Integrated Design of Building Envelope and Mechanical Systems for Occupant Thermal Comfort through Building Simulation

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Abstract

The highly glazed building envelope currently dominates building design in the industry. While this provides better views and daylighting, the increased solar radiation can be problematic for occupant thermal comfort. This paper examined the peak operative temperature, peak solar gain, and exceedance hours as quantitative thermal comfort metrics to assist decision-making at the design stage. Using a highly glazed and densely occupied atrium as a case study, an occupant thermal comfort design workflow was developed for engineering practice using long-term building simulations. The integrated design approach in building envelope and mechanical system strategies helped achieve a design solution which reduced the number of exceedance hours in dissatisfied zones by 70-95%.

Introduction

Since the rise in popularity of highly glazed building designs, it has become common practice for building owners and designers to pursue almost entirely glazed exterior building enclosures in high-rise new constructions. The benefits of natural daylight and accessibility of views by use of extensive glazing come at the cost of higher heat transfer across the building envelope and increased discomfort from direct sunlight exposure (ASHRAE, 2019). Though mechanical systems are often designed to maintain the space air temperature and humidity within a comfortable range, the effects of direct solar radiation on the occupant's thermal comfort are often neglected (Arens et al., 2015). ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy is sometimes used for thermal comfort analysis during design. However, the design-day conditions (for cooling and heating) used in the approach do not reflect the dynamic operating conditions of the building and often do not represent the worst-case scenario with solar radiation considered. There is currently no standardized approach to optimizing building designs for thermal comfort with the help of building simulation. Therefore, it is critical to create a quantitative evaluation methodology and set up an integrated design decision-making workflow to solve the thermal comfort design problem in practice using building simulation.

In this paper, a highly glazed office tower atrium design (160 Front Street West in Toronto, Ontario) is used as a case study (Figure 1). Thermal discomfort during the summer season is recognized in the Base Design. An exceedance hours (EH) metric has been created to quantitatively evaluate the summer period thermal discomfort when solar radiation is problematic. Different strategies were explored to improve thermal comfort using long-term building simulation. Through an integrated design process with the architectural and mechanical designers, design options are narrowed down and culminated in an optimized design.

Figure 1: Northeast view of the highly glazed office tower with the atrium amenity space used in this study.

Methodology

Thermal Comfort

To improve the building's thermal comfort, the criteria used to quantify thermal comfort must first be established. In common practice, the Graphic Comfort Zone (GCZ) Method of Section 5.3.1. of ASHRAE Standard 55 is used to determine the acceptable thermal comfort zone based on the operative temperature (t_o). Where t_o is the average of the dry-bulb air temperature (t_a) and the mean radiant temperature ($\bar{t}_r$). Standard 55-2013 allowed t_a to be used in place of t_o when certain common conditions are met (ASHRAE, 2013a). However, since the 2017 revision of Standard 55, this substitution option no longer available under Normative Appendix A.

The use of the Section 5.3.2. Analytical Comfort Zone (ACZ) Method is now required in place of the GCZ Method in spaces where direct-beam solar radiation (I_{dir}) is involved since the approval of Addendum G in 2016 for Standard 55-2013 (ASHRAE, 2017c). The Effective Radiant Field calculation method developed by Arens et al. (2015) accounts for the impact of I_{dir} and is required to be factored

into the mean radiant temperature $\bar{t}_r$ calculation in the ACZ Method. This adjustment can significantly increase t_o. Therefore, in a highly glazed space, it is expected that maintaining a lower dry-bulb temperature t_a needs to be considered to offset the space thermal discomfort due to I_{dir}.

The ACZ Method also requires the use of the computer code in Normative Appendix B to calculate values of the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). Compliance using this method is achieved if the PMV is within ±0.5, which corresponds to a PPD of 10% (i.e. 10% of the people within the space would be thermally dissatisfied) (ASHRAE, 2017a; International Organisation for Standardisation, 2015).

To simplify the PMV thermal comfort criteria definition, the Centre for the Built Environment (CBE) Thermal Comfort Tool, a web-based tool developed by University of California at Berkeley, can be used to determine the acceptable comfort zone (Hoyt et al. 2019). The tool has been proven to produce the same results as the calculation procedure outlined by Standard 55 and is listed as an acceptable method in Addendum G (d'Ambrosio Alfano et al.; ASHRAE, 2017c). A case study by Luo, O'Sullivan, and Jackson (2018) also testified that it is sufficient to use the comfort threshold setup by this tool, the zonal averaged mean radiant temperature, and the relative humidity from Integrated Environmental Solutions Virtual Environment (IESVE) simulation results to evaluate thermal comfort.

Defining Acceptable Thermal Comfort Criteria

In this case study, the CBE Thermal Comfort Tool is used to help establish the acceptable thermal comfort criteria. As a conservative estimate, the occupant metabolic rate and clothing level is set to 1.2 (standing relaxed) and 0.59 (long sleeve shirt or light suits) respectively. The average air speed (v_a) is assumed to be 0.1m/s, since v_a rarely exceeds 0.2m/s in typical applications (ASHRAE, 2017c). The CBE Thermal Comfort Tool highlights the range that t_o for relative humidity of 50% should be within the range of 22.4°C and 25.9°C to maintain the zone PMV within ±0.5 as shown in Figure 2. This is consistent with the recommended summer comfort criterion of maintaining with ±1K of the 21-25°C t_o range for an office space type in CIBSE Guide A Table 1.5 (The Chartered Institution of Building Services Engineers, 2015).

However, the 25.9°C absolute maximum t_o threshold from the PMV method is not always suitable for use in simulation-assisted design. Standard 55 Section 6 outlines the compliance requirements during the design phase, which specifies that the design-day outdoor conditions from ASHRAE Standard 169-2013 Climatic Data for Building Design Standards to be used to determine the acceptable comfort zone based on PMV (ASHRAE, 2013b; ASHRAE, 2009; ASHRAE, 2017c). These design conditions differ from worst-case scenarios in the Canadian Weather Year for Energy Calculation (CWEC) weather data typically used in building simulations which take the highest solar gain into account. If the PMV criteria is used throughout the CWEC weather year, it encourages the mechanical system to be unnecessarily oversized. Therefore, it is not practical to apply the exact same compliance method in long-term simulations to guide the thermal comfort design.

Instead, the metrics: peak operative temperature ($t_{o,max}$) – the maximum t_o during occupied hours, peak solar gain ($Q_{b,max}$) – the maximum heat gain in the zone due to I_{dir} at the peak operative temperature, and the exceedance hours (EH) – the number of hours during where t_o exceeds the 25.9°C comfort zone threshold, are used to quantitatively evaluate thermal comfort for the design process. Based on CIBSE TM52's guidance, which limits the maximum EH to 3% of total occupied hours from May through September (Nicol and Spires, 2013), the design team determined that an EH limit of 100 hours for each zone from June 1st to August 31st should be the key acceptance criterion.

Defining the maximum EH provides a specific and constant key acceptance target for the design process which then allows the design team to take advantage of the ability of building simulation programs such as IESVE to easily quantify thermal comfort metrics. Using IESVE simulations, the t_o at the centre of each modelled zone is calculated at 10-minute intervals as the variable called dry resultant temperature. The VistaPro application within IESVE is also used to determine the date and time when the $t_{o,max}$ and $Q_{b,max}$ occur, as well as the EH found in each zone.

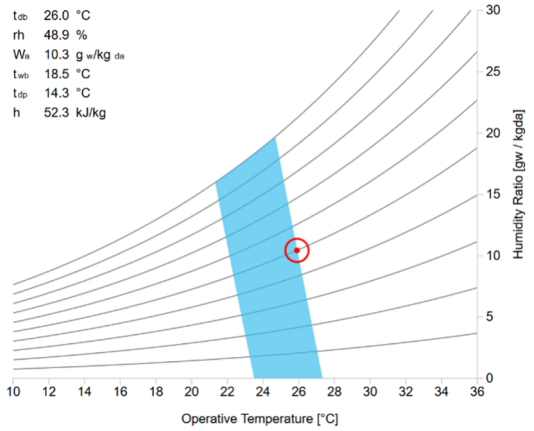

Figure 2: Acceptable thermal comfort zone as calculated using CBE Thermal Comfort tool.

Thermal Comfort Analysis Workflow

This study attempts to setup an effective workflow in practice to dramatically reduce the number of simulations necessary to find an optimal solution, as shown in Figure 3.

The investigations on the shading orientation and height optimization, the shading strategies, and the mechanical strategy can be done in parallel to narrow down the design options. Building simulation then accelerates the integrated design process by identifying well-performing design iterations using the thermal comfort metrics. The final design can then be decided based on cost and other factors.

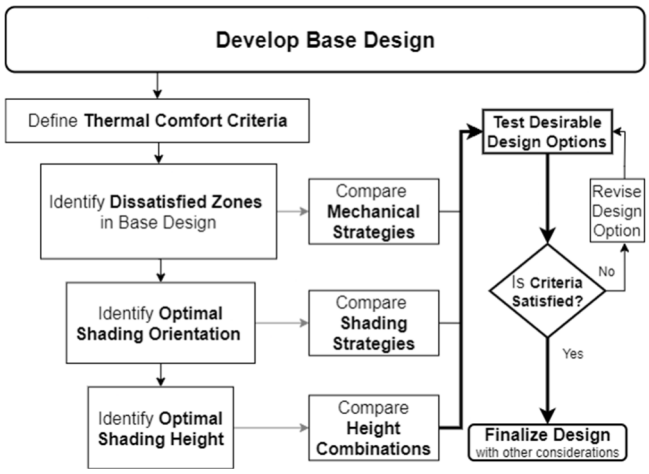

Figure 3: Thermal comfort simulation workflow.

Base Design Building Simulation

A 3D geometry of the building simulation model was set up in IESVE to reasonably match the existing atrium amenity design at the time without considering any additional shading elements. As shown in Figure 4, the zoning for the model has been divided based on orientation to closely match the zones used for mechanical design. Objects such as potted plants were not included in the model and it is assumed that there are no barriers between solar radiation and the occupied zones other than the core interior walls and the building envelope.

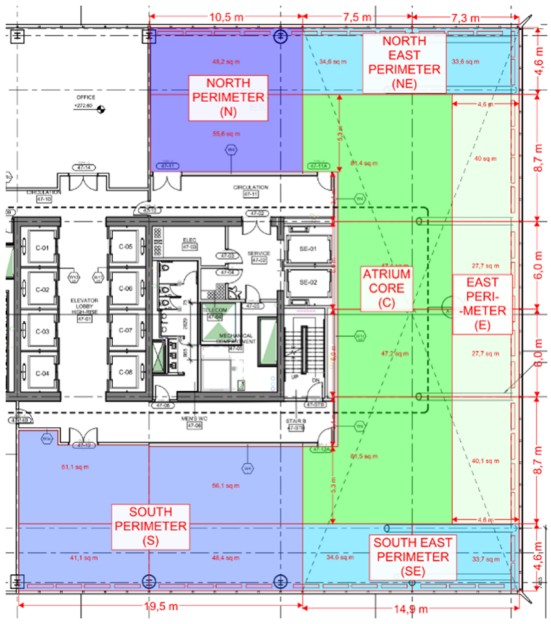

Figure 4: Modelled Zoning.

The sawtooth architectural pattern with alternating angled spandrel panels and glazing units was also reproduced in the model. The entire East façade is set up as full vision glazing. The upper parts of the sawtooth configuration on the South and North façade are opaque spandrel panels, while the bottom parts are vision glazing. The following thermal properties are set in the model based on the thermal report provided by the manufacturer: curtain wall vision glazing - effective U-value of 1.95 W/m^2.K and Solar Heat Gain Coefficient (SHGC) of 0.33; spandrel panels - effective U-value of 0.91 W/m^2.K.

The mechanical system was designed for a total occupancy of 145 people in the atrium amenity space. The heating, cooling, and ventilation is provided to the zones by air handling units through diffusers at about 7.6m above the floor level. Supplemental heating and cooling are provided by trench fan coil units at the perimeter zones.

The occupied hours of each zone are 8:00 am to 12:00 am. The occupant heat gains are assumed to be 80.4 W/person and 60 W/person for sensible and latent respectively according to the general offices building type in CIBSE Guide A Table 6.1. The receptacle and lighting load are assumed to be 2.7 W/m^2 and 13.3 W/m^2 respectively based on ASHRAE Standard 90.1-2016 and its User's Manual (ASHRAE, 2016; ASHRAE, 2017b). The temperature setpoint at the Occupant Level of the atrium is 24°C dry-bulb and 50% RH during summer operation. As there is no occupancy above 2m of the atrium, its temperature setpoint is left floating as shown in Figure 5.

Given these parameters, the model is simulated for the cooling season using the CWEC weather data for Toronto City (CAN_ON_Toronto.City.715080_CWEC2016.epw).

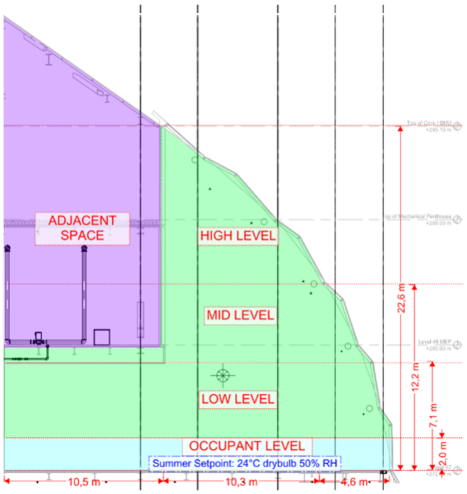

Figure 5: Temperature setpoint and height levels.

Thermal Comfort Analysis

Identifying Dissatisfied Zones in Base Design

The simulation results showed that $t_{o,max}$ in most zones far exceeded the acceptable temperature range due to high I_{dir}. The EH for these zones were also found to be very high. The $t_{o,max}$ during operating hours, EH and their relationship to $Q_{b,max}$ are examined for each zone from June through August. The t_o exceed the comfort threshold throughout 19-36% of the 1440 occupied hours during summer (about 2.7 to 5.5 hours/day). As shown in Figure 6, the South Perimeter (S) and North Perimeter (N) Zones experience significantly

less thermal discomfort. This finding allows the team to focus the analysis effort on addressing discomfort in the East Perimeter (E), South East Perimeter (SE), North East Perimeter (NE) and Atrium Core (C) Zones.

Table 1: Peak operative temperature, peak solar gain, and exceedance hours in the Base Design.

	Zones					
	N	**NE**	**C**	**E**	**SE**	**S**
$t_{o,max}$ Date	7/16	7/16	7/16	7/16	7/16	8/23
$t_{o,max}$ Time	9:30	11:30	8:30	8:30	10:30	11:30
$t_{o,max}$ (°C)	25.4	28.7	29.8	33.6	28.6	25.0
$Q_{b,max}$ (*W*)	6445	9273	19177	46019	9058	12232
EH (*hr*)	15	342	269	521	350	10

The areas which experience the highest $t_{o,max}$ are the E, SE and NE Zones. The peak temperatures occur often in the morning due to sunlight passing through the upper atrium space, as shown by the high $Q_{b,max}$ values in Table 1.

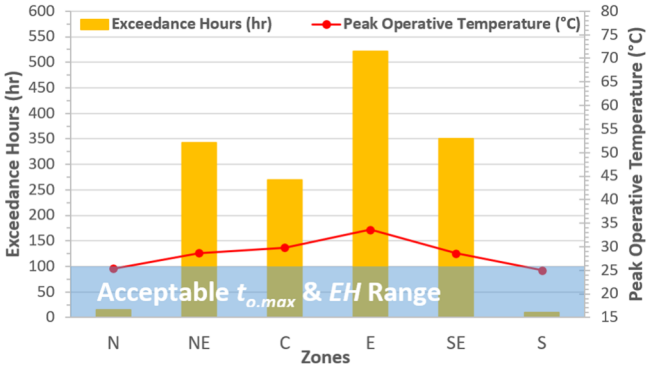

Figure 6: Base Design peak operative temperature ($t_{o,max}$) and Exceedance Hours (EH) for each zone.

The impact from solar heat gain decreases from noon to later in the day due to shading from the interior walls. As shown in the Figure 7, the zones have much higher t_o in the morning (as indicated by brighter yellow and light green on the left) compared to the much more shaded zones in the afternoon (as indicated by the dark green and light blue on the right).

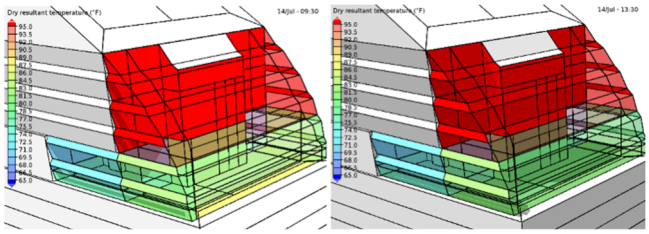

Figure 7: Comparison of internal wall shading on t_o at 9:30 am (left) and 1:30 pm (right).

The results from the Base Design simulation confirm that the atrium amenity space has difficulty maintaining thermal comfort. Since solar gain $Q_{b,max}$ has a significant impact on both $t_{o,max}$ and EH, it is necessary to improve the Base Design by considering low-SHGC glazing, adding shading elements, or increasing mechanical cooling.

Identifying Optimal Shading Orientation

To improve the Base Design and narrow down the design options effectively, it helps to identify areas of the façade where additional shading are most effective. While $t_{o,max}$ and $Q_{b,max}$ are also examined in the study, to simplify the presentation of results, only the key acceptance criterion – EH, is shown as the benchmark in this analysis.

Simulation results from Table 1 show that the spaces experiencing the most thermal discomfort all reach peak operative temperatures during the morning period between 8:30 am to 11:30 am on July 16. A quick solar study is done to examine the sun positions at this period.

As shown in Figure 8, the solar azimuth at the time of $t_{o,max}$ is only directed at the East façade. Shading interventions on the South façade can improve the thermal comfort of the SE Zone, but they will not significantly help the C, E, and NE Zones (which have the most discomfort.). Therefore, it is suggested that shading interventions be focused on the East façade, which would be the optimal orientation to reduce I_{dir} in these zones.

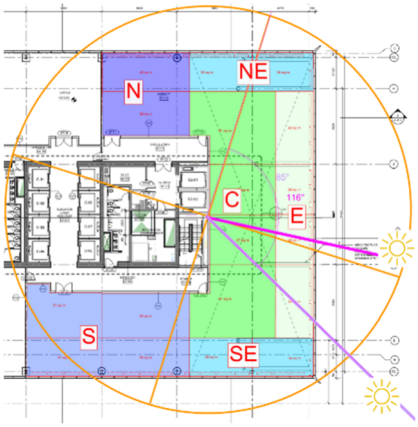

Figure 8: Solar azimuth of 85° at 8:30 am (pink) & 116 ° at 11:00 am (purple) on July 16.

Identifying Optimal Shading Height

Based on the weather data, the solar altitude is found to be 26° and 53° above the horizon for 8:30 am to 11:30 am respectively. Due to the curved geometry of the East façade, the optimal height for the shading placement was unclear from simple inspection. The effects of placing shading at various heights is then determined through simulation.

To perform this sensitivity study on shading height, 100% opaque spandrel panels are added to the model as an extreme-case test scenario for shading implementations. Each case was modelled by adjusting the Base Design building envelope from clear vision glazing to opaque panels at the height levels defined in Figure 5 while using the same U-value of 1.95 W/m^2.K for spandrel.

The results (Figure 9) confirm that adding shading to the East façade can significantly improve thermal comfort. The optimal height at which to place the shading elements depends on the trade-off between the comfort in the E Zone

and the S and NE Zones. Placing shading at the High Level as shown in Case 1 reduces the greatest number of EH overall but does not address the discomfort at the E Zone. On the contrary, Case 3 provides significant improvement on the E and C Zones but does not help the other zones.

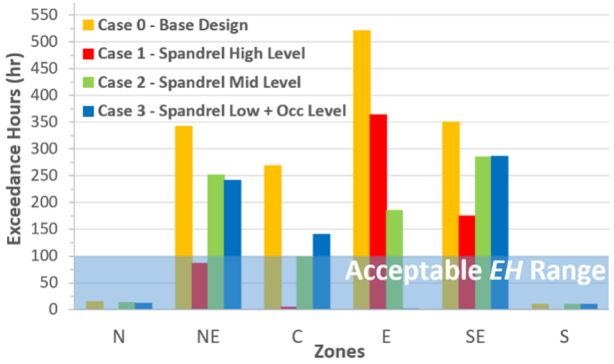

Figure 9: EH in different shading height options.

Comparing Optimal Height Combinations

As per discussion with the architectural team, combinations of opaque spandrel shading positioned at various height levels on the East façade are then tested to find the optimal strategy. These combinations are summarized below.

Table 2: Shading placement combinations at various height levels on the East façade.

	Height Level			
CASE	**High**	**Mid**	**Low**	**Occ.**
4	Y	Y	Y	Y
5	Y	Y	Y	-
6	Y	-	Y	Y
7	Y	-	Y	-

The simulation results showed that, apart from Case 7, most shading combination configurations meet the acceptable EH range of less than 100 hours, but one perimeter zone is usually barely within range and would likely not be thermally satisfied when some opaque spandrel panels are replaced with glazing.

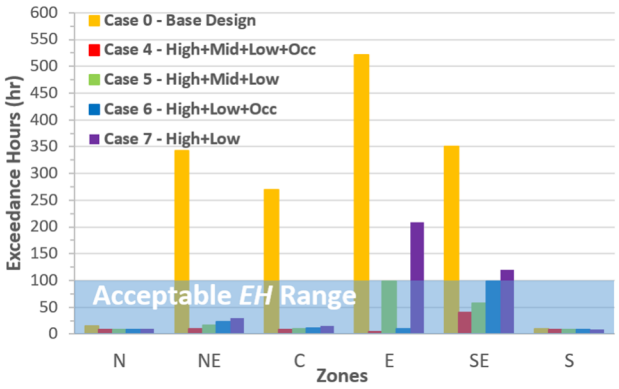

Figure 10: EH at different shading height combinations.

The combination study concludes that while placing shading at the Low Level benefits the E Zone, where the highest solar gain is encountered, the other zones would benefit more by a placement at the Mid to High Level on the East façade. Without shading at the Occupant Level, EH in the E Zone is significantly higher. However, as shown in Case 5, with addtional shading at the Mid Level, an acceptable comfort range can be achieved. Therefore, it is possible to leave the Occupant Level glazing clear for view considerations.

Comparing Envelope Shading Strategies

Besides the shading positioning, various building envelope shading strategies are investigated when the East façade is identified as the optimal orientation for additional shading. The strategies modelled include fritted glazing, interior fabric shades, and electrochromic glazing.

Fritted glazing with 40% density white custom frit pattern (Frit) is modelled with a Centre of Glass U-value of 1.40 W/m^2.K and SHGC of 0.25.

Automated fabric shades (Shades) are modelled with a solar transmittance of 0.03, solar reflectance of 0.09 and solar absorptance of 0.88. They are installed directly behind the existing glazing, automatically rolling down when the incident irradiance exceeds 75 W/m^2.

Electrochromic glazing (Chromic) is modelled with a Centre-of-Glass U-value of 1.59 W/m^2.K. The SHGC can change from 0.40 at its clear state to 0.08 at its fully tinted state. The glazing begins to tint when the incident irradiance is above 75 W/m^2 and becomes fully tinted at 155 W/m^2.

These thermal properties are set based on manufacturer's data. Each of these three shading strategies was simulated by changing the envelope properties of the East façade in the Base Design model to match the above properties. The simulation results are shown in Figure 11.

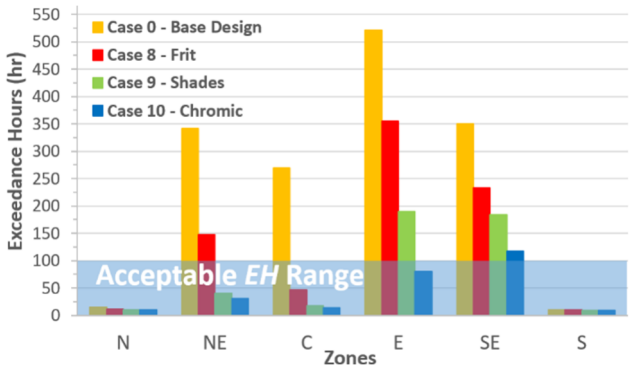

Figure 11: EH of each zone given each shading strategy.

Based on this shading strategies comparison, the fritted glazing option showed worse performance than other options. This is because the fritted glazing's effective SHGC is higher than both the electrochromic glazing at its fully tinted state or the Base Design glazing with the fabric shades rolled down. The automatic roller shades are the least visually intrusive since they can be hidden from sight when undeployed, but they absorb the sun's shortwave radiation and re-emitting it into the zone as convective heat and longwave radiation. Electrochromic performs the best but comes at a high cost-premium.

Comparing Mechanical Cooling Strategies

Besides the addition of shading elements, an alternative approach to reduce the t_o is to reduce the t_a of each zone using the mechanical system. As noted in the Methodology, reducing t_a can partially compensate for the higher $\bar{t}_r$ in each zone driven by solar gains. This is referred to as the Enhanced Cooling strategy for this study.

To examine the effect of Enhanced Cooling on thermal comfort, the mechanical system in the Base Design is modified to maintain an air temperature of 22.2°C (reduced from 23.9°C) while all other settings remain identical.

The results shown in Figure 12 confirm that enhanced cooling within the amenity space is highly effective at reducing the EH in summer. It is recommended to integrate this strategy with the explored shading strategies and combinations to improve the E Zone's thermal comfort.

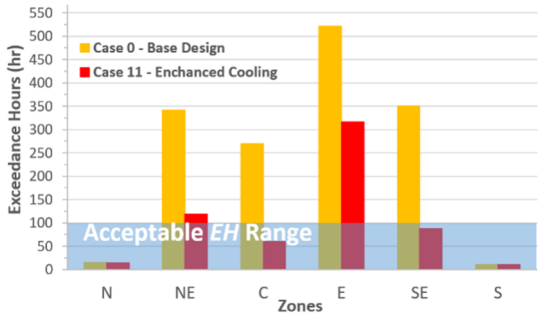

Figure 12: EH under Enhanced Cooling strategy.

Design Optimisation Results

Based on the comparisons above, the architectural team suggested several desirable design combinations to be tested through simulation. At the same time, the mechanical design team performed system calculation and sizing to meet the demand of the Enhanced Cooling strategy.

In addition, the architectural design team emphasized the consideration that the occupant level vision glazing should be remain as clear as possible to provide a high-quality view for the occupants.

Testing Desirable Design Options

Several of desirable shading options are considered based on these discussions. These options implement combinations of automated fabric shades, electrochromic glazing, or fritted glazing on the East façade at the various heights as shown in Table 3.

Table 3: Summary of combined strategy options

	Height Level			
CASE	**High**	**Mid**	**Low**	**Occ.**
12a	Chromic	Chromic	Chromic	-
13a	Chromic	-	Shades	Shades
14a	Frit	-	Shades	-
15a	Frit	-	Shades	Shades
16a	Frit	Frit	Frit	-

The model results showed that implementing combinations of the automated fabric shades, electrochromic glazing or fritted glazing alone is insufficient in reducing EH to the acceptable range. Although Case 12a and 13a can bring EH close to the acceptable range in most zones, the E and SE Zones still experience more than 100 hours of discomfort.

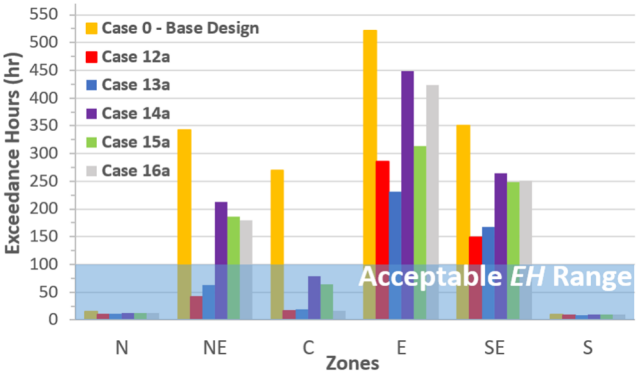

Figure 13: EH in combined strategy options.

Enhanced cooling is added into these combined strategy design options to improve thermal comfort. The mechanical system model is updated to provide Enhanced Cooling to maintain the room temperature setpoint of 22.2°C.

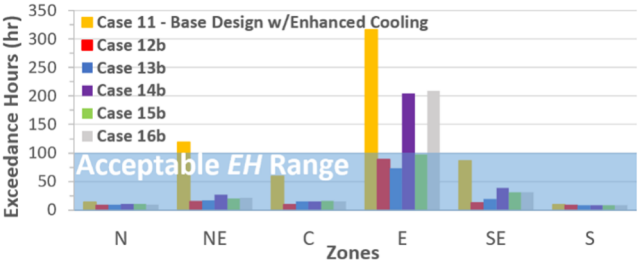

Figure 14: EH in combined strategy options with Enhanced Cooling.

Simulation results from Figure 14 showed that, apart from Case 14b and 16b, all other design options explored are able meet the acceptable comfort range. The EH in the E Zone (the space which experiences the most difficulty in maintaining comfort) in each Enhance Cooling design option (b) is compared to Base Design (Case 0) in Figure 15. The equivalent % occupied hours, defined as the EH hours divided by the total occupied hours from June through August, is also presented in the figure.

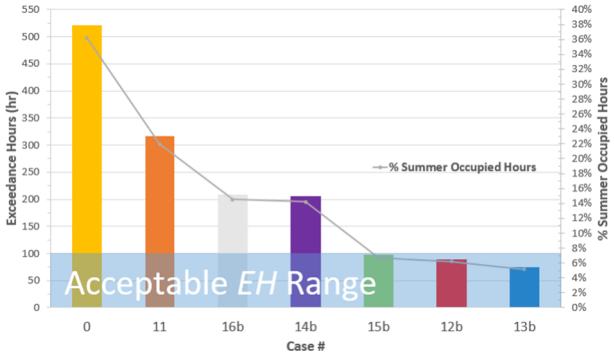

Figure 15: EH in the East Perimeter Zone and the equivalent % occupied hours.

It is concluded that the Enhanced Cooling strategy is highly effective in maintaining occupant thermal comfort. With the consideration to maintain clear vision glazing at the Occupant Level, Case 12b, 13b, and 15b all fall within the acceptable comfort range and meet the team's criteria.

Final Design

The design is then finalized based on considerations balancing between comfort, cost, construction, glare, and aesthetics. Ultimately, Design Case 15b (40% density fritted glazing at High Level and automated shades at Low + Occupant levels) is chosen. Table 4 summarizes the simulation results of the finalized design option.

Table 4: Peak operative temperature, peak solar gain, and exceedance hours in the Case 15b.

	Zones					
	N	**NE**	**C**	**E**	**SE**	**S**
$t_{o,max}$ Date	7/16	7/16	7/16	7/16	7/16	8/23
$t_{o,max}$ Time	9:30	11:30	8:30	8:30	10:30	11:30
$t_{o,max}$ (°C)	24.3	26.5	25.5	30.0	26.2	23.5
$Q_{b,max}$ (W)	3061	3648	11003	8867	3745	5566
EH (hr)	11	21	15	98	36	9

Figure 16 compares the final design simulation with the Base Design. A reduction of 423 EH (from 36% to 7% of total occupied hours over summer) and reduction of 4 K $t_{o,max}$ are achieved in the E Zone.

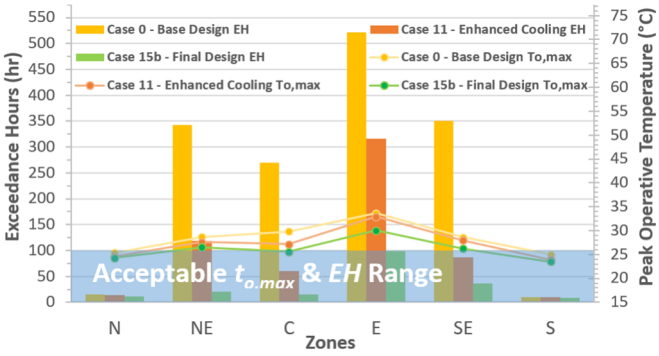

Figure 16: Comparison of Base Design and Final Design in terms of EH and $t_{o,max}$ at each zone.

Discussion

The main challenge in the design problem lies with the innumerable design options to be considered to improve thermal comfort. It is not always obvious which design options are more effective than others without performing simulations, and it can be time consuming to parametrically simulate every option (if only 3 orientations are considered for shading implementation, having 4 height levels, 4 shading strategies and 2 mechanical cooling strategies yields 96 options). The key is to filter them through heuristics such as the solar study, shading location exploration, and shading strategies study shown here to narrow down the effective design strategies. In this case study, the design options are filtered based on the following observations:

1. Solar study shows envelope design interventions are most effective on the East façade.
2. Adding shading/envelope improvements at the High and Low Level heights of the East façade is the most effective approach to reduce solar gain. Leaving the Occupant Level with clear vision glazing is possible, but combinations of shading at different height levels are necessary.
3. Using automatic fabric shades to reduce EH is better than the fritted glazing design option. Electrochromic glazing gives the best performance.
4. Enhanced cooling is significantly reduces EH.

Desirable combinations of these design options are then proposed by architects based on cost, construction practice, view quality, and aesthetics considerations.

As shown, it is an effective integrated design approach involving teamwork between the architectural, mechanical and building simulation teams. Although the EH is used as the guiding metric in this workflow, as opposed to using a multi-criteria benchmark which also include $t_{o,max}$ and severity of exceedance, the final design still managed to reduce $t_{o,max}$ to 30.0°C. This is practically within the recommended maximum of 4K above t_o threshold (25.9°C) according to CIBSE TM52 (Nicol and Spires, 2013).

While this case study only showcases the use of building simulation to assist in the thermal comfort design in a single highly glazed atrium, the workflow outlined can be adopted by most highly glazed building design projects which experience direct-beam solar radiation.

Due to project time constraints, CFD simulation was not performed for the worst-case scenario. Therefore, the location of outlets and returns, stratification, local air speed, and local temperature gradient have not been explored. The impact of zoning variations and different configurations of HVAC systems were also not included in this study.

Conclusion

This case study examined quantitative metrics for design stage thermal comfort analysis and demonstrated a practical workflow for occupant thermal comfort design in engineering practice using building simulation.

To bridge the gap between current standards/guidelines for thermal comfort and design in practice, an acceptable number of exceedance hours (EH) of 100 from June through August is established as the key criterion to quantify comfort in simulation results and to help steer the direction of the integrated design process. Peak operative temperature ($t_{o,max}$) and peak solar gain ($Q_{b,max}$) are examined as secondary metrics which influence EH.

The workflow demonstrated that the integrated design process can be significantly accelerated by carrying out a solar study, exploring effective shading locations,

comparing shading strategies, and examining enhanced cooling. The analysis helped navigate the (over 96) potential design options by only performing 21 simulations.

Guidance from building simulation enabled the interdisciplinary team to optimize integrated strategies to reduce both mean radiant and average air temperature in the dissatisfied zones. A final design which implements enhanced cooling with fritted glazing at the atrium's High Level and automated fabric shades at the Low and Occupant Levels was chosen. This design successfully reduced EH by 70-95% (up to 423 hours) from the Base Design.

Design problems like this case study are commonly overlooked in highly glazed multi-storey towers. It will be increasingly important to define thermal comfort as a guideline for initial design, and to further quantify comfort through building simulation. Future work on this research topic can include adding CFD analysis within the workflow and generalizing the approach for all building types, as well as performing post-occupancy measurements to verify the success of the design process. There is also a need to develop rules of thumb to help identify design conditions when significant thermal comfort problems may arise and when simulation-assisted thermal comfort design is necessary. With the advent of predictive control devices which can dynamically adjust zone setpoints to maximize energy savings (Carli et al., 2019), there will be greater opportunities to perform thermal comfort evaluation and design assistance through simulation in a manner similar to the work being done for whole building energy performance modelling today.

Acknowledgement

The authors are grateful to Adrian Smith + Gordon Gill Architecture and Cadillac Fairview Corporation Limited for collaborating on the project design and sharing the project information with the academic research community.

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