DIRECT SUN AND OCCUPANT COMFORT

Practical applications of the CBE SolarCal Method in the design process

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ABSTRACT

Direct sun on the body is a known potential cause of thermal discomfort for occupants, yet most thermal comfort simulations do not capture its effects, because the simulations run on engines that account for the effects of solar radiation on a space, but not the occupant within that space. The Center for the Built Environment (CBE) recently published a solar calculator (SolarCal) that establishes parameters to calculate the solar adjustment in mean radiant temperature (MRT) due to short-wave solar radiation on the body (dMRT). The SolarCal methodology accounts for the combined effect of the direct beam solar, diffuse solar from the sky, and reflected solar from surrounding surfaces. When integrated with existing thermal comfort analysis workflows, CBE's calculations help paint a more accurate picture of the occupant thermal environment, which in turn helps set reasonable client expectations and influences building design development.

This study evaluates two thermal comfort analysis approaches that integrate dMRT calculations using the SolarCal model into existing thermal analysis workflows in practice. Each method was created for and applicable to different projects at different stages of design. The first approach is spreadsheet based, combining simulation results from an EnergyPlus model, epw data, spatial approximations, and Python scripting, to calculate annual hourly adjustments to hourly operative temperature. This approach is appropriate for early concept calculations and assists in setting reasonable client expectations and guides façade design. The second uses solar Radiance software simulations to account for complex geometry and sophisticated spatial conditions. The Radiance simulation approach proposed collapses the calculations established by SolarCal by simulating the incident radiation on a body. This approach accommodates more developed spaces and shading systems, which are regularly encountered in later design phases of a project. Both approaches account for the influence of direct sun on the human body, allowing this dynamic aspect of the thermal environment to become a performance metric that influences design decision making.

KEYWORDS

health - comfort – IEQ, design processes, parametric workflows, future trends, thermal comfort, solar radiation, radiance

INTRODUCTION

As energy performance requirements for today's buildings become more stringent, design teams increasingly turn to passive design strategies and mixed-mode systems to maintain thermal comfort conditions in a space. And in buildings where mechanical systems do less, the design must do more; the construction and operability of the building envelope, as well as space planning and building program are interconnected and have direct impact on occupant thermal comfort. Buildings are more energy efficient through climate responsiveness, and the public's attitude toward hermetically sealed, thermally consistent spaces is becoming less positive. In response to this shift, environmental designers must quickly advance thermal comfort analysis methods to more accurately reflect the nature of the occupants' thermal environment, rather than using these types of analyses as a means to the end of establishing mechanical system setpoints or guaranteeing constant thermal comfort conditions.

Thermal comfort simulations common in current practice center on operative temperature outputs from energy models at zone level resolution. These outputs are then measured against established thermal comfort or acceptability standards, such as ASHRAE-55 PMV or Adaptive Comfort models. When climate-based, this type of analysis can accurately depict general thermal conditions of the space, such as the effects of solar radiation on surface and mean radiant temperature (MRT), but will not capture other key factors that influence the occupants' thermal environment. A body in direct sun, for example, will experience a change in mean radiant temperature (dMRT) and will experience thermal sensations ranging from alliesthesial delight to severe discomfort. The thermal potential of a space is an important design driver; accurate analysis methods and tools for all stages of design are critical to creating buildings that prioritize thermal autonomy and occupant comfort.

Two analysis methods, presented here, were developed and integrated into existing thermal comfort simulation workflows to account for the effects of dMRT due to direct sun. The methods were developed in response to project-specific requirements, concurrent with the schematic and design development phases. In the first project, a tech office space with an exposed multi-story atrium, spatial conditions were similar across the floorplate. The dMRT analysis during the concept through design development phases helped set and maintain reasonable design team and client expectations, as well as inform façade construction and operability, programming, and building management system operation. The second project, a dining hall, is unlike the first project, that is consistent in solar exposure. The complexity in the shading and geometry of the dining hall space required a grid-based approach to calculating direct sun across the floorplate. Architectural and spatial changes were driven by the variation in comfort conditions across the space. The analysis methods were developed in response to specific project requirements, space and program types, but either approach is applicable to a variety of projects to better understand thermally dynamic spaces.

BACKGROUND

Thermal comfort is an extensively studied and regulated area of building design, but there are still factors that affect thermal comfort that are only now being incorporated into technical standards (ASHRAE, 2013). The six factors—radiant temperature, air temperature, airflow, humidity, metabolism, and clothing—that affect thermal comfort can be used to calculate whether an individual will be statistically likely to be comfortable in a space (Levitt, 2013). The ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy establishes the acceptable ranges occupants will be exposed to for both PMV/PPD and Adaptive models. Because an individual's direct solar exposure changes the perceived mean radiant temperature, an occupant in direct sun may be uncomfortable or experience other thermal comfort factors differently. The Center for the Built Environment at UC Berkeley has quantified this effect in a public online tool and published paper (Arens, 2015).

The CBE paper describes an approach to modeling the change in MRT due to direct solar radiation based on solar conditions, simplified space geometry, and body properties (Arens, 2015). The paper uses "effective radiant field (ERF), a measure of the net radiant energy flux to or from the human body" to calculate the change in MRT. The solar ERF is roughly equal to the total solar radiation on the body, modified by the emissivity/absorptivity of the body. The solar radiant flux on the body (in W/m^2) is equal to the sum of the direct beam solar, diffuse solar from the sky, and reflected solar from surrounding surfaces. The CBE methodology uses separate formulas to calculate each of these solar components based on:

- Direct beam solar: projected body area, total body area, fraction of body exposed to sun, direct beam (normal) solar radiation, glazing properties
- Diffuse sky: sky vault view factor, climatological diffuse sky irradiance, glazing properties, body exposure
- Reflected solar: floor reflectance, sky view factor, glazing properties, horizontal direct and diffuse irradiance, body exposure

The CBE published online tool makes this approach to calculating dMRT widely available. The tool does not provide a visualization of spatial inputs and allows for singular point in time calculations. The graphical user interface and associated inputs are shown in Figure 1.

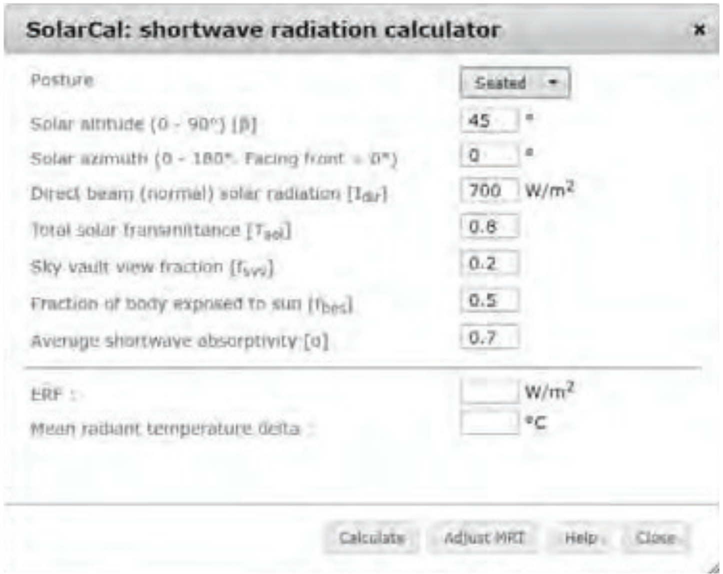

Figure 1: CBE dMRT Comfort Calculator available at http://comfort.cbe.berkeley.edu/.

Comfort standards are still catching up to current research and requirements related to occupant based metrics such as effect of direct solar gain are slowly being incorporated. The approach to calculate dMRT proposed by the CBE has now been included in ASHRAE 55 via an addendum (ASHRAE, 2016).

METHODS

Two thermal comfort analysis methods were developed for spaces with varying complexity and different phases of design. The first method was applied to a space consistent in section, where solar exposure and shading conditions did not vary substantially throughout the floorplate. The second method was applied to a space with complex shading that resulted in varied solar exposure across the floorplate. The two methods are described below.

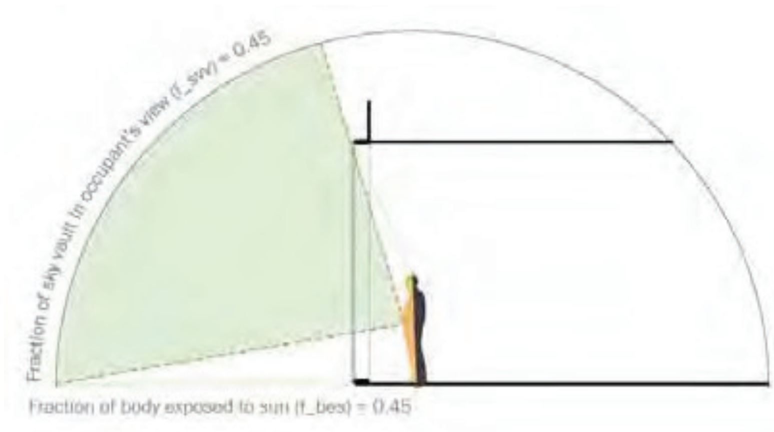

Figure 2: Section diagrams illustrating potential spatial conditions appropriate for Method 1.

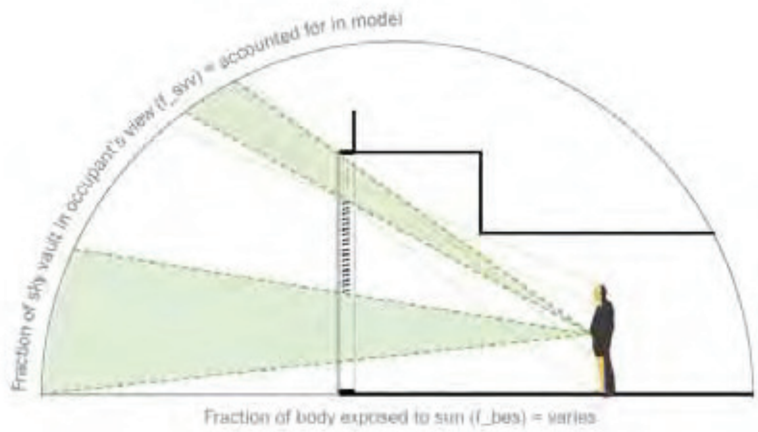

Figure 3: Section diagrams illustrating possible spatial conditions appropriate for Method 2.

METHOD 1 – SPREADSHEET BASED CALCULATION

This approach was developed to evaluate occupant thermal conditions in a multi-story, south and west facing, fully glazed atrium in San Francisco, California. The atrium space is highlighted Figure 5 and Figure 6. The approach is useful to determine a general "worst case" scenario of the heating effect of direct sun on a body in space, where the body remains in one position relative to glazing and is constantly exposed to direct sun throughout the year. Method 1 is an Excel based implementation of the SolarCal method described by Arens et al, assuming several inputs as constant to obtain dMRT results for each hour of the year.

Annual hourly air and operative temperature results output by an EnergyPlus model at the zone level for each floor of the atrium space were used in conjunction with typical climate data as well as spatial assumptions and material assumptions to determine each variable required to perform the SolarCal equations (Arens, 2013). Climate data that is available in .epw files and relevant to the SolarCal equations include direct solar beam intensity, diffuse solar intensity and total horizontal intensity. The consistent geometry of the space allowed for simplified assumptions to be made as to surface area and length of exposure of a body in space to direct sun; the body was assumed to be always in sun, standing facing a floor to ceiling glass wall running the length of the space (see Figure 3 for section diagram of spatial assumptions).

METHOD 2 – RADIANCE SIMULATION BASED CALCULATION

This approach uses Radiance solar radiation simulation results as the inputs for the direct solar comfort calculations, to accurately account for complicated external geometry or other factors that may affect incident radiation. The dMRT simulation approach proposed collapses the fraction of body exposed to sun, direct beam (normal) solar radiation calculations into the simulation and accounts for complicated room and opening geometry by simulating the incident radiation on an approximation of a body. By using a series of points, the amount of direct and diffuse & reflected solar radiation falling on the body can be calculated separately. This automatically accounts for the fraction of body exposed to sun and sky view factor instead of using approximated values. The simulation approach allows for complicated spaces and shading, which is encountered regularly in environmental design work.

This simulation approach was combined in a grasshopper script and uses six points to approximate a body. The six-point body simplification was used to calculate the annual hourly incident radiation in different locations throughout a space. This accounts for partial shading by averaging the incident radiation on different points. The simulated direct beam solar radiation on these points is used to calculate the direct beam contribution, while the diffuse and indirect radiation are combined in another simulation. The direct solar radiation values are used in lieu of the value for incident radiation value in the direct contribution calculation in the CBE method, eliminating the need for the shading coefficient/skyview factor calculation and fraction of body exposed to sun. Because this only determines the weighted intensity of radiation, the project area of the body based on the Fanger method is still necessary to determine the total increase in MRT due to radiation based on altitude and azimuth. The direct and diffuse radiation are separately integrated into the calculation. The entire workflow was integrated into a python script that included calculated incident radiation, sun position, glazing properties, body posture, and body characteristics as inputs. Following the methodology outlined by the CBE, the script calculates the anticipated change in mean radiant temperature.

This method was applied to a dining facility with a large south facing glazed wall. The solar and sky vault exposure was different throughout the space and could not be approximated by a single value used in the Method 1 spreadsheet calculation. In addition, various shading options were under consideration and changed the solar exposure significantly. The Radiance simulation in Method 2 allowed a more accurate assessment of the direct sunlight and potential discomfort in the space.

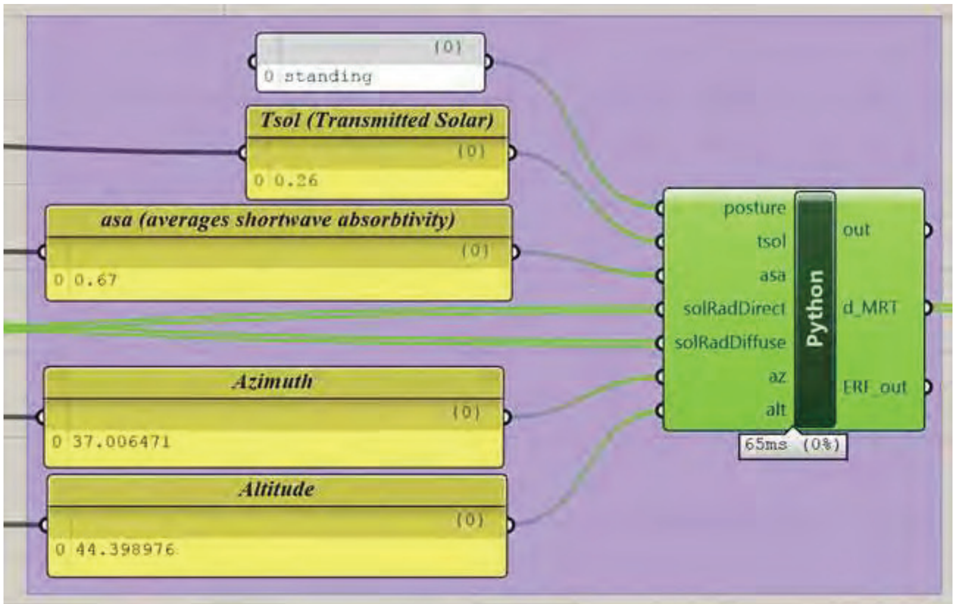

Figure 4: Python script implementation of SolarCal in Grasshopper for Rhino.

RESULTS & EXPLANATION

METHOD 1

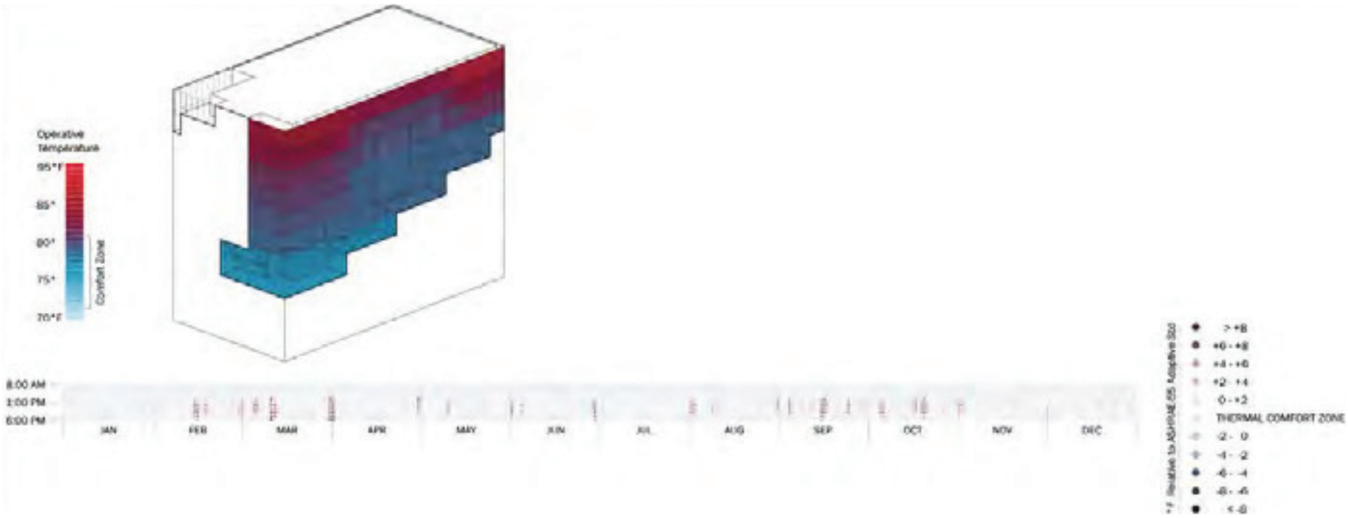

Figure 5: Top - Axonometric showing zone level operative temperatures for a point in time. Bottom - Annual hourly operative temperature results for top level.

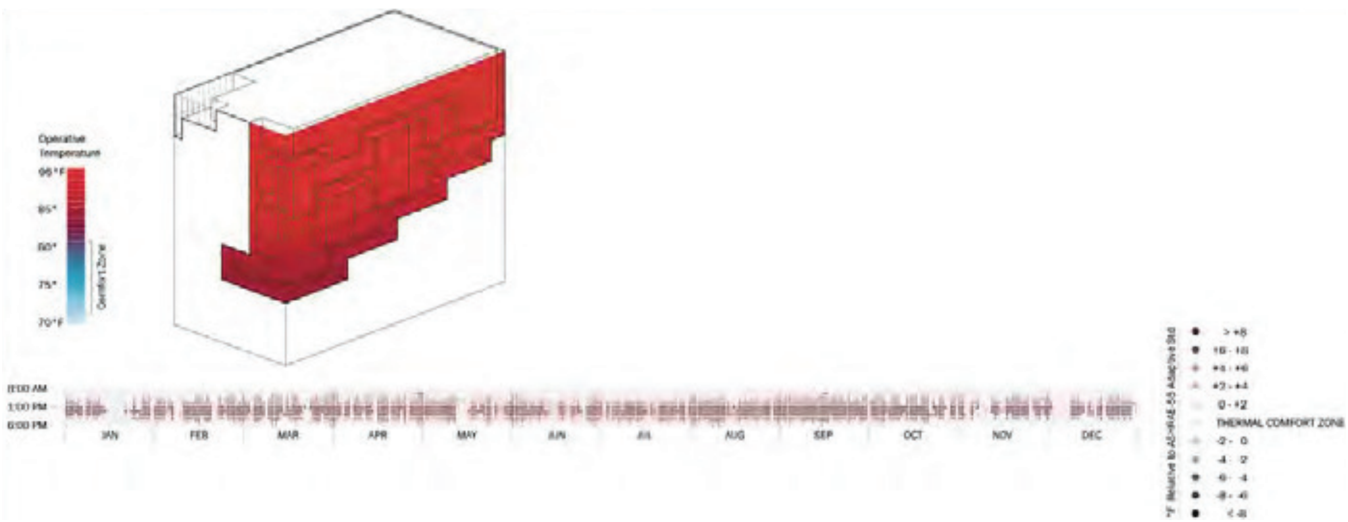

Figure 6: Top - Axonometric showing zone level operative temperatures for a point in time accounting for dMRT. Bottom - Annual hourly operative temperature results for top level, post-processed using the SolarCal method to account for dMRT.

The axonometric diagrams in Figures 5 and 6 show operative temperatures for a single point in time in a multistory atrium space at different levels. The graph Figure 5 shows the annual hourly operative temperatures as they are output from the uppermost level zone of the EnergyPlus model for the volume shown in the diagram, plotted relative to ASHRAE-55 Adaptive Model 80% Acceptability limits. The annual hourly graph in Figure 5 shows operative temperatures in the uppermost zone exceeding 80% acceptability limits for a total of 762 annual occupied hours. 48 of those hours exceed acceptability limits by 8 °F or more. Figure 6 shows annual hourly operative temperatures that account for dMRT, calculated using Method 1 for the same zone, to show the potential thermal effects on an occupant in the zone. These post-processed results show 2734 annual occupied hours exceed acceptability limits and 1226 exceed acceptability limits by 8 °F or more.

Method 1 uses simulated zone temperature outputs as a proxy for a body in space. The unprocessed temperature outputs from the EnergyPlus model (Fig. 5) show results for a zone, where the effects of direct solar radiation are accounted for to determine surface temperatures, thus MRT. Without applying SolarCal modifications, zone operative temperatures may be used as a proxy for occupant operative temperatures only if the occupant is assumed to be constantly in shade. Postprocessing the temperature outputs with SolarCal equations using Method 1 (Fig. 6) assumes that body is constantly in sun. The comparison of the two sets of results Figures 5 and 6 show he impact of providing effective exterior shading: an improvement in comfort conditions of nearly 2000 hours or half of annual occupied time. Comparing these images, it is clear that including the effects of direct solar gain on occupants in the space gives a much different result, and leads to different design decisions to mitigate potential thermal discomfort.

METHOD 2

Method Two, applied to a dining facility with a large glazed southwest facing façade with a large roof overhang and an additional trellis above head height, shows the variation in comfort across the floorplate due to sun position. Multiple points in time were selected to show the change in discomfort due to direct sun within the space.

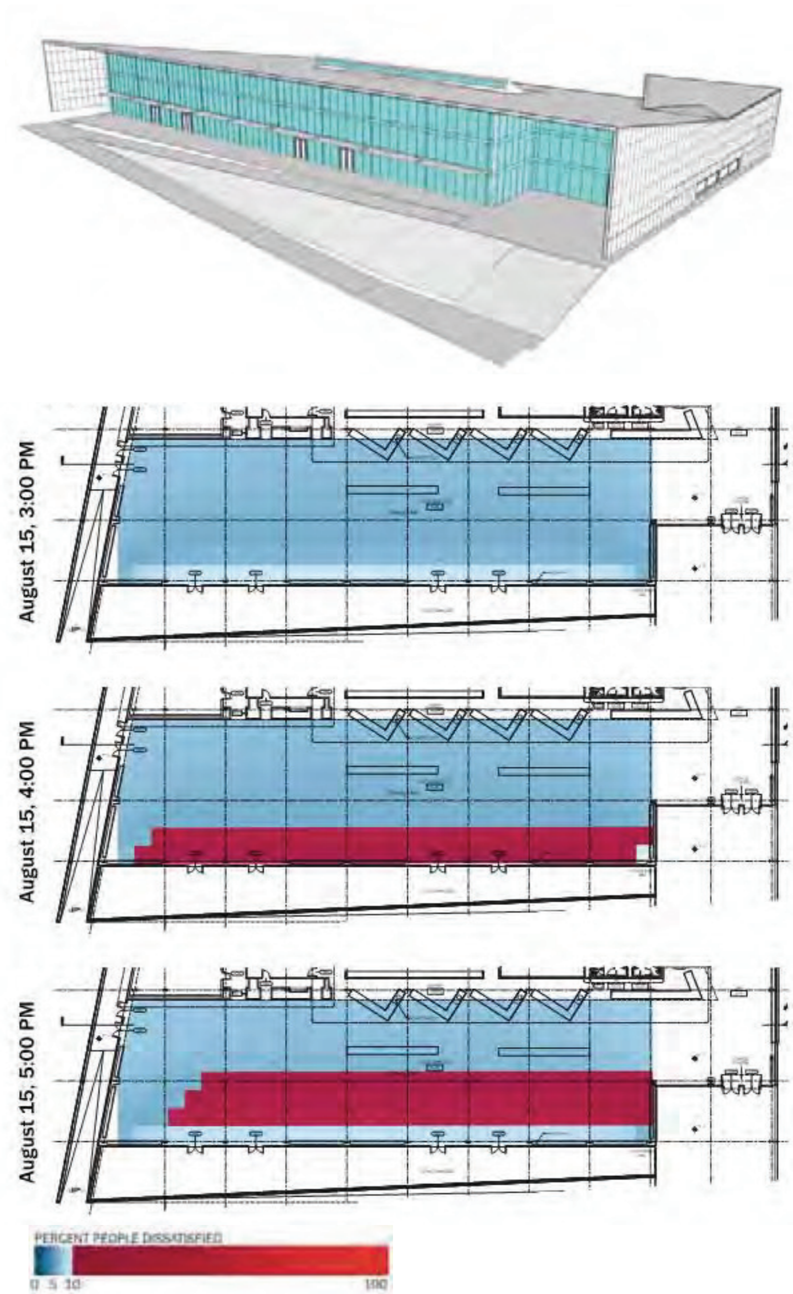

Figure 7: Top - Axonometric showing dining hall space in Method 2 Analysis. Bottom – Plan diagrams showing change in MRT across the floorplate at multiple points in time.

Method 2 captures variation in solar exposure across the floorplate. Figure 7 shows the effect on an occupant's comfort of a large external overhang and an additional horizontal shade part of the way up the glazed façade. The deep overhang protects the area deeper within the façade, while the lower shade creates a protected band adjacent to the glazing. Direct light still reaches the remainder of the floor, causing increased radiant temperatures, although this can be mitigated with additional external shading or by deploying internal blinds that block the direct sunlight.

CONCLUSION AND FUTURE WORK

The results emphasize the importance of solar radiation control methods, especially external shading and localized controls. The results derived from both approaches to calculating potential discomfort due to solar radiation were instrumental in explaining to clients, including architects and building owners, the importance of an effective solar control strategy for the first project using Method 1. The hourly charts showing hours when occupants would be comfortable with and without the presence of direct light galvanized the design team to create innovative solutions to shading due to the magnitude in improvement. Similarly, the second project maintained the glazed wall with its important views, but understood the frequency and extent of blind deployment.

Each method of calculating the change in mean radiant temperature due to solar radiation is a reasonable means of more accurately assessing an occupants thermal environment, but they should be applied with discretion depending upon architectural geometry and complexity. The spreadsheet method is appropriate for assessing the effect of direct solar radiation on thermal comfort in spaces without complex geometry and with uniform solar exposure throughout the year. The spreadsheet approach in Method 1 is sufficient to calculate dMRT as long as diffuse radiation, direct radiation, solar position, anticipated exposure information can be calculated quickly and is the less time-consuming method. In contrast, for spaces with more complex geometry, the simulation approach in Method 2 accurately describes variation in mean radiation temperature for multiple points within that space.

While the Method 1 approach shows results for an abstracted point in a zone throughout the year and Method 2 shows a grid applied to a space at a single point in time, a third grid and time-based metric could be developed to show potential discomfort across both time and space. Using the simulation method, annual hourly comfort results for all points in a grid could be determined. This would result in a metric similar to spatial daylight autonomy or other annual daylighting metrics and could show hours of discomfort or percent of occupied hours that fall within the comfort range.

Additional future work includes exploring the use of a simplified geometric human model for calculating radiation on a body. This would collapse the three radiation component calculations into a single simulation. This approach would remove the Fanger body projection approach, increasing the accuracy of the calculation. The Method 2 simulation approach only simplifies determining shading on a body for annual hourly incident radiation values. Using a mannequin approach would further simplify the calculations by combining all three radiation sources and would more accurately account for uneven radiation distribution on the body. Further research is required on determining an accurate body simplification and validating this approach against the CBE comfort tool.

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