ABSTRACT
This paper describes a case study that integrates an environmental performance analysis workflow with a design approach. This is achieved with the utilization of various energy simulation tools and software packages for a hypothetical office building located in New Delhi, India. After the initial set-up of the base building energy model (BEM), steps were taken to improve on various aspects such as (1) building design, (2) shading and daylighting, (3) building envelope, (4) lighting controls, (5) HVAC, (6) natural ventilation, (7) thermal coupling, (8) indoor air quality, and (9) site renewable energy. The outcome of these strategies resulted in a 71% reduction in building energy use intensity (EUI) from the base case. The intent is to help designers and energy modelers consider a step-by-step process that promotes the consideration of passive strategies in high performance building design, together with a relevant suite of software packages to conduct the required analysis.

INTRODUCTION
The importance of integrating energy analyses into the architectural design process in order to make informed design decisions has been discussed in numerous papers (Lieve & Verbeeck, 2010) (Lam, 2012) (Attia, Hensen, Beltrán, & De herde, 2012). With a wide variety of building performance simulation (BPS) tools developed by numerous parties available in the market, the choice falls to architects and designers based on their needs during the design process (DP). The American Institute of Architects (AIA) has endorsed the use of energy simulations by architects (The American Institute of Architects, 2012), but also notes that the holy grail of energy modeling software has yet to be found, all tools have pros and cons.

This paper promotes an integrated use of multiple tools based on their effectiveness in analyzing a particular facet of building performance. The aim is to utilize the pros of each software package for a particular DP step, while reducing the potential shortfall of garbage in, garbage out (GIGO) scenario in conducting the analyses. While not all of the software packages might be available to architects and designers due to limitations such as cost and licensure, the authors are hopeful that the described workflow will be useful as a guide in helping an integrated project team (IPT) make decisions during the DP.

The case study for this paper is a typical new construction office building located in New Delhi, India. It is 3-stories in height with a concrete column and beam structure with surrounding site context as shown in Figure 1. The goal is the minimization of energy consumption, as well as the use of a mixed-mode ventilation strategy for the building. This is achieved with the integration of passive and active strategies for a high performance building.

METHODOLOGY
The process begins with an analysis of the base case building energy model in its climatic context that closely matches the average energy consumption of the same building typology in the area. With dominant cooling loads and climate data indicating high solar gains, it was necessary to first design adequate shading. Next, the components affecting building optimization such as building envelope, lighting controls, and HVAC systems were tested. Subsequently, natural ventilation strategies such as buoyancy-driven, wind-driven, and ceiling fan assisted ventilation were coupled with the existing mechanical cooling system to further improve on the building’s energy performance. Only after the prioritization of these building level design and performance strategies was site renewable energy
considered. Figure 2 shows the design and simulation workflow process with the corresponding software tools utilized.

**SIMULATION WORKFLOW**

**Climate**
The weather data used for the analysis was for New Delhi, India, provided by the Indian Society of Heating Refrigerating and Air Conditioning (ISHRAE), downloaded from the EnergyPlus portal as an EnergyPlus weather format (EPW) (U.S. Department of Energy (DOE), 2015). Ecotect Weather Tool (Autodesk, 2015) was used to analyze the climate information. A monthly diurnal averages chart was generated as shown in Figure 3. Understanding the climate helped with the decision making process for optimal building design strategies.

**Thermal Comfort and Indoor Air Quality (IAQ)**

In this case study, both the Predicted Mean Vote (PMV) as well as Adaptive Comfort Method under the American Society of Heating Refrigeration and Air Conditioning (ASHRAE) Standard 55-2013 were referenced (Hoyt, Schiavon, Piccioli, Moon, & Steinfeld, 2013), and verified at various stages of the DP to ensure that thermal comfort conditions during the occupied hours for the majority of the building occupants are met.

In the context of India, the Energy Conservation Building Code (ECBC) cross references the National Building Code (NBC) for its ventilation guidelines in naturally ventilated buildings, recommending the use of an adaptive comfort model (Thomas, de Dear, Rawal, Lall, & Thomas, 2010). In terms of IAQ performance criteria and the verification of CO₂ concentrations as an indicator, ASHRAE Standard 62.1-2010 (ANSI / ASHRAE Standard 62.1-2010, 2010) and calculations associated with determining the minimum ventilation rates in breathing zones are referenced.

**Base Case Model Settings**
The base case scenario was modeled in DesignBuilder/EnergyPlus (DesignBuilder Software, 2015) and is shown in Figure 4. Core and perimeter zones were divided using virtual partitions for greater accuracy of the simulation results. The walls, columns and slabs were specified as concrete, it was also assumed that the building is covered with a single glazed glass curtain wall system on all facades, with no operable windows and / or shading devices. All parameters were selected as closely match the properties of a typical office building in New Delhi (see Table 1). The surrounding context was modeled as component blocks, while the void where the stair core is located was modeled as an internal opening.

The internal heat gains for occupancy, equipment, and lighting, as well as the HVAC heating and cooling schedules, were based on compiled values from various research sources (Deru, et al., 2011). In assuming that the base case model is completely mechanically conditioned, the PMV model was used to determine the heating and cooling set-point temperatures within the thermal comfort range at 20.3°C and 26.7°C.
respectively. The CBE Thermal Comfort Tool (Hoyt, Schiavon, Piccioli, Moon, & Steinfeld, 2013) was used, with a relative humidity (RH) of 50%, an air speed of 0.1 m/s, and a metabolic rate (MET) of 1.1 for an office environment. The cooling set-point assumed a clothing level (CLO) of 0.5 which is typical for the summer, while the heating set-point assumed a CLO of 1.0 which is typical for the winter.

**Table 1 Base case design parameters**

<table>
<thead>
<tr>
<th>DESIGN PARAMETERS</th>
<th>BASE CASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shading</td>
<td>None</td>
</tr>
<tr>
<td>Construction</td>
<td>Light weight concrete, Wall U-value: 0.35</td>
</tr>
<tr>
<td>Glazing</td>
<td>Single clear curtain wall glazing, Solar Heat Gain Coefficient (SHGC): 0.86, U-value: 5.89</td>
</tr>
<tr>
<td>Lighting Control</td>
<td>None</td>
</tr>
<tr>
<td>HVAC</td>
<td>Fan-coil unit, Coefficient Of Performance (COP): 1.67</td>
</tr>
<tr>
<td>Natural Ventilation</td>
<td>None</td>
</tr>
</tbody>
</table>

**Base Case Energy Consumption Results**

The normalized annual site EUI for the base case was 268 kWh/m². Different examples of similar typologies in the region were examined to ensure that the base case scenario was a close match. The energy performance of a conventional office building in the nearby city of Noida, located in the same climate zone as New Delhi was 231 kWh/m² (The Energy and Resources Institute (TERI), 2010). Also, the ECBC compliant ITC Green Centre located in the nearby city of Guragon had an estimated conventional energy performance of 261 kWh/m² (The Energy and Resources Institute (TERI), 2010). A report that studied 17 properties in India estimated a median EUI of 302 kWh/m² (The Urban Land Institute (ULI) Greenprint Center for Building Performance, 2010). With the reference research, the base case energy consumption results are within an acceptable range.

**Base Case Shading Model and Results**

In addition to conducting BPS in DesignBuilder/EnergyPlus, Ecotect (Autodesk, 2015) was used to analyze the impact of the sun and surrounding context on the case study building. The building geometry was imported into the software with analysis nodes set up on all four façade orientations. The orthographic sun-path diagram method (Szokolay, 2007) was used to determine on annual basis the building’s exposure to the sun and potential internal solar gains in order to analyze the base case performance.

Figure 5 shows the worst performing locations for all facades. The building is exposed to the sun for most of its occupied hours (weekdays from 9am – 5pm), especially on the South, East, and West facades. The 3rd floor performed the worst as the surrounding context was not able to help provide some shade. Table 2 shows the shading recommendations from the analysis.

**Figure 5 Base case shading model results**

<table>
<thead>
<tr>
<th>SOUTH</th>
<th>EAST</th>
<th>WEST</th>
<th>NORTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Floor</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2nd Floor</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3rd Floor</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Building Envelope Design Strategy**

Well-designed vertical and horizontal shading can block direct sunlight from penetrating into the interior spaces, minimizing the internal solar heat gain. The various façade orientations should be treated in accordance with the relative angles and orientations of the sun. The north façade does not need as much shading as it is already in shadow for much of the year. The shading can be optimized to maximize natural daylight into the interior spaces. Light shelves are integrated into the shading strategy to help bring daylight deeper into the floor plate. These strategies are summarized in Figure 6.

The wall construction and glazing systems can be improved to make the building envelope more energy efficient. Lighting controls can also work with the building’s shading design to reduce lighting electricity consumption when natural daylight is sufficient. The selection of more efficient HVAC systems will help to further reduce the cooling loads.

**Shading Design Performance Results**

Based on the analysis of solar data for New Delhi and the occupancy schedule of the offices spaces, it was
determined with Ecotect that the building should be shaded from March 1st to October 31st from 9am to 5pm. This reduces the amount of internal solar heat gains contributing to cooling energy consumption. During the rest of the year, it is highly recommended that the building be shaded as well. A diagram of the shading design strategy based on the orthographic sun-path diagram is shown in Figure 7.

The shading design for the East and West facades is a combination of horizontal and vertical shading, a tradeoff between Vertical Shading Angle (VSA) and Horizontal Shading Angle (HSA) (Szokolay, 2007). The lowest sun angle at 9am for the period of March 1st to October 31st was used in the design process. To resolve the low shading angle at 5pm which would block a large amount of natural daylight, the design aimed to fully shade before 3pm. Therefore, for certain months of the year, interior blinds would need to be used to block incoming sunlight from 3pm to 5pm. For the South facade, the strategy is similar with a greater emphasis on horizontal shading as the surrounding context provides shade for most of the low angle sun in the early morning and late afternoon. A concurrent goal of the shading design was also to reduce solar heat gains, especially in a cooling dominated climate such as New Delhi, and in an office building with internal heat gains. For the North facade, the base case analysis showed that it was already shaded by the building itself and its surrounding context. Therefore, no specific shading strategies were implemented. These shading calculations are summarized in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>SOUTH</th>
<th>EAST</th>
<th>WEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 1 (9am)</td>
<td>VSA: 48.0°</td>
<td>VSA: 29.6°</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HSA: 62.9°</td>
<td>HSA: 27.1°</td>
<td>-</td>
</tr>
<tr>
<td>Mar 1 (3pm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mar 1 (5pm)</td>
<td>VSA: 41.7°</td>
<td>-</td>
<td>VSA: 17.0°</td>
</tr>
<tr>
<td></td>
<td>HSA: 71.1°</td>
<td>HSA: 18.9°</td>
<td>HSA: 18.9°</td>
</tr>
<tr>
<td>Oct 31 (9am)</td>
<td>VSA: 34.1°</td>
<td>VSA: 34.1°</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HSA: 37.2°</td>
<td>HSA: 37.2°</td>
<td>-</td>
</tr>
<tr>
<td>Oct 31 (3pm)</td>
<td>-</td>
<td>-</td>
<td>VSA: 36.6°</td>
</tr>
<tr>
<td></td>
<td>HSA: 39.1°</td>
<td>HSA: 39.1°</td>
<td>HSA: 39.1°</td>
</tr>
<tr>
<td>Oct 31 (5pm)</td>
<td>VSA: 34.1°</td>
<td>VSA: 7.5°</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HSA: 37.2°</td>
<td>HSA: 7.5°</td>
<td>HSA: 20.1°</td>
</tr>
</tbody>
</table>

The shading performance is tested by checking the orthographic sun-paths of the different facades; this is shown in Figure 8. For the East and West facades, the implementation of the shading strategies is seen to perform successfully in shading between 10am and 3pm for the whole year. This is also applicable to the South façade. For the North façade, the existing base case is sufficient.
normalized annual EUI after introducing the shading design was 240 kWh/m². Compared to the previous result of 268 kWh/m², there is a 10% reduction in total energy consumption (see Figure 9).

Figure 9 Shading performance energy results

Daylighting Performance Results
Balancing the provision of natural daylight with the reduction in internal solar gains ensures design integration between the building shading and fenestration, space use, and furniture layout. DIVA (Solemma, 2015) was used to analyze the daylighting performance of the building spaces. The simulation results shown in Figure 10 verify that a majority of the key spaces such as open plan offices and meeting rooms are receiving sufficient natural daylighting based on the building’s occupancy schedule. The target illuminance is set to 500 lux (Richman, 2007) to provide adequate lighting for tasks performed in an office setting.

Figure 10 Daylighting Performance Result

Building Envelope, Lighting Controls and HVAC Systems Results
Although reducing the window-to-wall ratio (WWR) would have been a possible strategy, it was decided that a higher glazing ratio should be maintained, particularly on the North and West facades as they face open areas according to the case study context. The external shading strategy discussed balances between views, accessibility, and energy performance (see Figure 11).

Figure 11 Case study building with exterior facade

The U-value of the existing lightweight concrete construction was improved. The existing single clear curtain wall glazing was replaced with a double clear curtain wall glazing with an improved U-value and reduced SHGC. The normalized annual EUI was 235 kWh/m². There is a 2% reduction in energy consumption from the previous model iteration. It is likely that the shading strategy has mitigated most of the external solar gains. A Low-E glazing option was also tested and found to have a negligible effect on the normalized annual EUI, it was therefore not considered as a glazing option in the iterative model.

With lighting controls enabled in the DesignBuilder/EnergyPlus model, electric lights are set to be controlled according to the availability of natural daylight. Illuminance levels are calculated at every time step during the simulation and then used to determine how much the electric lighting can be reduced based on the occupancy schedule. The normalized annual EUI was 202 kWh/m². There is a 14% reduction in energy consumption from the previous model. This strategy builds upon the success of the daylighting design.

The HVAC systems modeled in the base case model was improved to meet a COP of 6.1. This was selected to closely match the ECBC compliant ITC Green Centre located in Guragon, which had 3 water cooled screwed chillers with the same COP (The Energy and Resources Institute (TERI), 2010). The normalized annual EUI was 108 kWh/m². There is a 46% reduction in energy consumption from the previous model. This shows the effectiveness of a low energy and efficient
HVAC system significantly reducing the cooling energy consumption of the building.

Figure 12 shows a graph of the impact on the building’s energy consumption of these strategies. In comparing the current results to the base case, there is a 60% decrease in overall energy consumption. The cooling load has decreased most significantly, followed by lighting consumption. This shows that in the design and simulation workflow so far, the strategies have been effective in improving the energy performance of the case study building.

When wind is coupled with buoyancy driven ventilation, the space can be cooled for more hours than purely by buoyancy. This contributes to improved air velocity in all spaces. The size of openings can be adjusted to ensure comfortable wind speeds in the interior spaces. The wind-driven pressure distribution is generally positive on the windward side and negative on the roof and leeward side.

Ceiling fans are introduced to help with the reduction of felt temperature in the interior spaces. This might also result in an increase in speeds in the various areas, which should be ensured that it does not exceed maximum velocity (0.75 - 1.0 m/s) that would make the space uncomfortable in an office environment.

**Natural Ventilation Simulation Methodology**

Due to the limitations of DesignBuilder/EnergyPlus for natural ventilation, CFD simulation software (FloVENT) (MentorGraphics, 2015) was chosen to analyze the proposed design strategies. In DesignBuilder/EnergyPlus, a zone is considered as one node, air temperature is also assumed to be uniform within a zone. It is therefore difficult to accurately predict energy loads when non-uniform indoor temperature distribution is significant. The advantage of CFD software allows for temperature and airflow distributions to be evaluated, it also can more accurately account for buoyancy-driven ventilation, and can take surrounding buildings into account (see Figure 13).

FloVENT was used in order to evaluate the effects of natural ventilation in the building. The model was built according to the redesigned building in Rhinoceros (Robert McNeel & Associates, 2015) and imported into FloVENT as geometry. The ambient temperature was set at 26.7°C; the radiant temperature was set at 28.7°C according to the ASHRAE 55-2010 thermal comfort model (Hoyt, Schiavon, Piccioli, Moon, & Steinfeld, 2013). As FloVENT performs point-in-time simulations, the annual worst case scenario is April 30th at 12:00pm. According to the EPW data, the average day maximum global horizontal solar radiation in April is 1168W/m².

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**Table 3 Iteration case design parameters**

<table>
<thead>
<tr>
<th>DESIGN PARAMETERS</th>
<th>BASE CASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shading</td>
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<tr>
<td>Construction</td>
<td>Light weight concrete, Wall U-value: 0.26</td>
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<tr>
<td>Glazing</td>
<td>Double clear curtain wall glazing, SHGC: 0.76, U-value: 2.84</td>
</tr>
<tr>
<td>Lighting Control</td>
<td>Yes</td>
</tr>
<tr>
<td>HVAC</td>
<td>Direct Expansion, COP: 6</td>
</tr>
<tr>
<td>Natural Ventilation</td>
<td>None</td>
</tr>
</tbody>
</table>

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**Figure 12 Case study building energy performance**

**Figure 13 DesignBuilder/EnergyPlus and CFD comparison**
For internal gains and materials, the settings were chosen to align closely with the DesignBuilder/EnergyPlus model. Internal gain sources were placed in the CFD model to simulate internal heat gains from equipment, light, and occupants. Sensors were placed to measure point-in-time temperatures at key points in the case study building. They can also be used to measure parametric values over a range of temperature settings. Figure 14 shows the location of sources and sensors.

The mesh size of the simulation was approximately 300,000 – 400,000 cells for all iterations. This was selected due to the amount of computing power and time available during the analysis period. The macro geometry of the CFD model also allowed for a less accurate mesh boundary. To ensure that the results were as accurate as possible with the mesh count, a simulation convergence procedure was adopted.

- If a simulation diverges, the problem definition and setup were verified to be correct, all defined objects and attributes were also checked.
- If a solution failed to converge successfully, the mesh grid was checked to verify that there are no poor aspect ratio grid cells and large jumps in grid size between adjacent grid cells.
- If the above steps do not result in the solution converging, the temperature sensors were used to sensibly assess whether the solution converged to a required accuracy of +/- 0.3°C (see Figure 15).

Buoyancy-Driven Natural Ventilation

CFD simulations for the buoyancy-driven ventilation condition were conducted. Temperature, speed, and velocity analysis were generated by FloVENT with false color image results (see Figure 16). In terms of temperature, the 1st and 2nd floors perform better as compared to the 3rd floor. However, the thermal comfort criteria as described in the earlier section of this paper have not been met. In terms of speed and velocity, the majority of the spaces have acceptable wind flow with minimal stratification, especially the 3rd floor with the dedicated stack. Sections taken through the atrium and stair-core spaces show that buoyancy-driven ventilation strategy is effective.

Buoyancy and Wind-Driven Natural Ventilation

For the buoyancy and wind-driven scenario, the effect of dominant prevailing wind directions was taken into account to analyze its combined effectiveness. Based on the climate analysis, the dominant wind directions are from the North-West and South-East. Figure 17 shows the wind pressure results from the CFD simulation for both wind directions. Due to the schematic nature of the case study building in terms of accurately simulating pressure losses due to openings, ducts, and filters, as well as the varying velocities of the prevailing winds over time, only wind pressure was considered.

There is a greater wind pressure difference between the inlet and outlet locations for the North-West prevailing winds as compared to the South-East, the difference in wind pressure is sufficient to affect the resultant airflow.
A CFD simulation combing buoyancy and wind-driven natural ventilation was not conducted due to the software’s point-in-time analysis limitation, as well as the associated complexity of considering both velocity and temperature parameters that fluctuates on an annual basis.

Natural Ventilation and Ceiling Fans
In referencing the Adaptive Comfort Model (Hoyt, Schiavon, Piccioli, Moon, & Steinfeld, 2013), the impact of ceiling fans on the thermal comfort of the internal spaces was assessed. The velocity of the interior spaces with natural ventilation and fans were set at a maximum of 0.9 m/s based on research conducted (Manu, et al., 2014).

Natural Ventilation and Thermal Coupling Methodology
Based on data collected from both DesignBuilder/EnergyPlus (energy simulation) and FloVENT (CFD), the results were coupled to determine the impact of natural ventilation and thermal comfort on the energy consumption of the building. DesignBuilder/EnergyPlus provides information on cooling energy consumption on an annual basis, while FloVENT analyzes parametric temperature values. Based on the monitor points as shown in Figure 14, FloVENT can run a parametric simulation of temperature for each interior monitor point with a step of 1°C. The worst temperature value from the monitor point results for each floor was selected, and subsequently compared to the respective external ambient temperature for the simulation ran. These temperature values were inputted to the CBE Thermal Comfort Tool as Operative temperature and Prevailing mean outdoor temperature. The maximum external ambient temperature (T\text{threshold}) that falls within the thermal comfort range was selected, complying with ASHRAE 55-2013 (see Table 4 and Figure 18).

### Table 4 Maximum external ambient temperature (T\text{threshold}) values for CFD simulations

<table>
<thead>
<tr>
<th>CFD SCENARIO</th>
<th>1\textsuperscript{ST} FLOOR</th>
<th>2\textsuperscript{ND} FLOOR</th>
<th>3\textsuperscript{RD} FLOOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buoyancy-Driven</td>
<td>26.7°C</td>
<td>24.7°C</td>
<td>23.7°C</td>
</tr>
<tr>
<td>Ceiling Fans</td>
<td>29.7°C</td>
<td>27.7°C</td>
<td>25.7°C</td>
</tr>
</tbody>
</table>

In DesignBuilder/EnergyPlus, an energy simulation with mechanical ventilation was conducted. The hourly data with outdoor temperature (T_0) can be exported together with cooling energy consumption (see Figures 19 and 20).

![Figure 19 Cooling consumption with mechanical systems always on](image)
The energy consumption can be deducted when the value of $T_0$ is lower than the $T_{\text{threshold}}$ calculated by FloVENT. This can be calculated in a program like excel to determine the final energy consumption (see Figure 21). The cooling consumption is set to zero when natural ventilation is adequate for indoor thermal comfort. The final energy consumption is then calculated by summing up the values after deduction.

**Natural Ventilation and Thermal Coupling Results**

The coupling results were separated according to floor based on the parametric temperature monitor point locations. As DesignBuilder/EnergyPlus does not break down the cooling energy consumption by floors, it was assumed that the energy consumption was distributed proportionately by floor area.

There is a 61% decrease in annual energy consumption (see Figure 22) from the base case. There is also a 33% decrease in the number of hours required for mechanical ventilation as compared to the base case scenario of having the mechanical systems always on.

**IAQ Performance Results**

In a naturally ventilated building, IAQ can be valued by the Breathing Zone Outdoor Airflow. According to ASHRAE Standard 62.1-2010 (ANSI / ASHRAE Standard 62.1-2010, 2010), the outdoor airflow required in the breathing zone of the occupied spaces in a ventilation zone i.e. the breathing zone outdoor airflow ($V_{bz}$) shall be no less than the value determined in accordance with the formulas below:

$$V_{bz} = R_p \times P_z + R_a \times A_z$$

$$V_b = V_{out} \times A_{out}$$

Where:

$V_{bz}$ = breathing zone outdoor airflow (L/s)

$A_z$ = zone floor area: the net occupied floor area of the ventilation zone (m²)

$P_z$ = zone population: the number of people in the ventilation zone during typical usage

$R_p$ = outdoor airflow rate required per person

$R_a$ = outdoor airflow rate required per unit area

$V_b$ = design building outdoor airflow (L/s)

$V_{out}$ = design building outflow velocity (m/s)

$A_{out}$ = design building outflow area (m²)

According to ASHRAE Standard 62.1-2010, the $R_p$ value for an office space 0.3 L/s . person, while the $R_a$ value is 2.5 L/s . m². FloVENT was used to generate the airflow rate in the building; the outflow rate at the solar chimney is approximately 1.05 m/s (see Figure 23). The
total solar chimney opening area is 11m² (A_out) as designed.

![Image](image1.png)

**Figure 23** Case study building outflow false color image

Based on a P_z value of 70 occupants and an A_z value of 493m², the calculations yield a V_{bz} value of 323 L/s and a V_{b} value of 1150 L/s. As V_{bz} < V_{b} the Breathing Zone Outdoor Airflow is much more than the minimum amount required by ASHRAE 62.1-2010. This ensures that the IAQ of the offices spaces are met.

**Site Renewable Energy**

To minimize the final energy consumption, solar photovoltaic (PV) panels are recommended for installation on the roof. The web-based PVWatts calculator was used (National Renewable Energy Laboratory (NREL), 2015). The same EPW file was used in the analysis, with a tilt angle of 24.8°, a total Solar PV roof area of 50m², and a reduction in the incident solar radiation from shadows considered taken into account when calculating the system losses. A standard module size with a direct current (DC) system size of 8 kW, in a fixed (open rack) array configuration was specified. The calculated annual energy output is 12,844 kWh (see Figure 24).

![Image](image2.png)

**Figure 24** Solar PV energy generation and installation footprint

**DISCUSSION**

In the natural ventilation and thermal coupling process, the cooling consumption is set to zero when natural ventilation is adequate for indoor thermal comfort. It should be noted that although there is probably part-load performance from the direct expansion HVAC system’s stand-by mode, the energy consumption was not taken into account in this workflow for ease of calculations.

**CONCLUSION**

There is a predicted energy saving of 190 kWh/m² in annual energy consumption, which is 71% less as compared to the base condition for the case study building. In terms of greatest energy reduction, the strategies consisting of building envelope, lighting controls, and HVAC systems, contributed the most. Although the passive strategies employed were not the most effective, the natural ventilation strategies (together with a mixed-mode HVAC system) contributed to an overall reduction of 33% in the number of hours annually when mechanical cooling is required (see Figure 25). This is challenging especially in a hot and humid climate like New Delhi, India, with the need to maintain thermal comfort in the office spaces.

This paper has described a design and simulation workflow with a walkthrough of the various software packages used, as well as the various processes involved in the execution of the simulation and calculation analysis. The intent is to help designers and energy modelers consider such BPS workflow as an additional option in the DP for future projects, in order to minimize energy consumption of buildings.

**ACKNOWLEDGMENTS**

The authors would like to thank Ali M. Malkawi, Holly W. Samuelson, and Alejandra Menchaca for their advice and guidance.
REFERENCES


