Integrated evaluation for energy and comfort quantification of windows in a residential apartment of Mumbai

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Abstract

This paper aims to understand the energy and comfort performance of glazings for residential apartments in Mumbai. Firstly, an integrated workflow was developed on Ladybug tools to conduct thermal, energy and daylight simulations using a single model. Secondly, the developed workflow was deployed to simulate multi- comfort (visual & thermal & energy performance) for a 2 Bedroom, Hall and Kitchen (BHK) apartment as case study. Two glazing types, clear (U-value 5.6, SHGC 0.85, VLT 0.85) and high performing (U-value 2.5, SHGC 0.27, VLT 0.34) were analysed. The results demonstrated that high performance glazing reduces the energy consumption by 37%, improves the thermally comfortable area from 34% to 85% and also provides better visual comfort (DGP <30%).

Lastly, the research was extended to analyse 8 different types of glazings with incremental variation of SHGC and VLT to generate an integrated metric. This metric compares the performance of all glass options in terms of cooling consumption, thermally comfortable area and glare probability in the space, enabling the stakeholders to select an optimal window configuration for their project. The results demonstrate that use of ideal option (G8) is is providing highest thermally area comfortable (80%) and lowest DGP (27%) with reduced energy consumption (47 kWh/m2).

Keywords - integrated metric, energy efficiency, thermal comfort, visual comfort, ladybug tools, residential apartment

1. Introduction

The world we live in is changing, and so are our lifestyles. People spend about 80–90% of their time indoors and research has clearly established that problems with indoor environmental quality (IEQ-thermal, acoustic, visual, air quality) of buildings has a direct effect on comfort, health, productivity of the occupants. IEQ is affected by multiple parameters and just looking at one in isolation might not be enough to understand its impact on other parameters. (ASHRAE, 2013) Thus, a holistic & integrated approach is required to understand, correlate & analyse the complex & conflicting relationship between IEQ parameters in conjunction. (Yang & Moon, 2019)

Thermal and Visual comfort are the key parameters of occupant well being affected by indoor air-velocity, radiant temperatures, and illuminance & luminance levels in a space respectively. With respect to glazing properties, these are conflicting comfort parameters which need to be evaluated in conjunction with energy efficiency to find optimal glazing specification & envelope design. Which means that higher daylight availability will also bring higher direct solar gains thereby increasing the energy consumption. (Jakubiec et al., 2017)

Impact of radiant temperature (short- wave & long wave radiation) across spatial-temporal range is important to understand thermal comfort. (Arens et al., 2015) Similarly, glare, quality views,and daylight availability holistically represent visual comfort. (Mardaljevic et al., 2012)

Thus, a workflow has been developed that can generate spatial thermal comfort (Christopher Mackey, 2017) & conduct view based radiance renderings indicating visual comfort. This paper proposes an integrated workflow to understand multi-comfort performance of indoor spaces based upon which the optimal specifications can be proposed for improved IEQ and thereby, wellbeing. The workflow is developed on Ladybug tools (LBT) which is capable of conducting thermal, energy & daylight simulations using a single geometric model. (Roudsari & Pak, 2013)

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The paper also demonstrates a case study example of 2 BHK apartments in Mumbai. The developed workflow was deployed to optimize glass specification (SHGC, U-Value & VLT) for conflicting multi-comfort parameters with lowest cooling consumption. The scope of the study was to develop a single model which can be linked to various simulation engines to conduct thermal, energy & visual simulations in an iterative loop. (Mathur et al., 2021)

2. Methods

2.1 Developing integrated simulation workflows (single model across energy, comfort, daylight

The workflow should be capable of using single model across thermal & daylight simulation and should be able to generate the 3 following parameters-

1. **Cooling EPI**- It indicates total cooling energy consumed in a building over a year per square meter of the floor area. This is affected by many factors including the envelope materials (windows, walls etc.). In windows, the SHGC and U-Value of the glass determines the heat gains against which the cooling energy is required to be offset.

2. **Thermal Comfort**- Is indicated by operative temperature (T_{op}). Top is calculated as the resultant of air temperature (T_{air}), and radiant temperature (T_{mrt}) caused by both direct solar radiation through glazing (shortwave) and temperature of all internal surfaces (long wave). (ANSI/ASHRAE, 2017) For windows, these parameters are a resultant of U-Value and SHGC of glass. Typically, Top is computed using the following formula:

$$t_{op} = \frac{(T_{mrt} + (T_{air} \times \sqrt{10 v_{air}}\,)}{1 + \sqrt{10 v_{air}}}$$

- Expression below is used to calculate mean radiant temperature, where F is the fraction of the spherical view occupied by a given indoor surface and T is the temperature of the surface. N refers to the number of surfaces within the room, indicating that the equation above is summed for all surfaces surrounding an occupant.

$$mrt = \left[\sum_{i=1}^{N} F_i T_i^{\,4}\right]$$

Further to compute solar adjusted mean radiant temperature, methodology has been developed and validated (Mackie, 2015) which is based on the SolarCal method proposed by (Arens et al., 2015). Traditionally, to determine this solar adjusted MRT, a radiation study of human geometry is performed, and this is then used to produce an Effective Radiant Field (ERF) through the following formula:

$$\alpha LW\ ERFsolar\ =\ \alpha SW\ Esolar$$

- Where Esolar is the short wave solar radiant flux on the body surface (W/m2), αSW is shortwave absorptivity, and αLW is the long-wave absorptivity (typically around 0.95). The ERF can then be related to an MRT through the following formula:

$$ERF_{solar} = (0.5\, f_{eff}\, f_{svv}\, (I_{diff} + I_{TH}\, R_{floor}) + A_p\, f_{bes}\, I_{dir}/A_D)\, (\alpha_{sw} sw/\alpha_{lw})$$

I_{dir}, I_{diff}, I_{TH}: Direct normal, diffuse horizontal & total horizontal radiation
A_D: Geometry coefficients of the human body
R_{floor}: Ground reflectivity
f_{svv} and f_{bes}: sky view factor & fraction of the body visible to direct radiation

3. **Visual Comfort-** Daylight Glare Probability (DGP), which predicts the likelihood that an observer at a given view position and orientation will experience discomfort glare, is used as a metric to analyse visual comfort. (Naber et al., 2017)(Wienold & Christoffersen, 2006) It is a resultant of glass's visual light transmittance (VLT) that governs the quantity of light that enters the space determining overall visual contrast. (P. CHAUVEL, J. B. COLLINS & LONGMORE, n.d.)

$$DGP = c_1 \,.\, E_v + c_2 \,.\log\left(1 + \sum_i \frac{L_{s,i}^2 \,.\, \omega_{s,i}}{E_v^{a1} \,.\, P_i^2}\right) + \; c_3$$

Where,

E_v : *vertical eye illuminance (lux)* $c_1 = 5.87 * 10^{-5}$
L_s : *Luminance of source (cd/m2)* $c_2 = 9.18 * 10^{-2}$
ω_s : *Solid angle of source* $c_3 = 0.16$
P : *Position index* $a_1 = 1.87$

To cumulatively analyse the above parameters, an integrated workflow has been developed on the ladybug tools (v1.6) which allows linking a single geometric model across energy, thermal & daylight simulations. The backend engines used are Energyplus to conduct thermal & energy simulation and radiance to conduct DGP analysis. (Soi et al., 2022) LBT has been used due to its visual programming capabilities which allows us to conduct parametric simulation across multiple & conflicting parameters. Each comfort module (thermal, visual etc.) can also be simulated independently on the LBT platform, however, it has been interconnected with all components for faster computation and outputs. The following steps are undertaken to set the modelling process:

1. **Defining the geometry and internal parameters:** The workflow picks up model geometry from polylines and window to wall area ratio can be defined for each face. Specifications for both the comparative cases can be defined and rest all the parameters like internal gains, infiltration, activity templates & space programs can be directly applied with existing pre- defined templates as per ASHRAE 90.1 standards. Also, these analyses are spatial in nature, hence grid planes need to be defined along with spatial resolution for the analysis along with temporal range of analysis.

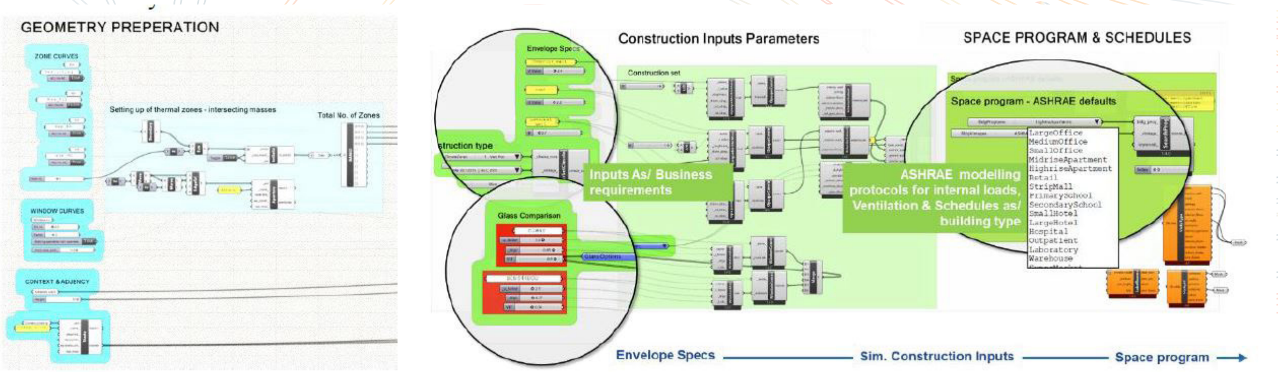

Figure 1: Geometry & construction inputs

2. **Result Visualization:** Once the script is set up the simulation can be run one by one or all at once for thermal, Energy & Daylight. Under thermal comfort- Spatial Operative temperature plots can be generated for point- in- time and cumulative across temporal range. Thermal comfort analytics have also been added to the script to precisely calculate metrics like '% area comfortable', average operative temperature etc. Under Energy Simulation, the workflow currently simulates EPI & Cooling load. Under daylight the script currently can simulate illuminance maps and annual metrics like sDA, DA & UDI along with DGP through view-based renderings.

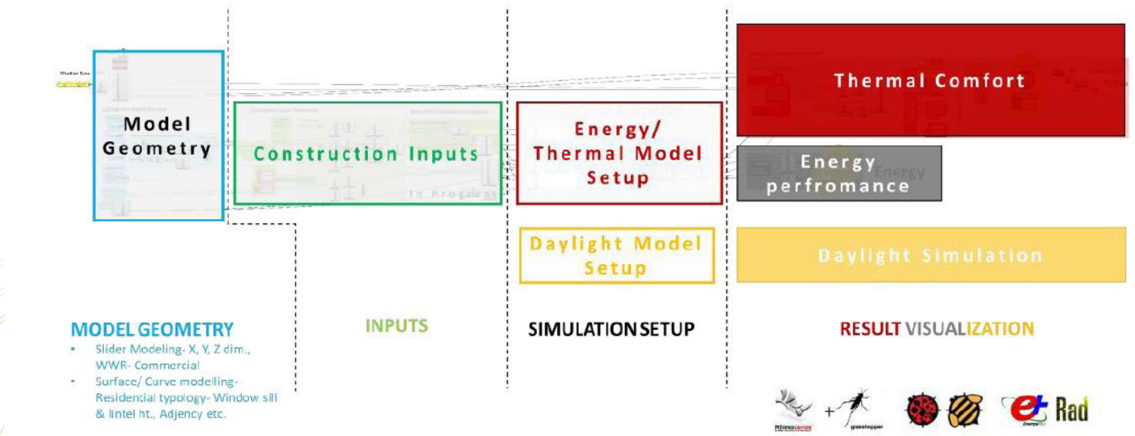

Figure 2: Integrated wor kflow Process flow

2.2 Case-study for a 2bhk apartment in Mumbai

As a case study example a typical high- rise residential unit in Mumbai has been modelled in Rhinoceros as per the floor plans shown in Figure 3.

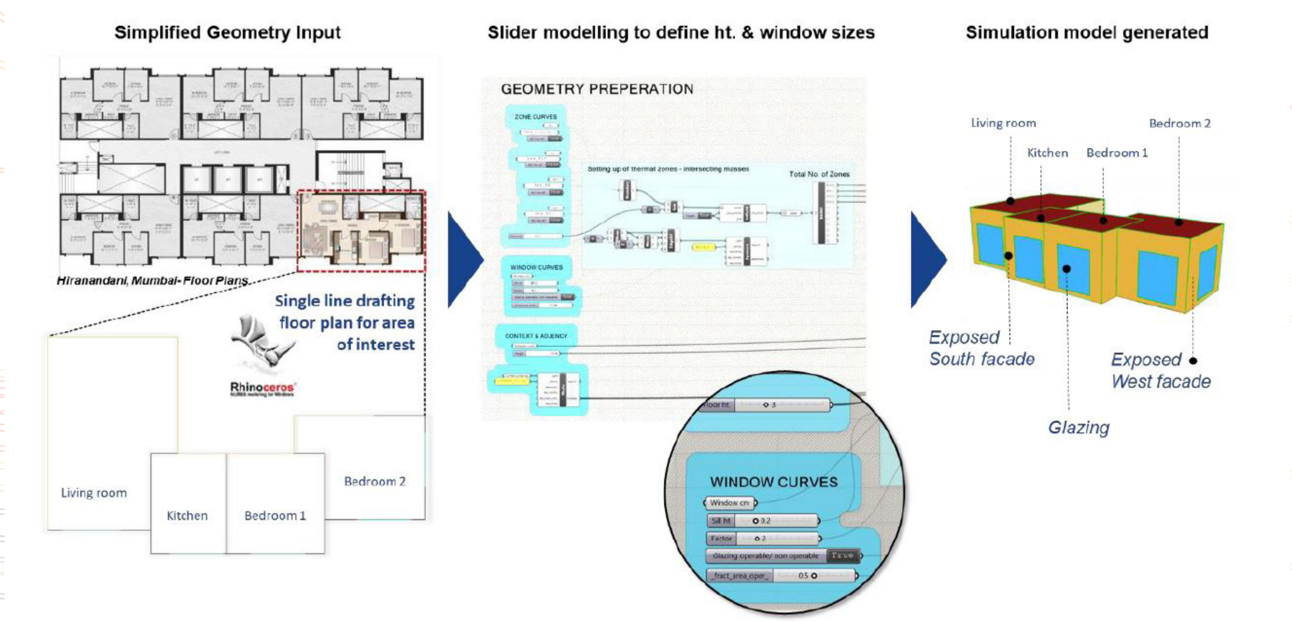

Figure 3: Model details for the residential apartment

The dwelling unit is oriented towards the South having a 70% window to wall area ratio. The building geometry is then linked to Ladybug tools daylight & thermal simulation components via grasshopper.

- **Thermal Simulation Inputs:** Since the residential buildings predominantly function as mixed-mode state in India, the indoor conditions are analysed for both air-conditioned and naturally ventilated state to get a holistic picture of the thermal conditions. ASHRAE 90.1 simulation protocols have been applied for space programs and schedules and the HVAC system is set up as Ideal air loads systems. Envelope specification has been defined as per business as usual considering 250mm AAC with U-Value of 1 W/m2K and 6mm clear glass. Adjacency of both walls & roof is set as adiabatic since; we are considering a middle floor of a typical high- rise building.

- **Daylight Simulation Inputs:** Interior wall surfaces reflectance have been defined as per IES standards for the following surfaces- Walls- 50%, Floor- 30%, Ceiling- 80% and 85% visual Light transmittance of clear glass. Daylight simulation has been conducted using Climate based sky for a typical weather file of Mumbai. The scene for DGP rendering was set up for the living room facing towards the window. Parallelly, the workflow was also tested by conducting a comparative case study between 2 glass types with following specification.

Parameters	**Clear** *(SGU)*	**Comparative case**
U Value *(W/m2K)*	5.60	2.5
SHGC *(%)*	0.85	0.27
Visual Light Transmittance *(%)*	85%	34%

2.3 Parametric analysis for glazings

The advantage of a combined workflow is the ability to conduct parametric analysis for multiple specifications of U-Value, SHGC & VLT across thermal, energy & daylight performance, on the same geometry as above. For the parametric analysis, there were a total of 4 SGU & 4 DGU glass types with SHGC varying incrementally in the multiples of 0.1. Similarly, for DGP analysis, VLT varied in the interval of 10%. The specifications of glass type in the parametric analysis can be refined for any thresholds of SHGC, VLT & U-Value or can be even made product specific. The intent of this workflow is to develop an informed glass selection workflow based upon thermal comfort, energy consumption & visual comfort. Further, a combined metric visualization is proposed to analyse the results from the parametric analysis and base decision on glazing performance.

Table 1: Glazing properties for the parametric analysis

Glass no.	**Glass Type**	**U Value** *(W/m2K)*	**SHGC**	**VLT** *(%)*
1	Single glazed	5.6	0.7	65%
2	Single glazed	5.6	0.55	55%
3	Single glazed	5.6	0.45	45%
4	Single glazed	4.9	0.35	35%
5	Double glazed	2.8	0.55	55%
6	Double glazed	2.8	0.45	45%
7	Double glazed	2.8	0.35	35%
8	Double glazed	2.8	0.25	25%

3. Results

3.1 Case study for a 2bhk apartment in Mumbai

In addition to energy efficiency, it is also critical to look at the ability of the glass product to improve thermal and visual comfort in space. The thermal comfort was analysed by plotting spatial-temporal contours of operative temperature for both air-conditioned and naturally ventilated conditions during the hottest week 21st- 27th May between 12pm- 4pm.

The analysis for residential apartment case study has been conducted in three parts: 1. energy efficiency 2. thermal comfort and 3. visual comfort inside the rooms. Firstly, the energy analysis (Figure 4) was conducted to understand the impact of glass selection on cooling EPI & Cooling load. Compared to a clear glass, a reduction of 10% in cooling EPI and 30% in peak cooling load can be observed due to high performing glass. The difference between the 2 cases is due to lower U-Value & SHGC of the high performing glass, which results in lower conductive and radiative gains.

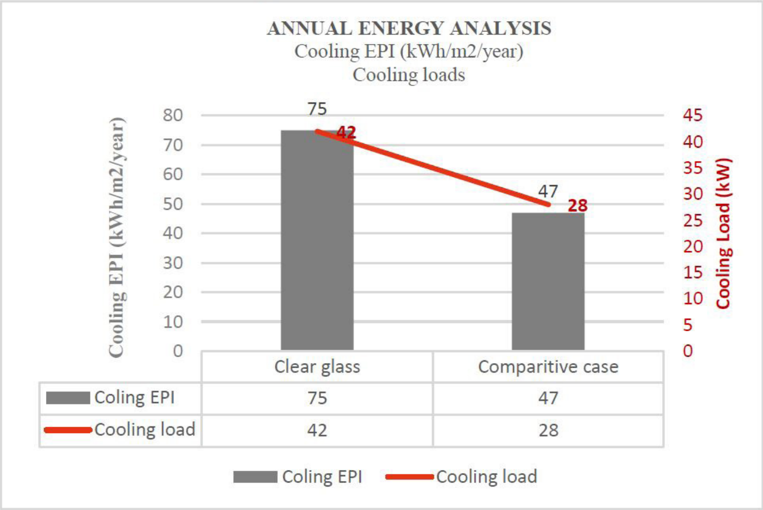

Figure 4: Annual Cooling consumption

For air-conditioned scenario, even with the set point of 24°C, the clear glass case exhibits average operative temperature of 27.7°C with only 34% area falling within thermal comfort limits, Also, uneven distribution of Top across the floor is observed, especially near windows is almost 30°C due the high glass surface temperature and direct solar radiation. With the use of high-performing glass the average temperature is observed to be reduced to 25.6°C with a significant increase in the thermally comfortable area as 85%. This is due to the better specifications of the glazing resulting in reduced solar heat gains.

For naturally ventilated scenarios, the conditions are worst case. Even though there are no ACs or fans in the space, the use of high-performing glass is resulting in a 5°C drop in average operative temperature in the space and improved thermal distribution across the floor plate (Figure 5).

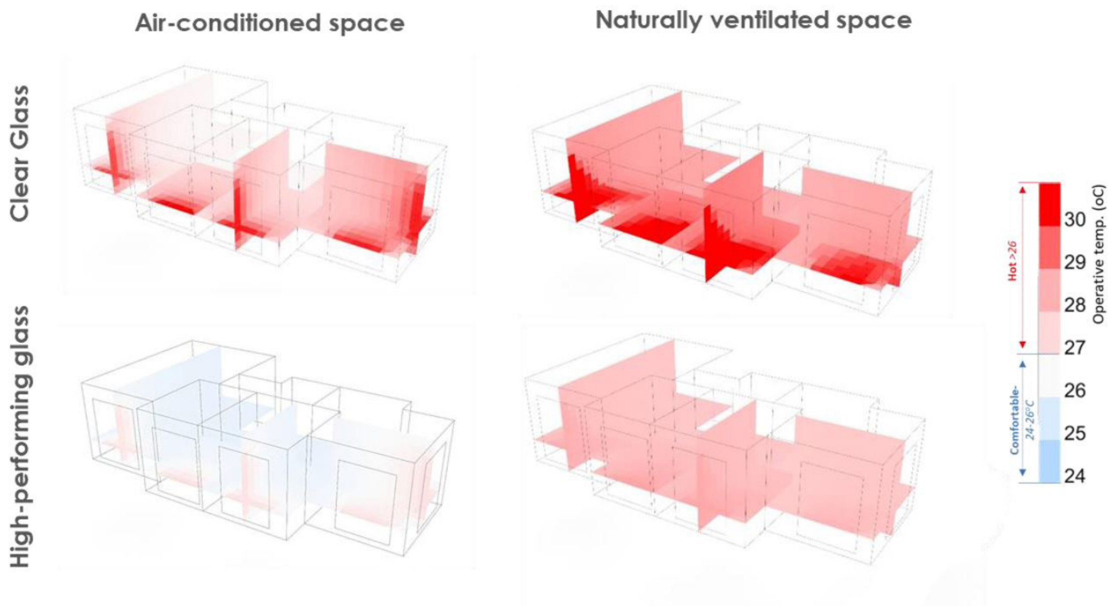

Figure 5: Thermal comfort contours for air conditioned and naturally ventilated scenario

Daylight analysis (Error! Reference source not found.) indicates good daylight availability and distribution across the dwelling unit but also excessively lit perimeter. Hence, the tendency of occupants will be to put on curtains which defeats the entire purpose of large windows and compromises views. In conjunction, DGP analysis indicated sky component towards south was

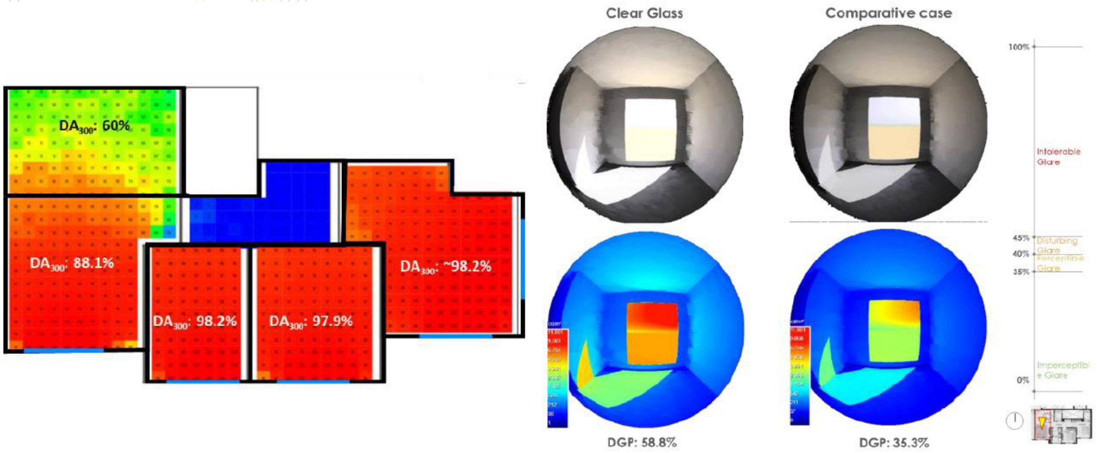

Figure 6: Illuminance & View Based Daylight Renderings (DGP)

significantly brighter than room interiors and hence, occupants will experience 'intolerable glare' (DGP58.8%) with baseline specification on 21st Dec, 2pm. Upon comparing with comparative cases, the DGP reduces to 35% i.e., imperceptible glare.

3.2 Parametric analysis for glazings

To analyse different glazing types, it is important to holistically look at its performance for both energy efficiency & comfort. For the parametric study, there are 8 types of glazing analysed for 3 conflicting parameters. The results are then converted into a 'combined metric' which is both visual and analytical. This enables better decision-making during product selection as it displays the overall efficiency of all product ranges in a single dashboard.

For thermal comfort quantification, the spatial operative temperature distribution across floors is translated into a metric 'percentage area thermally comfortable'. This is calculated using analytics which is pre- defined in the workflow, where upper and lower limits of thermal comfort are defined and the area falling under the same is computed. The energy consumption is expressed in annual EPI's and the Visual comfort is translated as DGP%, depicting the glare experienced by an occupant at a given point in time.

Hence, to be able to compare three different metrics a 'Combined or Integrated Metric' has been proposed in a form of X-Y scatter plot. The x-axis depicts 'Daylight Glare Probability (DGP%)' and the y-axis depicts 'Thermally Comfortable Area (%)'. The colour of each circle indicates EPI, and the shade becomes darker for higher EPI's.

The visualization dashboard helps correlate visual & thermal comfort parallelly while the combined metrics graph helps understand how that glazing type is ranked. For example, glazing type 3 (G3) has a DGP of 37 and 40% area thermally comfortable with 50 kWh/m2 EPI. As the SHGC of glass reduces the 'percentage thermally comfortable area' increases and reduction of annual EPI is observed due to lower SHGC. Similarly, with the reduction in VLT of glass the DGP reduces towards imperceptible glare.

Hence, glazing type (G8) is the most optimal specification based upon the highest thermal area comfortable (80%), lowest DGP (27) and energy consumption (45 kWh/m2).

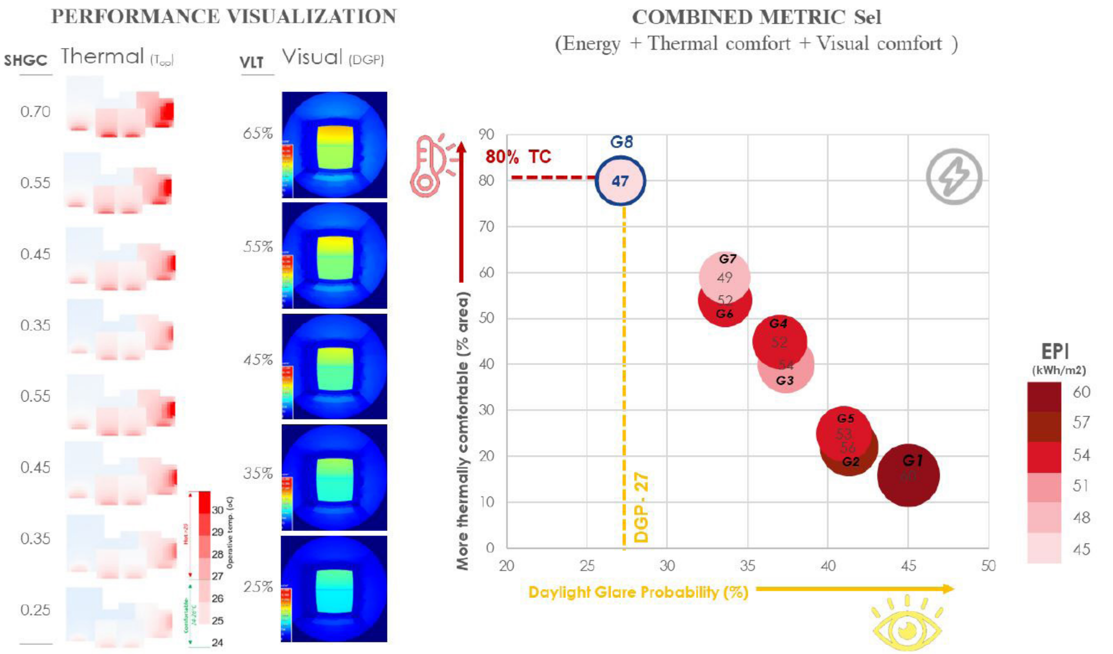

Figure 6 - I llumin ance & View Based Daylight Renderings (DGP)

4. Discussion

The paper attempts to mainstream and utilize technical metrics of thermal & visual comfort in conjunction withEPI to enable informed glass selection which will help stakeholder understand the impact of multi-comfort. Until now, such decisions have been mostly steered by energy savings but intangible benefits like thermal comfort, use of blinds/ curtains were not demonstrated or considered. Currently, workflow has been developed for 4 metrics- Thermally comfortable area (%), Energy Performance Index (EPI), Daylight Glare Probability (DGP) and Daylight availability (sDA, DA, UDI). These metrics should ideally be decided based upon the type of building, for example this typical dwelling unit has 80% WWR for spaces which aren't deeper beyond 4-5m hence, daylight availability is not the challenge. Rather, the perimeter spaces are prone to glare. Also, due to direct solar gains and limited shading on the façade the direct solar gains will cause radiant asymmetry. This analysis led to selection of these 3 metrics of this case.

But there might be future studies where the daylight availability might be more critical than glare. Energy Performance Index for each glass type can also be translated in terms of cooling energy cost and Carbon Emission Intensity as a part of future research.

The workflow allows to conduct parametric analysis for any specification of glass type. In case an analysis is needed to optimally select SHGC & VLT between 0.4-0.5 the number of simulation runs can be adjusted to an increment of 0.1. Thus, the input specification of glass can be refined to any threshold based upon the intent of the study.

5. Conclusion

This paper aims to understand the energy and comfort performance of glazing in typical high rise residential apartments in Mumbai using an integrated workflow developed on Ladybug tools capable of conducting thermal, energy & daylight simulations using a single model. The purpose of this study is to deploy an integrated workflow to optimize glass specification (SHGC, U-Value & VLT) based upon conflicting multi- comfort parameters with lowest cooling consumption. Thermal comfort is indicated by Spatial operative temperature and visual comfort is indicated by Daylight Glare Probability. In parallel to comfort the paper proposes energy performance as the third metric for glass selection optimization. Cooling EPI indicates total cooling energy consumed in a building over a year which is a resultant of envelope gains. The SHGC & U-Value of the glass determines the heat gains against which the cooling energy is required to offset.

Hence, an integrated workflow has been developed (single geometric model across energy, thermal & daylight simulations) on the ladybug tools (v1.6) which allows linking a single geometric model across energyplus to conduct thermal & energy simulation and radiance to conduct DGP analysis. LBT has been used due to its visual programming capabilities which allows us to conduct parametric simulation across multiple & conflicting parameters.

The workflow developed was first used to understand visual & thermal performance of a comparative case between clear glass and a high-performance glass. Two glazing types, clear (U-value 5.6, SHGC 0.85, VLT 0.85) and high performing (U-value 2.5, SHGC 0.27, VLT 0.34) were analysed. The results demonstrated that high performance glazing reduces the energy consumption by 37%, improves the thermally comfortable area from 34% to 85% and also provides better visual comfort (DGP <30%). Lastly, the research was extended to analyse 8 different types of glazings with incremental variation of SHGC and VLT to generate an integrated metric. This metric compares the performance of all glass options in terms of cooling consumption, thermally comfortable area and glare probability in the space, enabling the stakeholders to select an optimal window configuration for their project. The results demonstrate that use of ideal option (G8) is providing highest thermally area comfortable (80%) and lowest DGP (27%) with reduced energy consumption (47 kWh/m^2).

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