case D, the BES results indicated more than 60% of occupants were dissatisfied. However, in the CFD PPD results, a majority of the office is between 20% to 30% dissatisfied. Because the PMV results indicated the occupant was on the cooler side, the heat from the equipment keeps the occupant more satisfied. These results indicate the indoor temperature could be set higher to improve thermal conditions.

Velocity magnitude. The velocity magnitude results are shown in Figure 13 for April case A and Figure 14 for June case D. The results depict the air magnitude and direction. The biggest differences between the results are the supply air speed and air movement along the exterior wall. In April, the air supply rate is twice that of June indicating an increased cooling demand in the space. The increased airflow causes the air movement to circulate from floor to ceiling which creates a figure-eight pattern in the space. The air rises along the exterior wall, drops near the center of the room because of the air supply pushing the air down, travels under the small table, and then back up to the return above the door. This movement helps remove
the heat generated by the equipment and occupant as well as creates efficient air circulation. However, the strong downward air velocity can create drafts and cause the occupant to become uncomfortable. In June, the lower supply air velocity is overpowered by the heat from the occupant and equipment causing the air to move from ceiling to floor along the exterior wall. This causes two vortexes to form: 1) located from the air supply to the exterior wall, and 2) located from the air supply to the door. The heat generated from the occupant and equipment is trapped and recirculated in the space near the exterior wall. This reduces the air circulation of the overall office leading to lower air quality levels.

**DISCUSSION**

**Thermal Comfort**

In general, the high number of PPD and the corresponding PMV indicate occupants are too cool in case D and too warm in case A. This is further supported through the CFD results. For case A, the results imply the interior cooling temperature should be decreased as well as moving the occupant to be located more under the supply air. However, a decrease in temperature increases cooling energy demand. CFD results for June case D indicate the office is too cold. However, the interior temperature may be appropriate if the occupant is working near heat generating equipment, but inappropriate if the occupant was having a small meeting. An increase in
cooling temperature, in turn, would decrease building cooling energy demand. The winter interior temperature, on the other hand, may be set too low in all cases. The PMV, PPD, and MRT results are below the recommended range, and an increased interior temperature could improve thermal conditions. Again, an increased heating temperature could result in increased building heating energy demand.

The mid-April peak in PMV, PPD, and MRT, for all cases, suggests direct solar gain on the office. However, lack of the same effect in mid-October indicates it is more likely this is an anomaly in climate conditions, even though the PPD improves.

Visual Comfort

Visual comfort results remain relatively consistent across all cases when comparing day-to-day. Over the course of the year, however, the change in sun angle does affect the office visual comfort differently between cases. First, visual comfort results for case B now more closely follow case A. This indicates the addition of the second building in cases C and D in the BES affects visual comfort, but not thermal comfort.

Second, while the illumination levels are well below the recommended 1076-lux (100 footcandles) for office work, in cases C and D, less detailed tasks could still be performed in task area L. A reexamination into the office layout to position work surfaces within these higher illumination levels could decrease electric lighting needs without having the occupant being positioned directly next to the exterior wall, which could negatively impact the thermal comfort.

The addition of the second building in cases C and D blocks some of the summer sun reducing the amount of direct solar radiation. In winter months, the lower sun would cause radiation to reflect off the second building and into the office as a more diffuse light. The visual comfort results indicate the glare index comfort levels were never exceeded. However, glare is subjective and dependent on the sun’s angle, material properties, and occupant's position and perception. The limitations of the BES and microclimate model also influence the results. Solar radiation handling may have been diffuse rather than direct. The defined index points do not account for occupant behavior – the occupant is likely to move about the space, change eye level, and change body position.

CONCLUSION

The purpose of this study was to identify vulnerable indoor environment conditions that influence occupant thermal and visual comfort depending on factors of microclimate, urban planning, building design, and building occupant tasks. Thermal comfort was evaluated in terms of predicted mean vote (PMV), percentage of predicted dissatisfied (PPD), and mean radiant temperature (MRT). Visual comfort was evaluated for glare index and daylight autonomy.

The major findings from this study suggest simply simulating the future microclimate may aid in predicting thermal comfort, but falls short of predicting accurate future visual comfort. For this climate, the addition of the second building appears to have more of an impact in visual comfort results than the second building’s material properties. Additionally, while results indicate an improvement in occupant visual comfort, a significant deterioration in thermal comfort occurs - all of which have important implications for occupant health and well-being.

Future work includes a more detailed examination of occupant behavior for a more detailed input relating to occupant preferences and perceptions. The methodology presented in this paper will also be used to identify building control strategies and equipment to account for future vulnerable interior conditions, such as sensors and window shades. Additionally, the coupling of BES and CFD models will allow a more accurate picture of the comfort levels throughout the year.

REFERENCES


Autodesk Inc. (2015a). Simulation CFD (Version 15.1) [Computer program].


