ENVIRONMENTAL ANALYSIS AS A TOOL FOR BUILDING DESIGN REMEDIATION

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Abstract

Traditionally, the design process in architecture has been of creative nature, where primary driving factor is visually appealing aesthetics and spatial quality. Since aesthetic and spatial innovation both are mainly qualitative, it is mainly the decisions taken by the architect that shapes the outcome of a design process. There are some variables that typically affect the final outcome, such as; floor space ratio, and cost of construction, however, it is the aesthetic of building which is the delineating factor in design process.

If the goal is to develop an environmentally responsive building, there are climatic variables, which are quantifiable and thus the design can be tested against such variables. In this paper, a hypothetical case is assumed, and it is redesigned with a clear goal of improving its environmental performance. During the process, building performance quantification tools were used to test the hypothetical design across climatic variables. Based on initial testing, design objectives were defined and a design case was proposed, which was further tested across the same variables, and a comparative analysis of results was carried out.

Keywords

Building performance simulation, Environmental design, Daylight analysis, Illuminance, CFD, Energy Simulation, Climate analysis

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Acknowledgment

I am thankful to Professor Ali Malkawi for explaining the potential of environmental assessment during the design process and for detailed introduction of computational fluid dynamics and its use in building design testing. His lectures on CFD testing encouraged and inspired me to conduct iterative CFD analysis for nearly most of the design modifications.

I also thank Professor Yun kyu Yi for being my mentor and for providing detailed introduction on how performance measurement tools think and work. It opened up a new frontier for investigation. It made me realize that understanding of the software limitations and the underlying assumptions of a calculation engine can catapult the possibilities of time saving in simulation process as well as accuracy in final results.

I would also like to thank my friends and colleagues, Shadi, Mahnaz, Weiyue, and Steven for providing time saving tips during my simulation process. It enabled me to address my objectives in efficient manner.

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1. Introduction

It is a widely known fact that the building industry is the biggest contributor of carbon emission after manufacturing industry. And thus, there is significant push for the development and implementation of energy efficient building designs.

Carbon emission from buildings can be reduced by;

1. Lowering operation energy use in buildings by developing climate responsive designs,
2. Lowering the carbon emission from conventional supply of resources to a building, such as; potable water, gas, electricity, etc., by harnessing natural resources available on site.
3. Lowering the carbon emission from the process of material development, manufacturing, and transportation, by increased use of locally available materials and recycled materials.

Since the invention of air conditioning systems, the buildings have been designed to rely on mechanical systems to provide necessary comfort condition indoors. However, with a detailed analysis of climate climatic variables of a particular location, a climatically responsive building can be designed, where relevant design strategies will be employed to develop a comfortable setting indoors.

Designing a climatically responsive building requires an iterative environmental analysis of design decisions throughout the design process, so that the final design performs well across environmental indices, and satisfies the comfort criteria for potential occupants.

1A. Description of Assumed Building

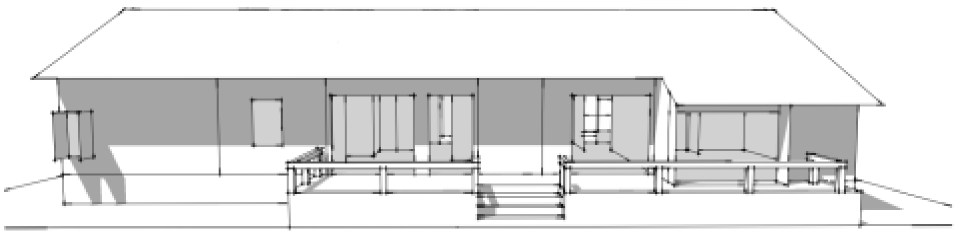


Fig.01 Front View of hypothetical building

A ground storey house in urban setting of Philadelphia was assumed for the testing and redesigning. The geometry was developed within a 3D modeling tool for spatial clarity, and design of the house. Later on in the process, the model was directly used for daylight testing and further design development.

Area: 271 m^2
Roof: Pitched roof with standard wooden frame, externally finished with brown colored shingled times

Floor: 120 mm P.C.C. (Plain Cement Concrete) on 300 B.B.C.C. (Brick Batt Cement Concrete) with direct earth contact. Floor is assumed to be finished with carpet with fiber pad.
Walls: Above grade dry walls are assumed to be standard wooden frame and plywood construction, with 25 mm fiber board sheathing (R-1.3), and R-19 batt insulation.
Windows: Double glazed, 6 mm bronze-tinted outside pane, with light-colored interior mini blinds. Window normal solar heat gain coefficient (SHGC) (Solar Heat Gain Coefficient) = 0.49. Windows are non-operable and mounted in aluminum frames with thermal breaks having overall combined U = 3.18 W/(m^2•K).

Occupancy: 0 people from 8:00 AM to 5:00 PM. (Schedule 01), 5 people from 5.00 PM to 8.00 AM (Schedule 02), 5 people from 8.00 AM to 8.00 AM.

Doors: Type 01_Opaque, Steel framed with polyurethane core, Type 02_Single clear 6 mm glass
Exterior Windows: Double low-e 3mm clear glass with 6 mm air gap in between

Window to Wall ratio: South 3.4% , North 7.3%, East 0.0%, and West 0.0%

Lighting: is defined by means of lighting power density for three types of space uses; residential (0.80 w/ft^2), Storage (0.50 w/ft^2), Storage (0.30 w/ft^2)
Equipment: Equipment density was assumed to be 0.80 w/ft^2 in residential area, and 0.15 w/ft^2 in laundry.
Water consumption: was assumed to be 20 gallons/ person/ day.

Infiltration: For purposes of this example, it is assumed that the building is maintained under positive pressure during peak cooling conditions and therefore has no infiltration. Assume that infiltration during peak heating conditions is equivalent to one air change per hour.

Weather data: Typical Meteorological Year 3 Philadelphia International Airport 724080 file was used for environmental analysis.
Inside design conditions: 22.2°C for heating; 23.9°C with 50% Rh for cooling.

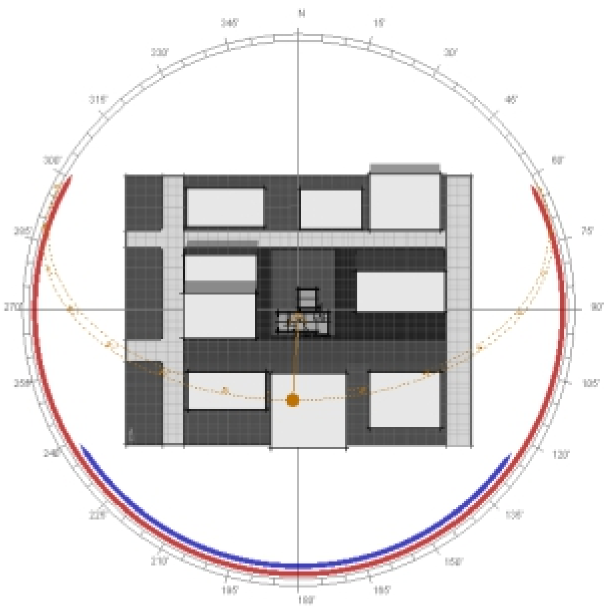


Fig.02 June 01st_Noon

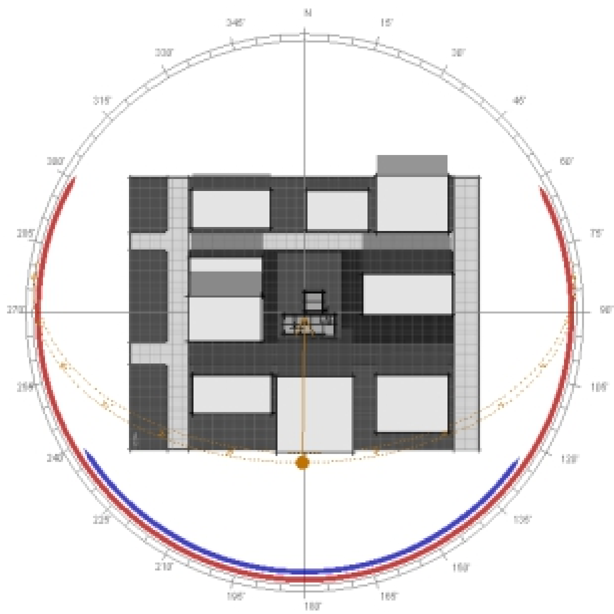


Fig.03 August 31st_Noon

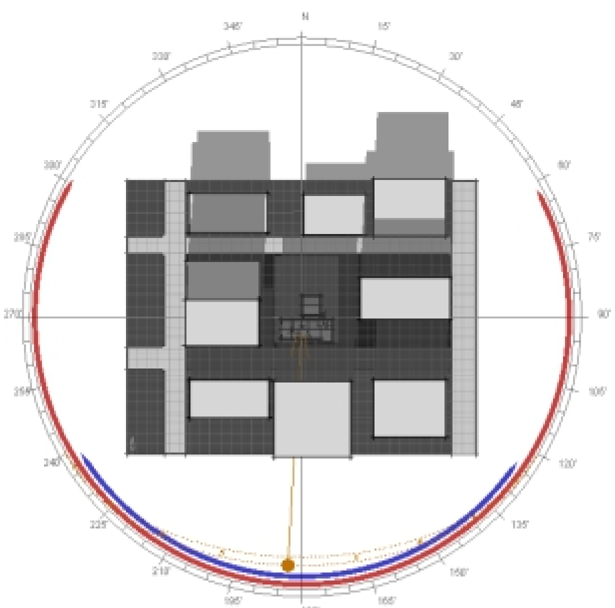


Fig.04 December 21st_Noon

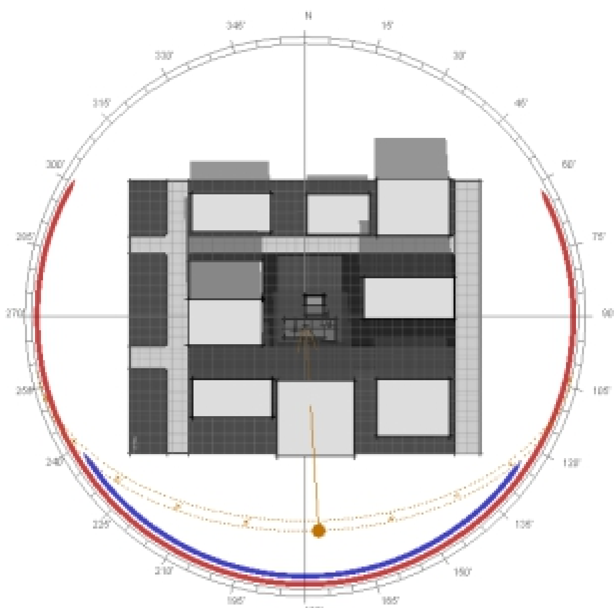


Fig.05 February 28th_Noon

2. Locating Building on Site

2A. Shadow Analysis

From shadow analysis, it becomes evident that the whole site remains shaded due to relatively taller building around site. In Philadelphia climate, harnessing solar radiation during winter months can be a good strategy. In addition to that, savings can be achieved with the use of daylight.

Since this analysis does not substantially provide directive for a beneficial building location, external wind accessibility analysis will be carried out to decide building location on site.

2B. Weather Analysis to Determine Probable Natural Ventilation Period

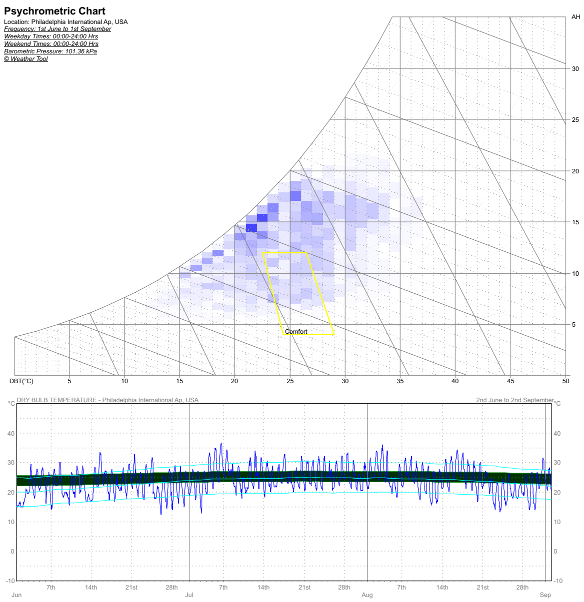


Fig.06
Psychrometric Chart + Dry bulb
June 1st to September 1st
Summer Period

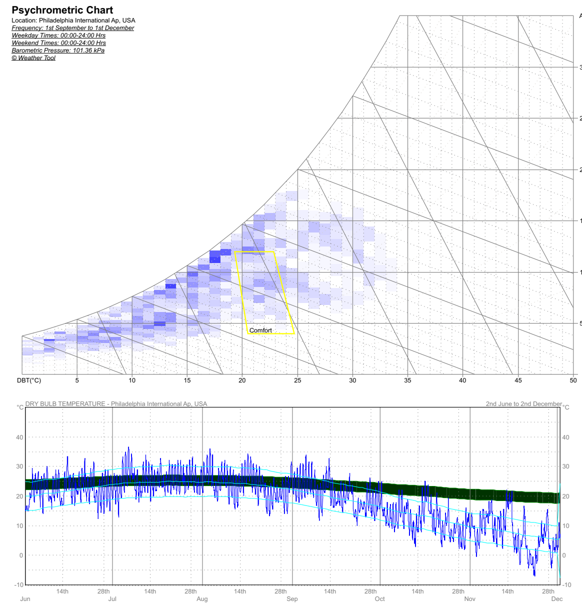


Fig.07
Psychrometric Chart + Dry bulb
September 1st to December 1st
Autumn Period

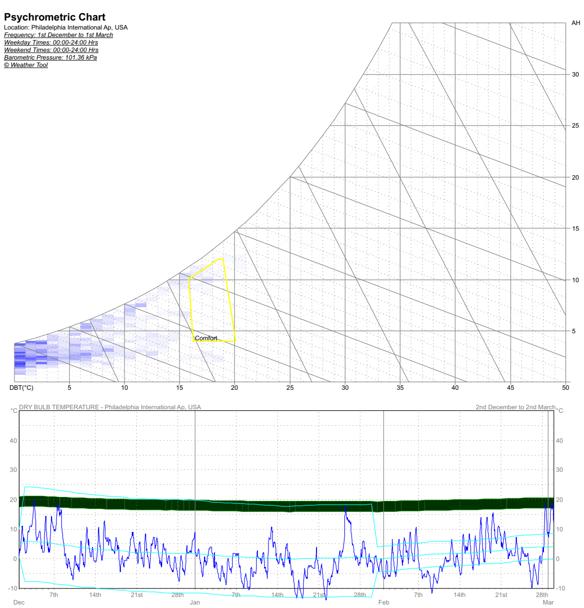


Fig.08
Psychrometric Chart + Dry bulb
December 1st to March 1st
Winter Period

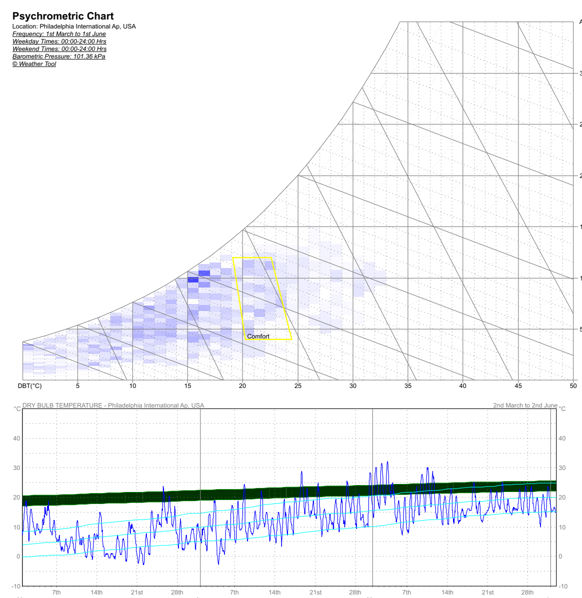
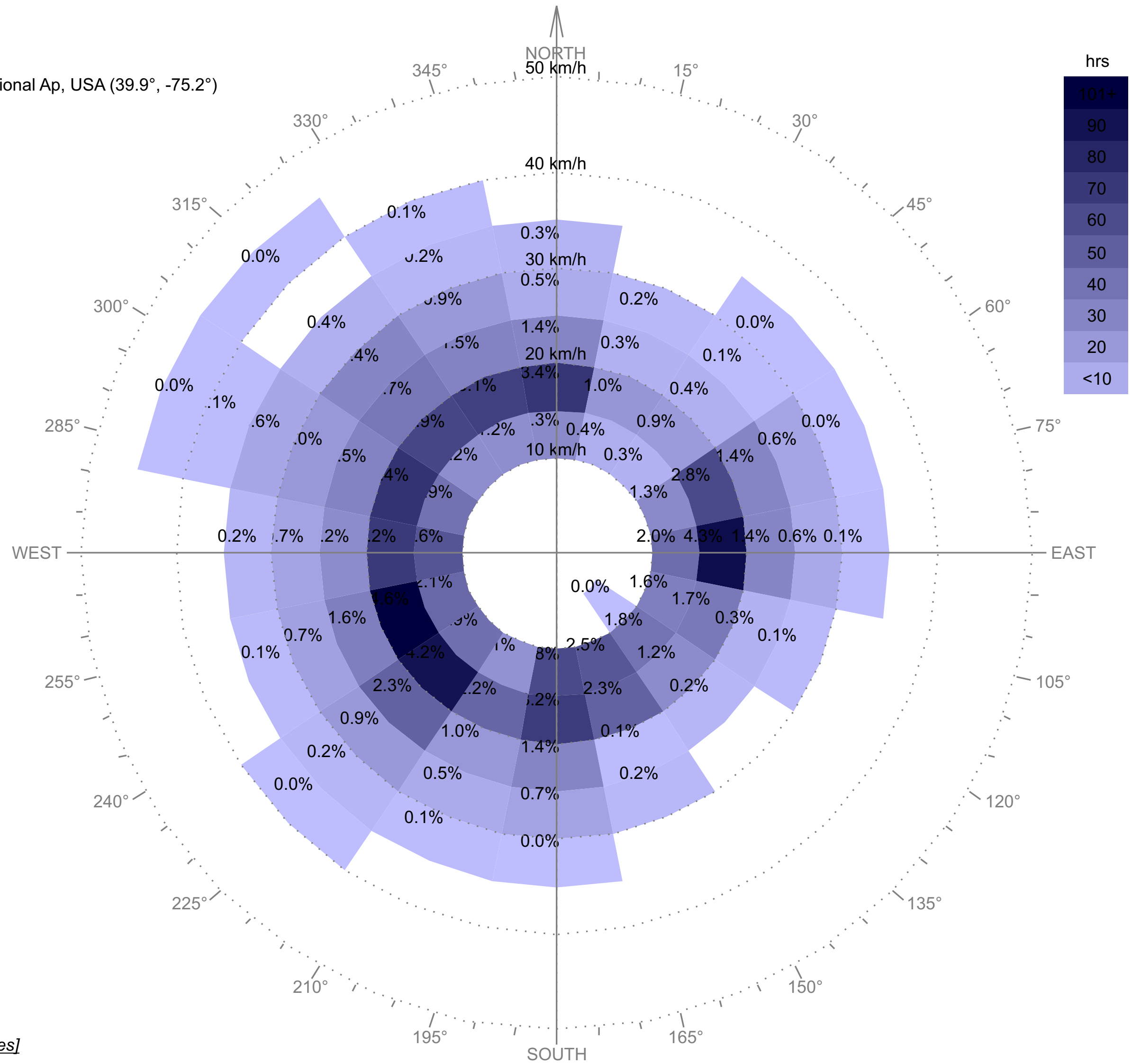


Fig.09
Psychrometric Chart + Dry bulb
March 1st to June 1st
Spring Period

Prevailing Winds

Wind Frequency (Hrs)

Location: Philadelphia International Ap, USA (39.9°, -75.2°)
Date: 1st June - 31st August
Time: 00:00 - 24:00
© Weather Tool



[Duration shown as percentages]

Psychrometric chart along with the dry bulb temperature profile for four seasons of Philadelphia was analyzed to determine the possible natural ventilation period for Philadelphia location. It was observed that although the temperature and relative humidity points in psychrometric chart falls under the comfort zone for autumn and spring periods, the dry bulb temperature for both periods do not stay in comfort range throughout the period. Hence, only the summer period can be utilized for possible natural ventilation strategy.

Wind rose diagram was analyzed for summer period in order to determine the prevailing wind direction for Philadelphia location. Based on percentage of wind frequency hours, it was noted that southwest is the prevailing wind direction for Philadelphia location. This wind direction and wind velocity will further be used to perform external wind accessibility analysis.

Fig.10 Wind Rose Diagram for
June 1st to August 31st.
Summer Period

2C. External Wind Accessibility Analysis

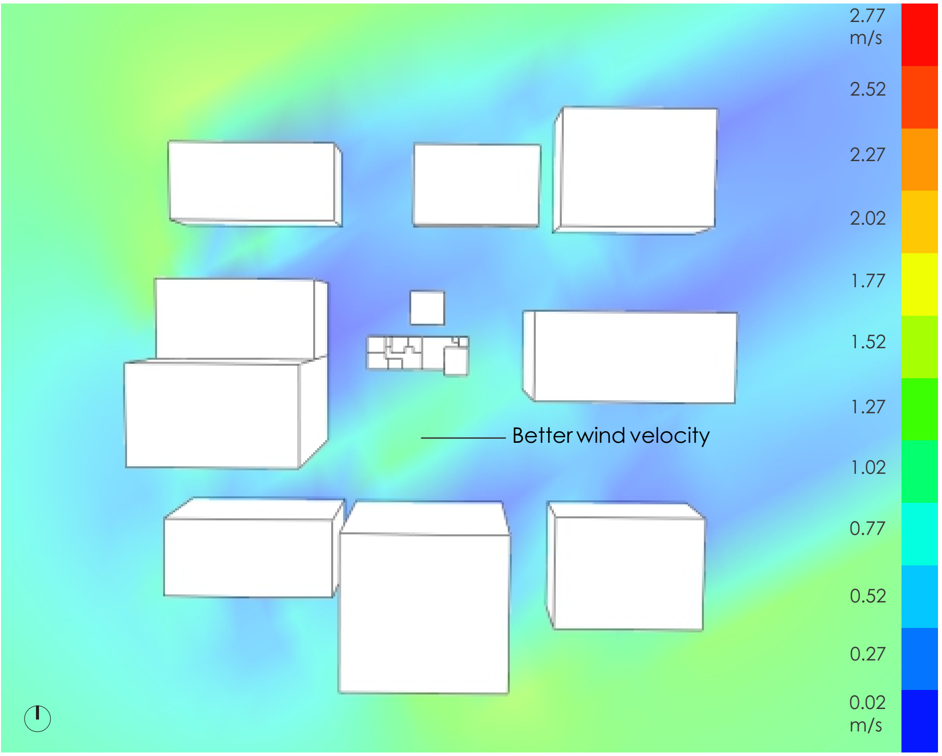


Fig.11 External Wind Accessibility Analysis for Position 01

In initial analysis, the building is located at the center of the site and it is observed that the wind velocity is greater near the southern end of site than the rest of the site. The adjacent buildings augment the local wind availability due to their close adjacency.

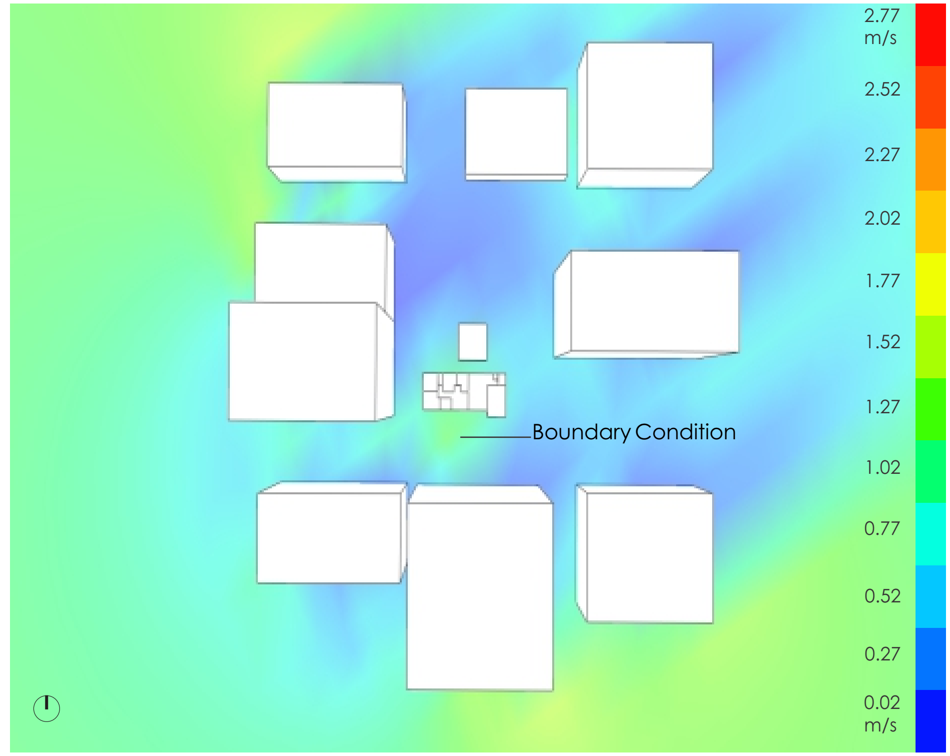


Fig.12 External Wind Accessibility Analysis for Position 02

Therefore, the building was shifted southwards in order to maximize the received wind velocity on the face of the wall. This wind velocity (1.02 m/s) will further be used for internal wind analysis as boundary condition.

3. Developing a Baseline Case

After the location of the building is determined, daylight studies will be conducted to evaluate the baseline model for illuminance levels and glare index. 4 cameras have been set up for daylight studies.

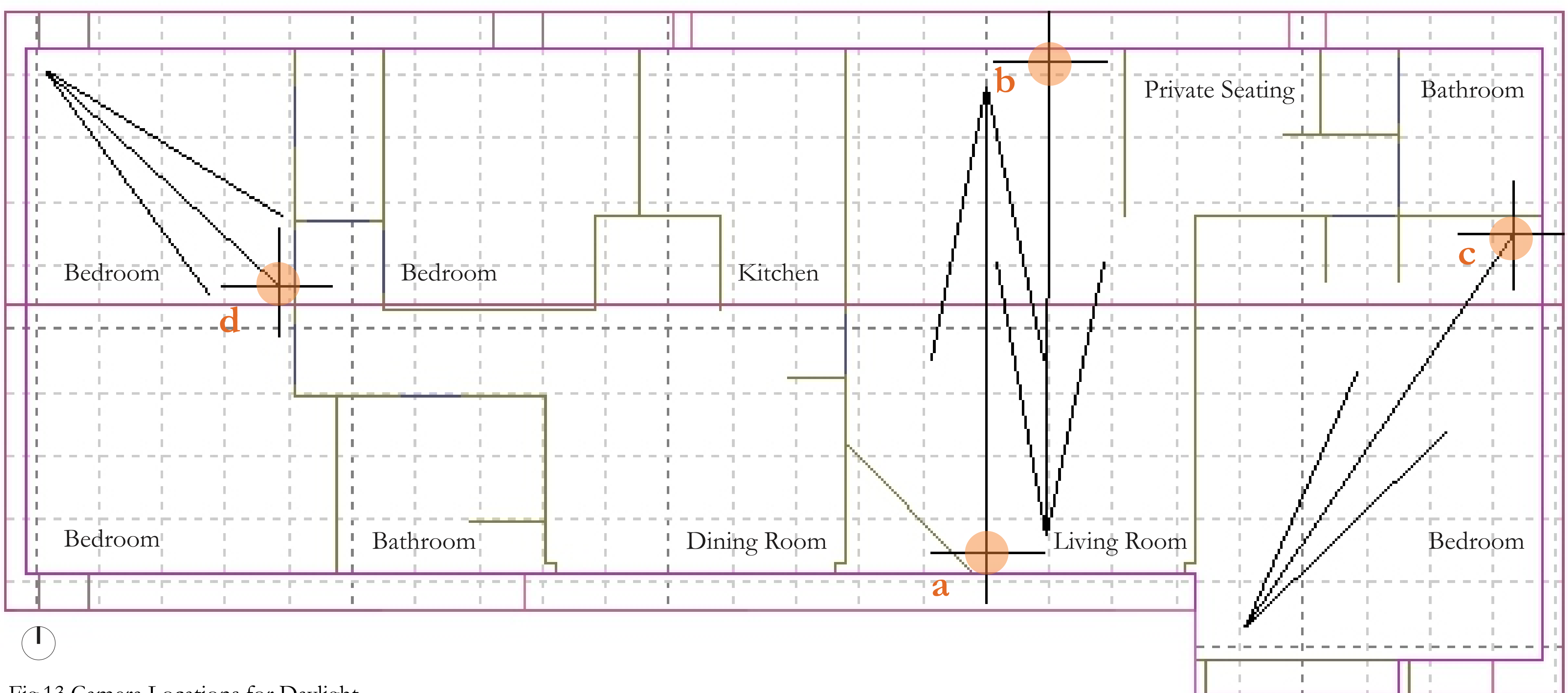


Fig.13 Camera Locations for Daylight

3A. Daylight Analysis

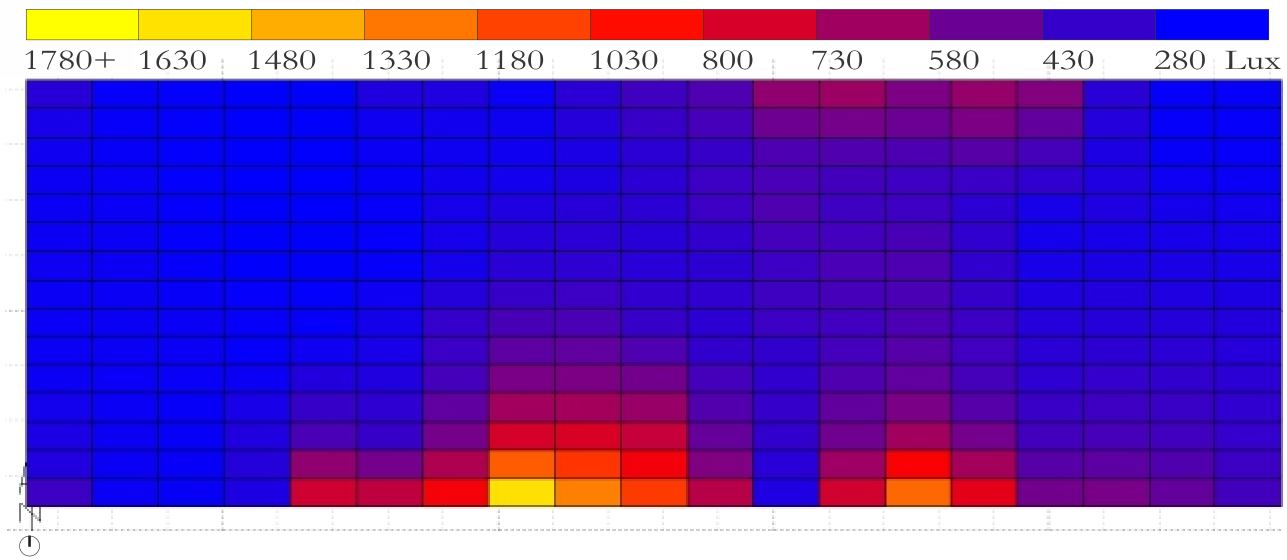


Fig.14 Illuminance Analysis at 750 mm from Floor

June 1st 12.00 P.M. Sunny Sky

Illuminance analysis for 1st of June under Sunny sky condition revealed that the average illuminance on the analysis plane is around 282 lux, which is less than sufficient for a well lit residential space for normal use.

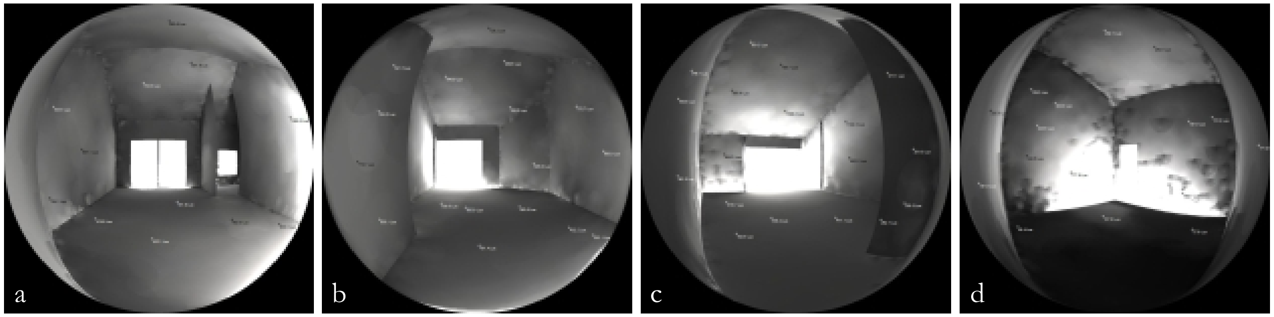
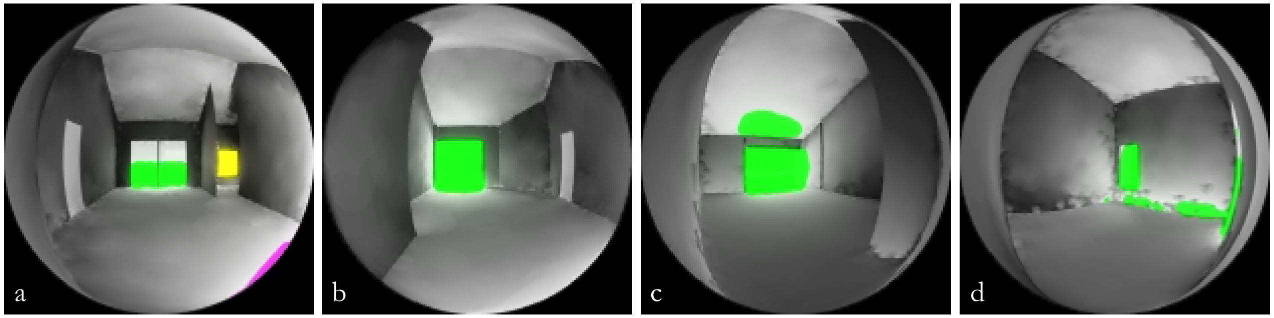


Fig.15 Illuminance (Lux)



DGI 19.38 DGI 19.46 DGI 17.76 DGI 18.29

Fig.16 Daylight Glare Index

- Imperceptible Glare
- Perceptible Glare
- Disturbing Glare
- Intolerable Glare

Fig.17 Illuminance Analysis at 750 mm from Floor

August 31st 12.00 P.M. Sunny Sky

Illuminance analysis for 31st of August under Sunny sky condition revealed that the average illuminance on the analysis plane is around 212 lux, which is less than sufficient for a well lit residential space for normal use.

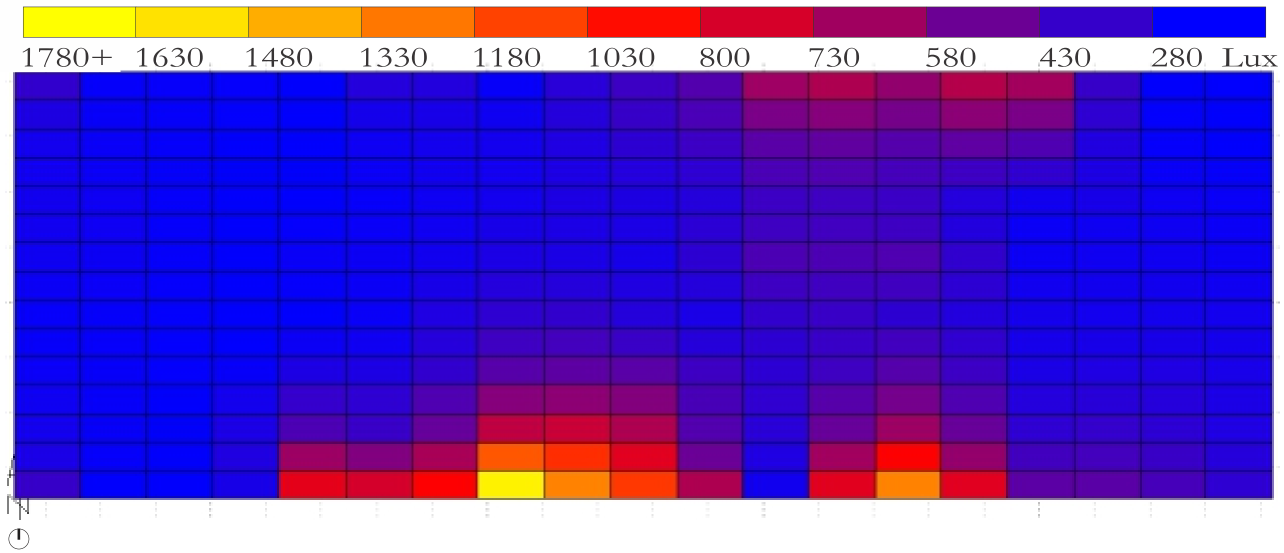


Fig.18 Illuminance (Lux)

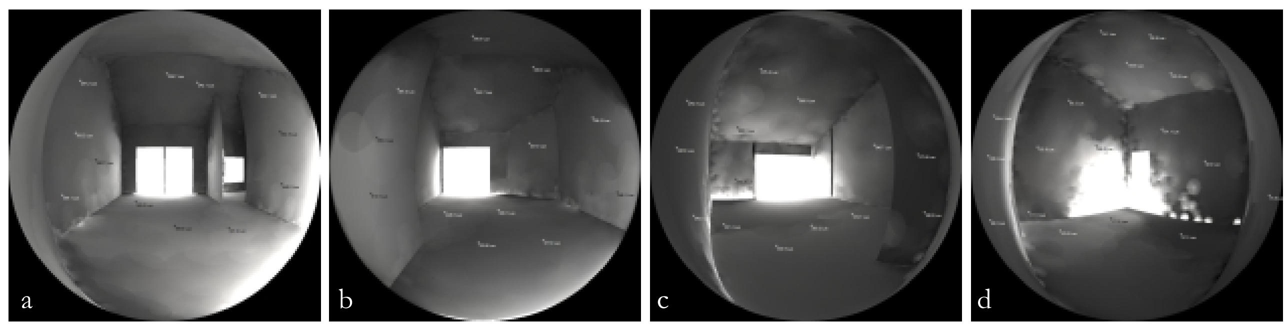


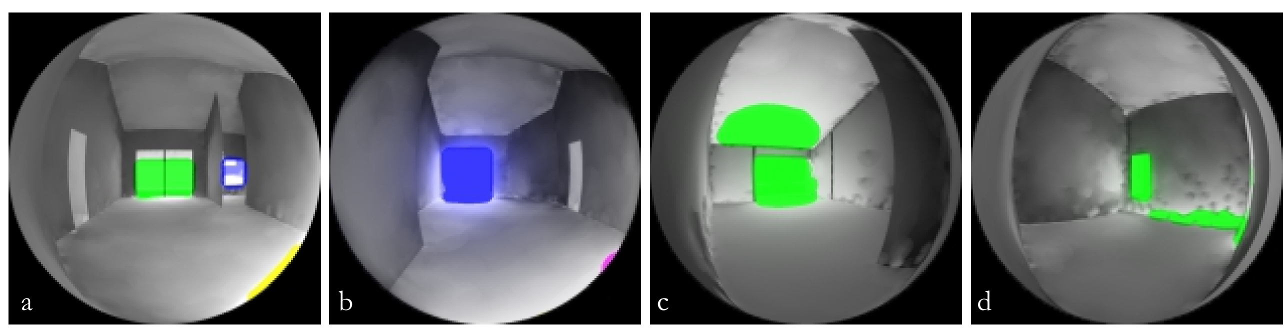
Fig.19 Daylight Glare Index

Imperceptible Glare

Perceptible Glare

Disturbing Glare

Intolerable Glare



DGI 21.98 DGI 20.91 DGI 15.02 DGI 18.13

Fig.20 Illuminance Analysis at 750 mm from Floor

December 1st 12.00 P.M. Overcast Sky

Illuminance analysis for 1st of December under Overcast sky condition revealed that the average illuminance on the analysis plane is around 92 lux, which is less than sufficient for a well lit residential space for normal use.

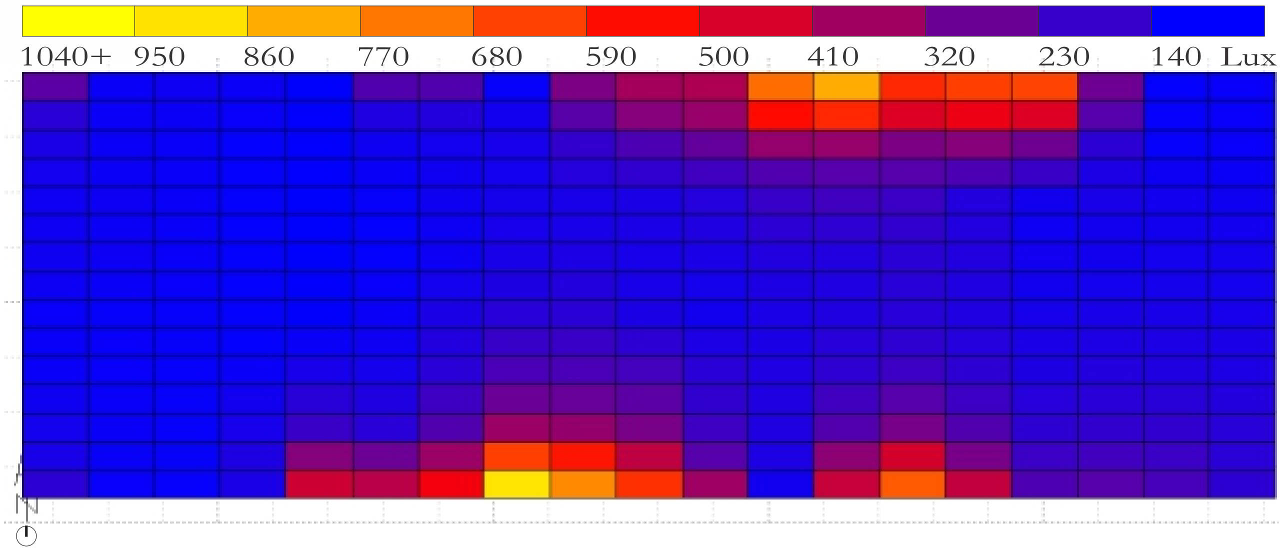


Fig.21 Illuminance (Lux)

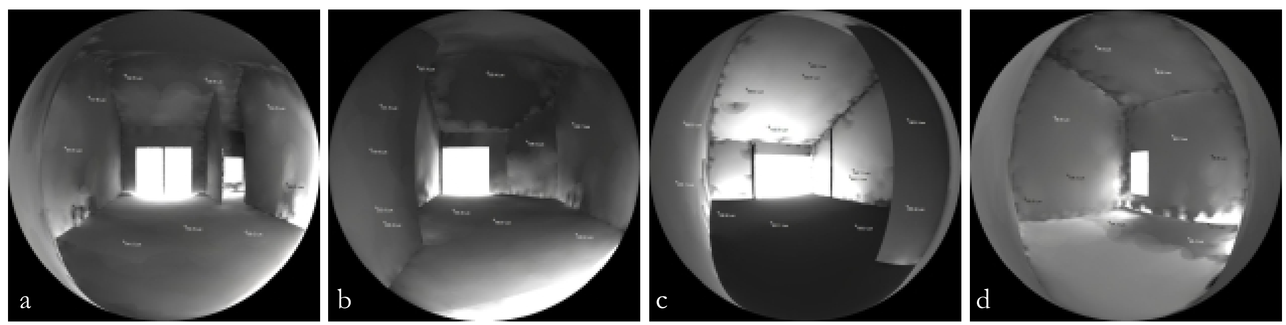


Fig.22 False Color Image

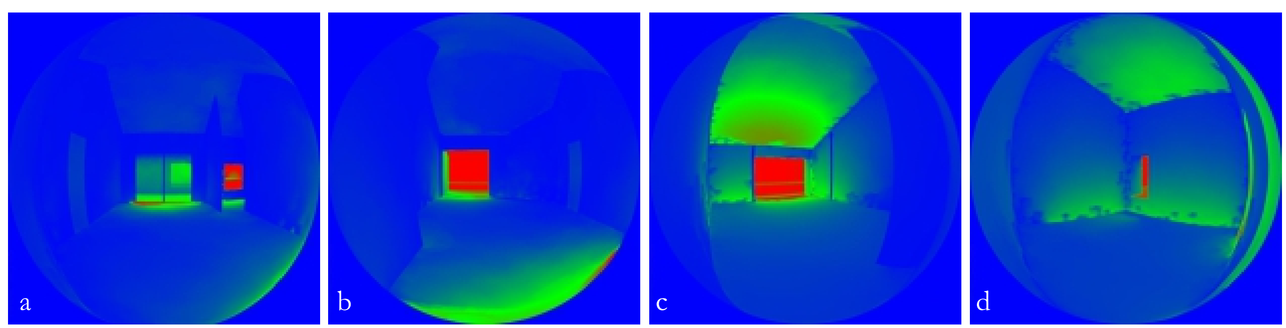


Fig.23 Illuminance Analysis at 750 mm from Floor

February 28th 12.00 P.M. Overcast Sky

Illuminance analysis for 28th of February under Overcast sky condition revealed that the average illuminance on the analysis plane is around 122 lux, which is less than sufficient for a well lit residential space for normal use.

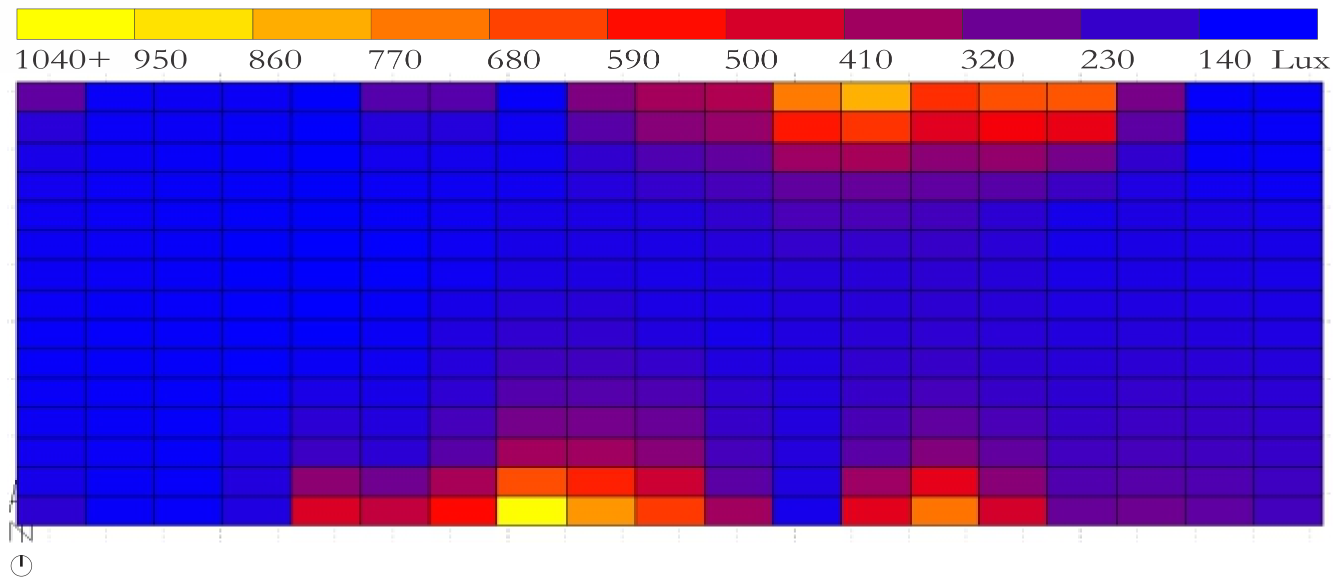


Fig.24 Illuminance (Lux)

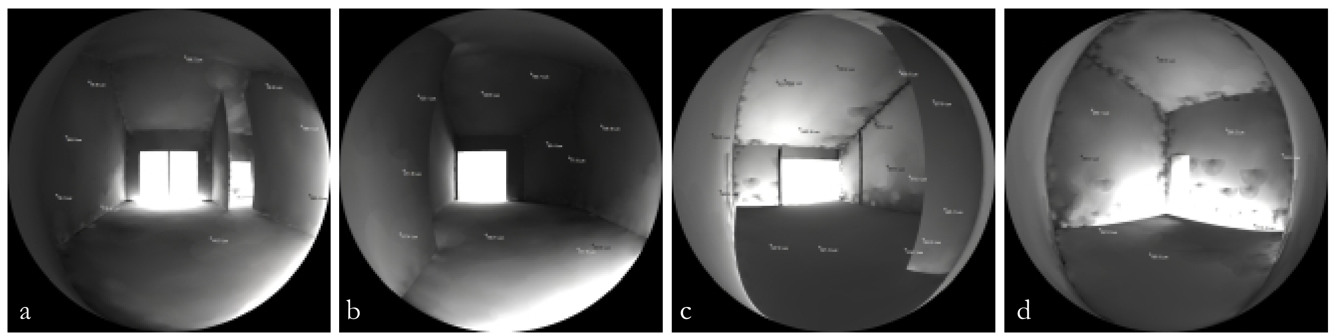
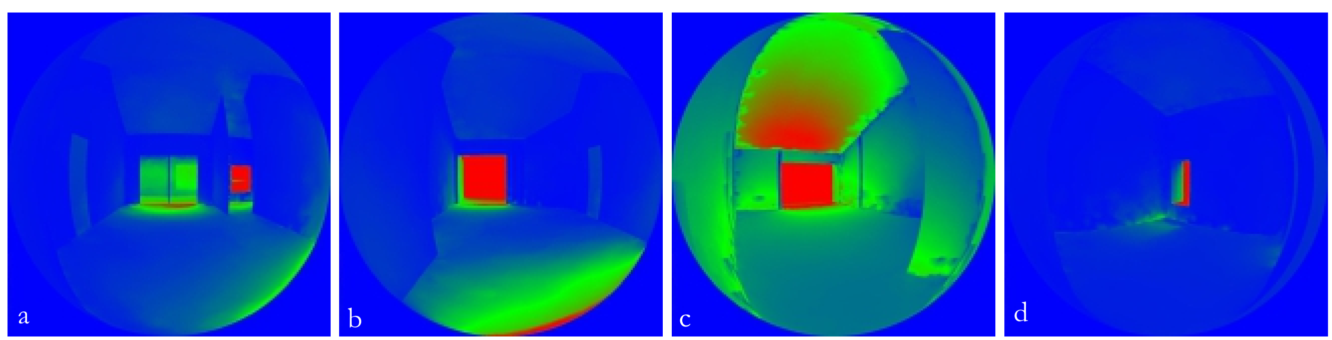


Fig.25 False Color Image



3B. Wind Velocity Analysis

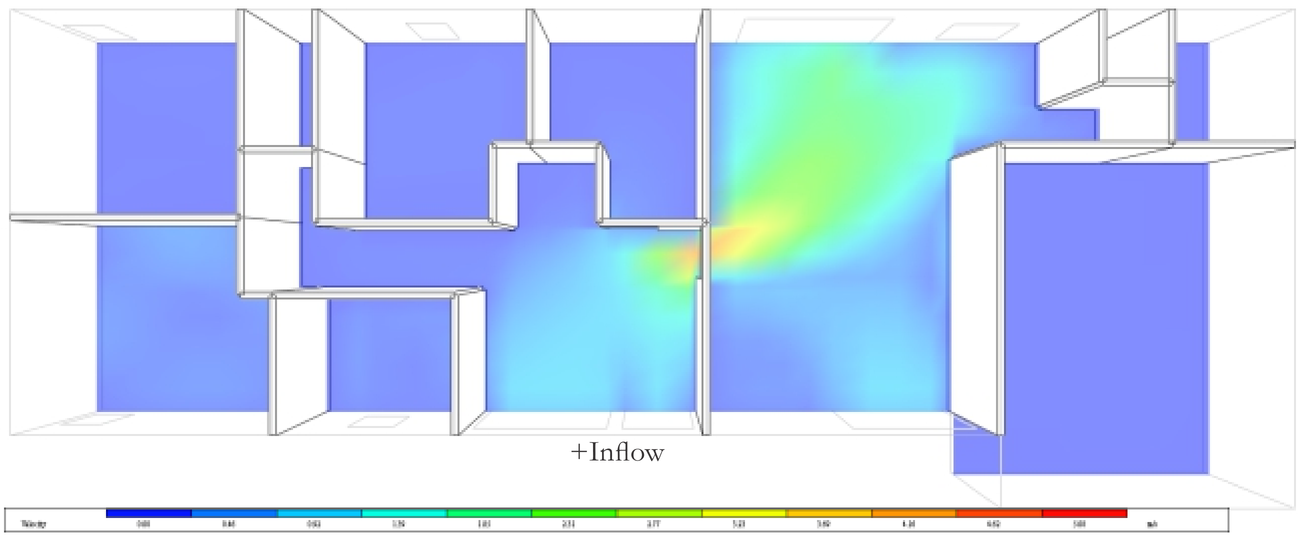


Fig.26 Velocity Contour at 1200 mm level from floor

Wind velocity in the rage of 1.0 m/s to 2 m/s ensures physiological cooling effect to the occupant of the space. Wind velocity derived in external analysis is used here in internal analysis as velocity at boundary wall.

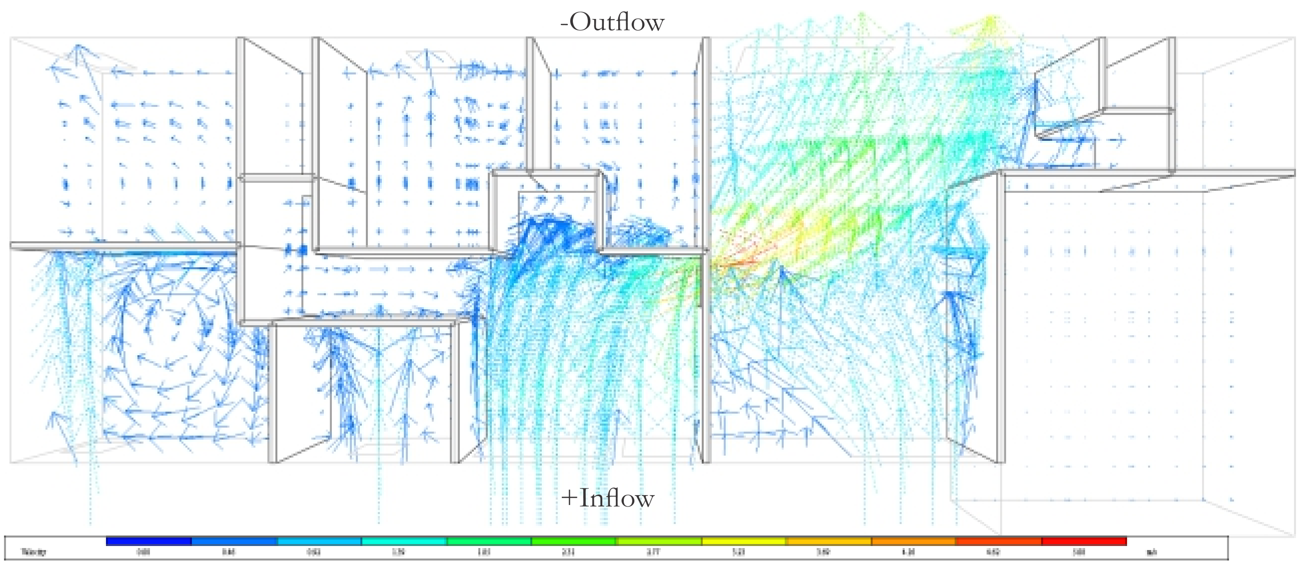
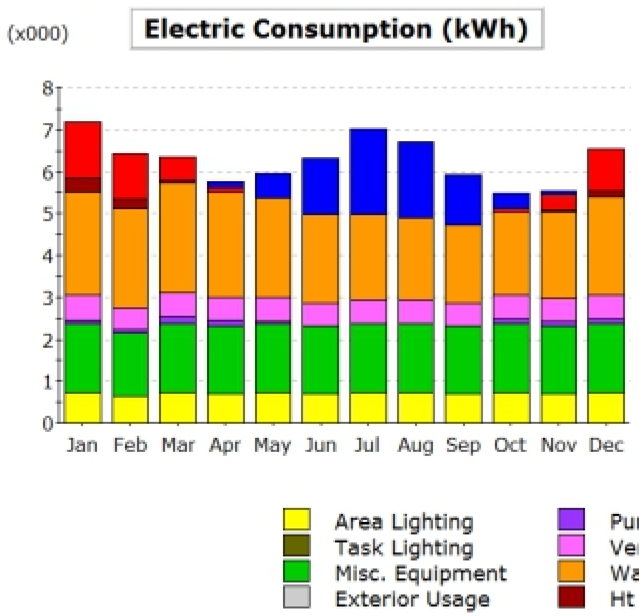
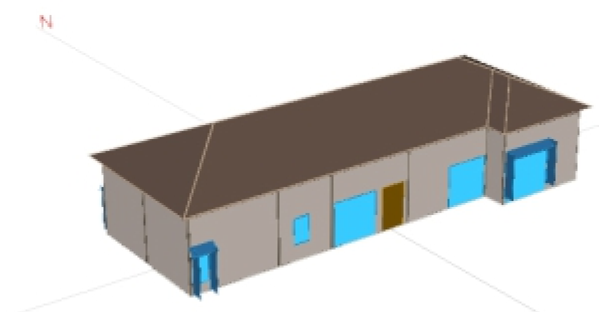


Fig.27 Velocity Vector at 1200 mm level from floor

The Wind Velocity Contour and Wind Velocity Vector displays that except the central area, most of the spaces are not sufficiently ventilated due to lack of strategical location of openings. Except the central area, rest of the areas of house receives wind at 0.46 m/s velocity, which needs to be amplified. However, the central area receives wind at 3.369m/s velocity, which requires to be reduced and a uniform wind distribution in all the spaces is desired.

3C. Energy Analysis





Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.12	0.61	1.34	2.05	1.83	1.21	0.37	0.08	-	7.61
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	1.34	1.08	0.55	0.13	0.00	-	-	-	-	0.08	0.37	1.01	4.56
HP Supp.	0.32	0.24	0.06	0.01	0.00	-	-	-	-	0.01	0.04	0.14	0.80
Hot Water	2.49	2.36	2.63	2.50	2.38	2.13	2.02	1.93	1.86	1.99	2.08	2.34	26.71
Vent. Fans	0.56	0.51	0.56	0.54	0.56	0.54	0.56	0.56	0.54	0.56	0.54	0.56	6.61
Pumps & Aux.	0.08	0.09	0.15	0.15	0.03	0.00	-	-	0.00	0.09	0.11	0.11	0.82
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	1.67	1.51	1.67	1.62	1.67	1.61	1.67	1.67	1.62	1.67	1.62	1.67	19.65
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.72	0.65	0.72	0.70	0.72	0.70	0.72	0.72	0.70	0.72	0.70	0.72	8.47
Total	7.18	6.42	6.35	5.75	5.97	6.33	7.02	6.72	5.93	5.49	5.54	6.55	75.24

Fig.28 Energy Simulation Result
Annual Electricity Consumption (Kwh)

In case of any analysis project, when design is modified with a goal of improving daylight levels and wind velocity, a thorough energy analysis is important. Since highly thermodynamic nature of buildings, any change in building's form to enhance daylight levels and wind velocity may ultimately warrant a greater energy consumption than the initial design. Therefore, energy simulation shall always be performed simultaneously to evaluate the performance of design solution across energy consumption indices.

In this case, baseline energy analysis shows that Water Heating and Equipment are the primary consumers of energy in this example. Since daylight is not kept on in energy simulation process, the area lighting energy is constant throughout the year. The analysis shows energy for cooling during summer months and energy for heating during winter months. This profile validates the behavior of energy model in conjunction with Philadelphia weather and energy model settings. High energy consumption of water heating indicates that building suffers from high infiltration all round the year and heat loss during winter months. That calls for a relatively more insulated envelope in Proposed case.

4. Preparing a Design Case

In order to reduce heating load during winter, changes will be made in envelope construction in terms of material selection and their order of composition in wall constructions. Strategies will be developed to harness daylight as much as possible for day use. However, necessary changes will be made in south facing facade to cut off radiation during the summer months to address the reduction in cooling load during the summer months.

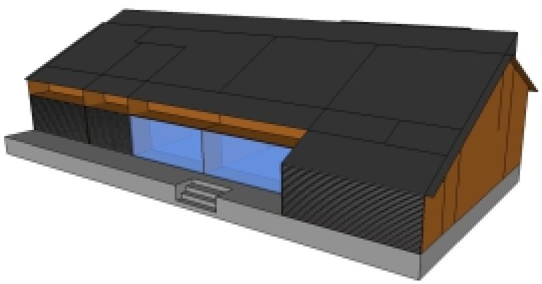


Fig.29 Louvers and Double Doors on south facade to block radiation in summer and to contain heat in winter

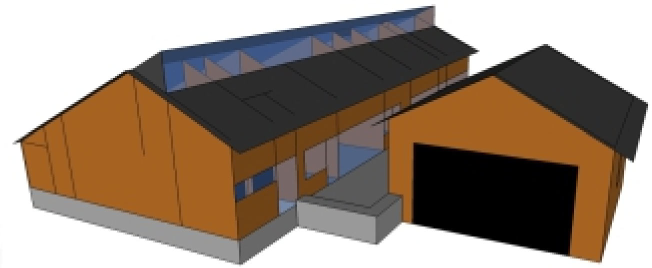
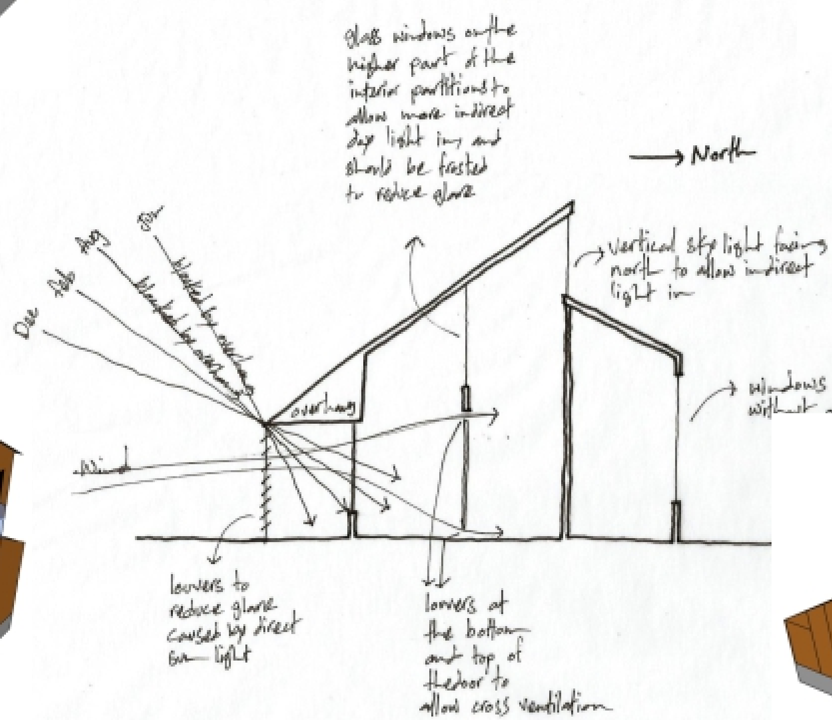


Fig.30 North Light and openings on north facade



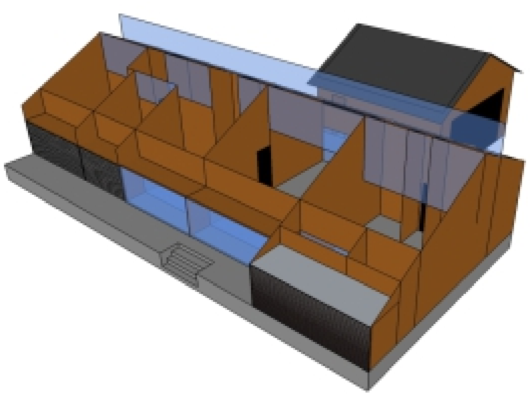


Fig.31 Fixed glass in top part of wall to bring in light from north facing skylight

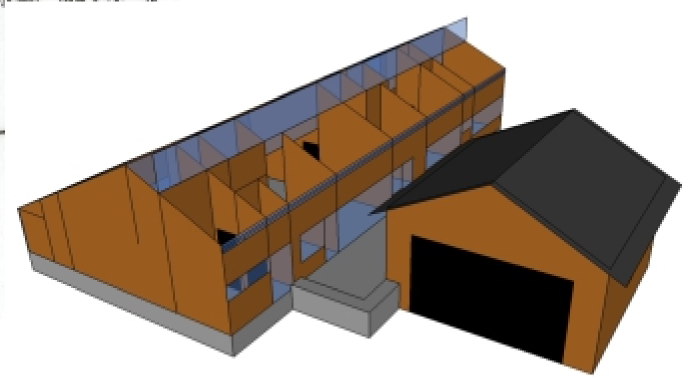


Fig.32 Operable louvers at the top of north facing wall for cross ventilation in summer

4. Testing the Design Case

4A. Daylight Analysis

Fig.14 Illuminance Analysis at 750 mm from Floor

June 1st 12.00 P.M. Sunny Sky

With shading arrangements and glass properties changed, the light distribution in house has been uniform. Illuminance is noted to be in the rage of 1000 lux compared to 90 lux in baseline model. With increased glass area, glare can be a potential issue, However, due to louvers in place the glare received from south in negligible.

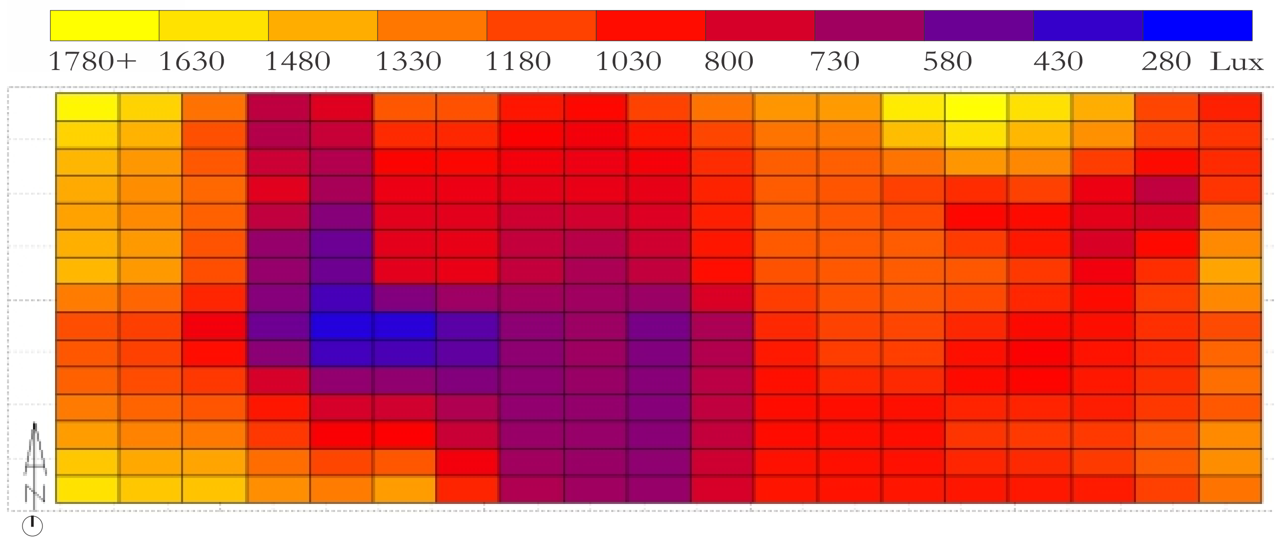


Fig.15 Illuminance (Lux)

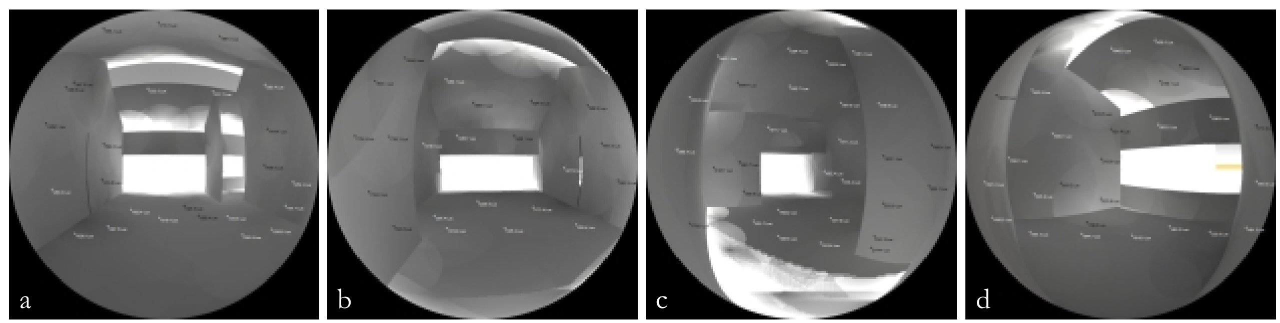
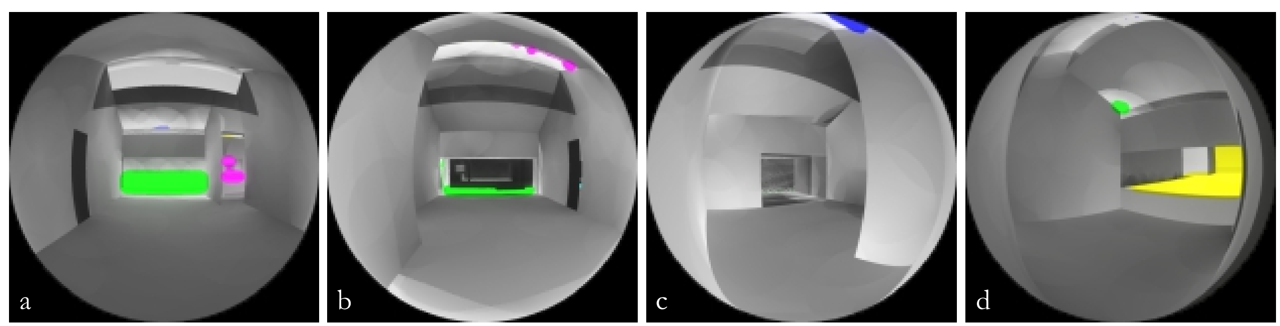


Fig.16 Daylight Glare Index

- Imperceptible Glare
- Perceptible Glare
- Disturbing Glare
- Intolerable Glare



DGI 16.94 DGI 8.33 DGI 12.18 DGI 12.29

Fig.14 Illuminance Analysis at 750 mm from Floor

August 31st 12.00 P.M. Sunny

Illuminanace remains in the range of 600-900 lux. North light opening and glassed portion of interior walls bring in diffused light from north. The louver angle have been changed to completely block the summer sun, even through, the light distribution in most usable areas such as bedroom, dining room and living room remains close to uniform.

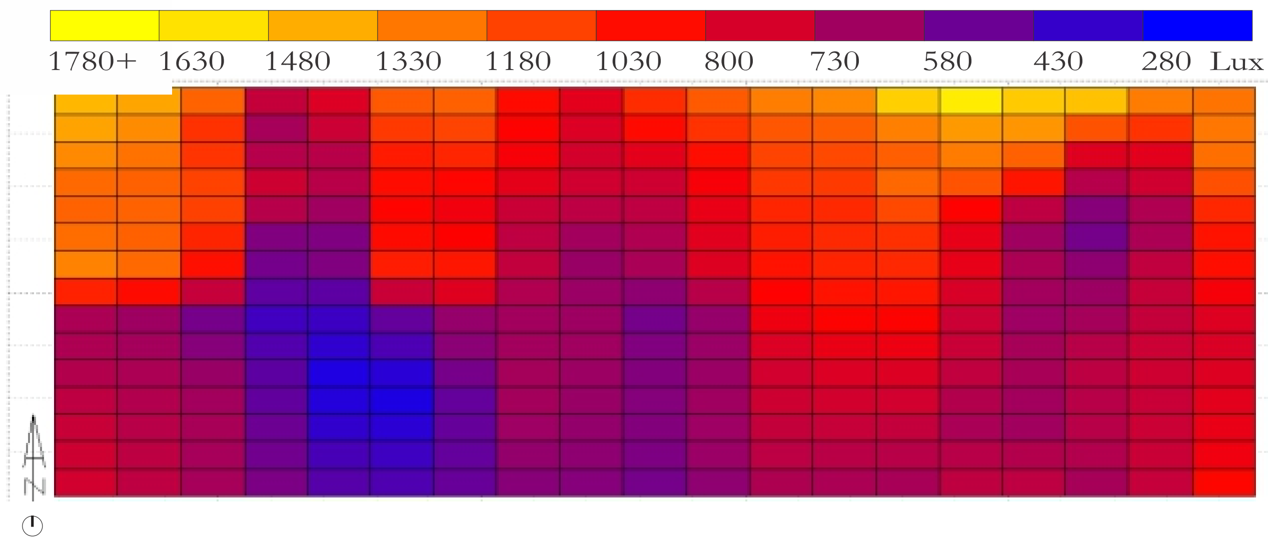


Fig.15 Illuminance (Lux)

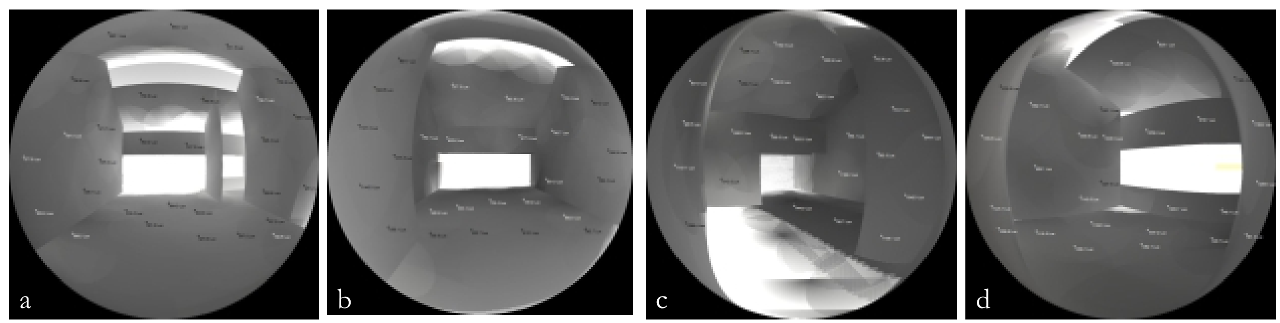
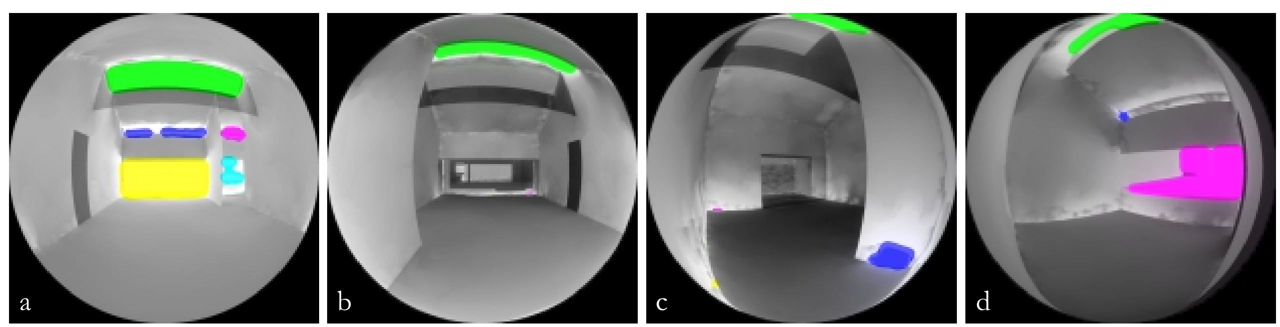


Fig.16 Daylight Glare Index

- Imperceptible Glare
- Perceptible Glare
- Disturbing Glare
- Intolerable Glare



DGI 19.92 DGI 12.54 DGI 4.36 DGI 15.12

Fig.20 Illuminance Analysis at 750 mm from Floor

December 1st 12.00 P.M. Overcast Sky

Illuminance throughout he house is noted to be improved from 2-92 lux to 500-600 lux. Increased window to wall area ratio on north facing wall and north light play important role in achieving required light levels in house.

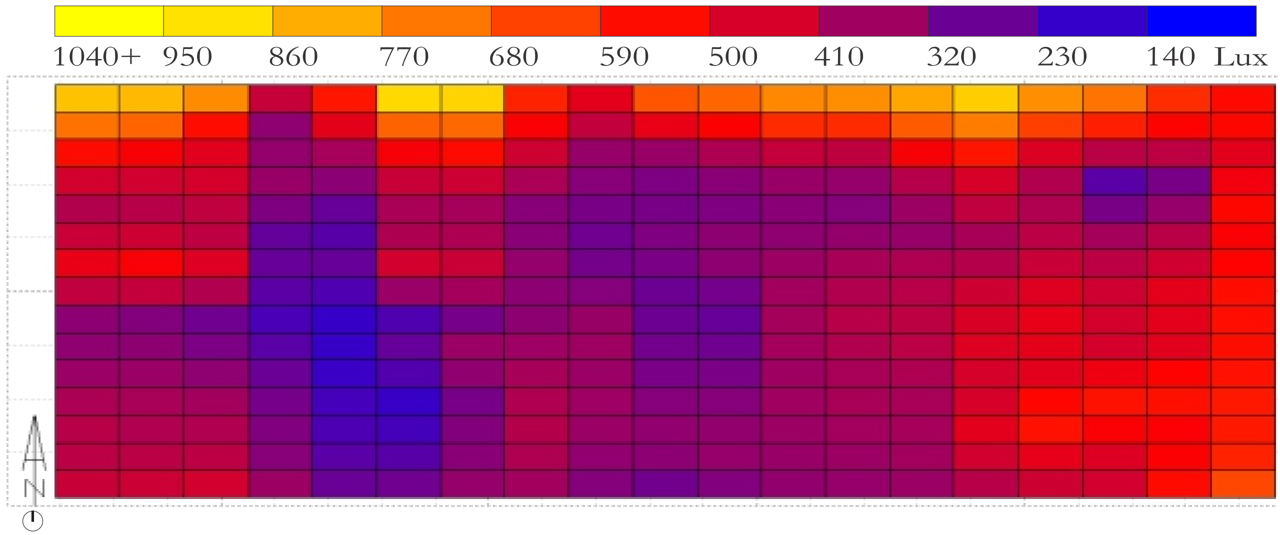


Fig.21 Illuminance (Lux)

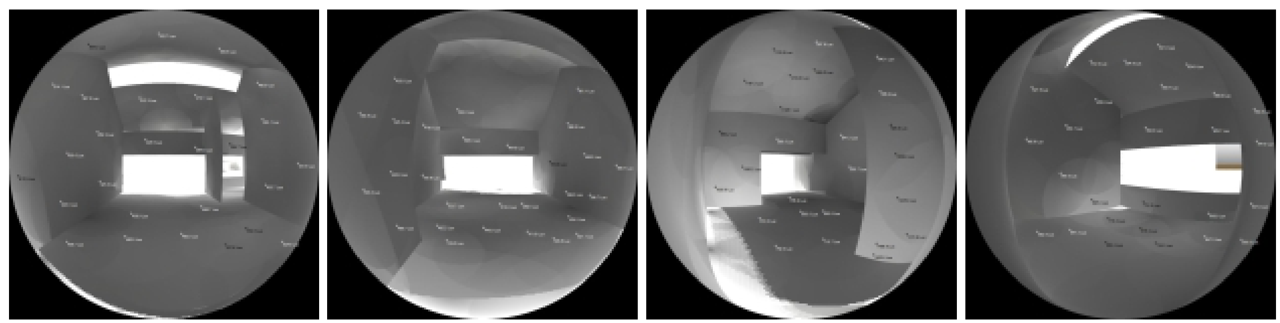
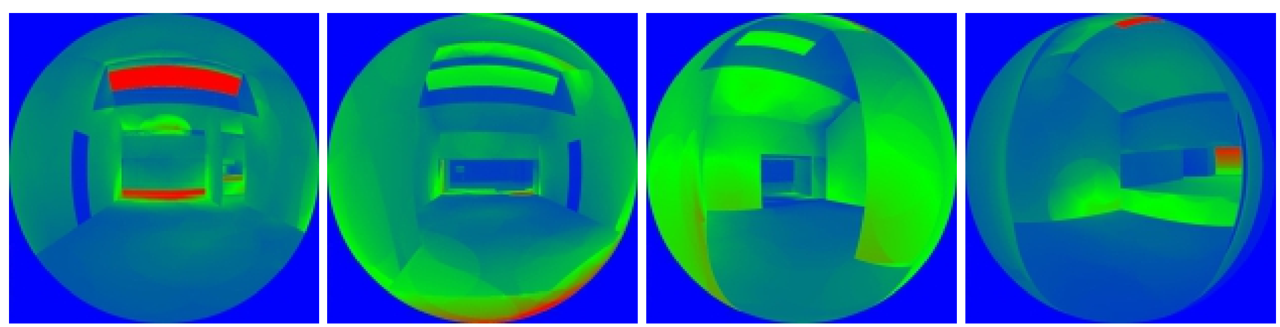


Fig.22 False Color Image



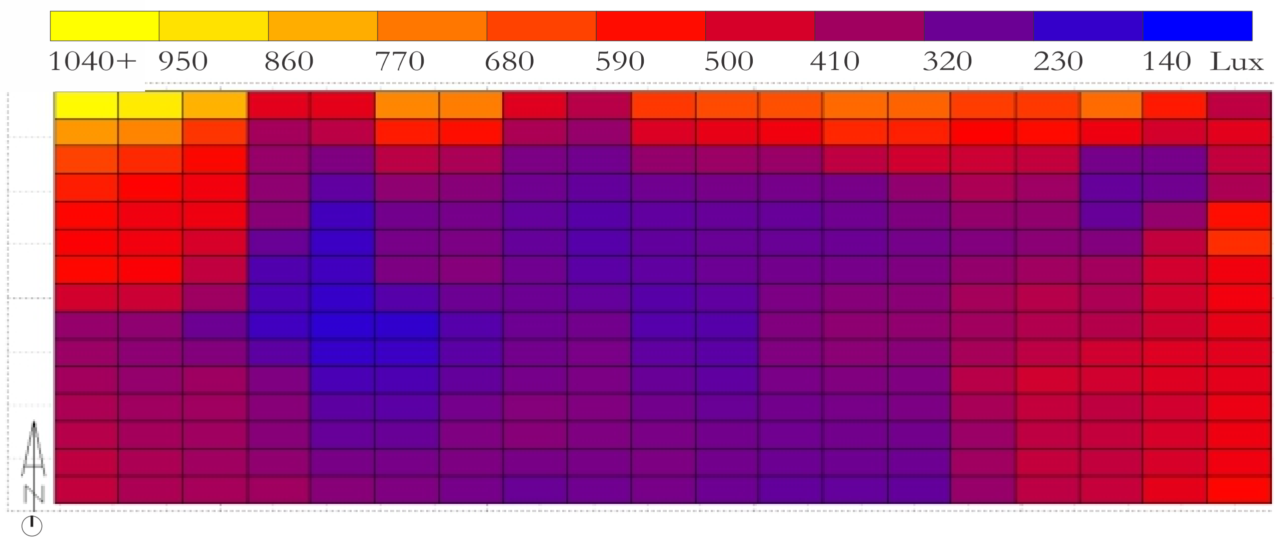


Fig.20 Illuminance Analysis at 750 mm from Floor

February 28th 12.00 P.M. Overcast

Illuminance throughout he house is noted to be improved from 2-122 lux to 500-600 lux. Increased window to wall area ratio on north facing wall and north light play important role in achieving required light levels in house. Yet due to depth of double door and overhangs on south facade, living room receives relatively less illuminance compared to other areas of house.

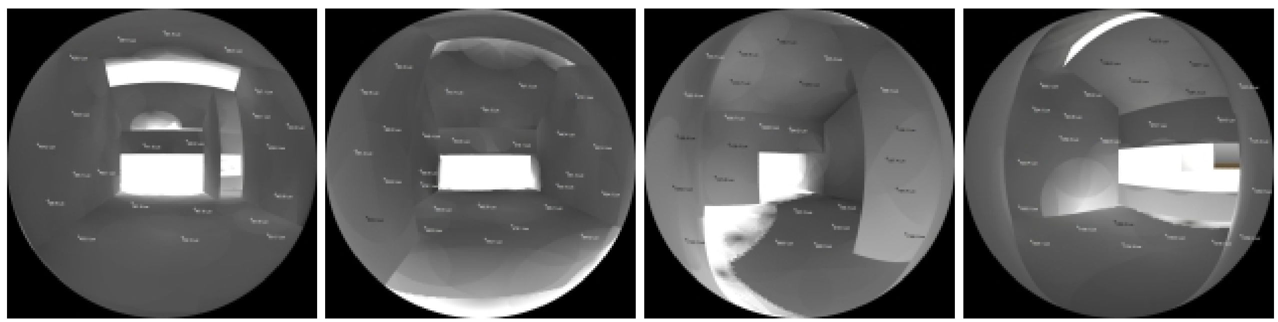


Fig.21 Illuminance (Lux)

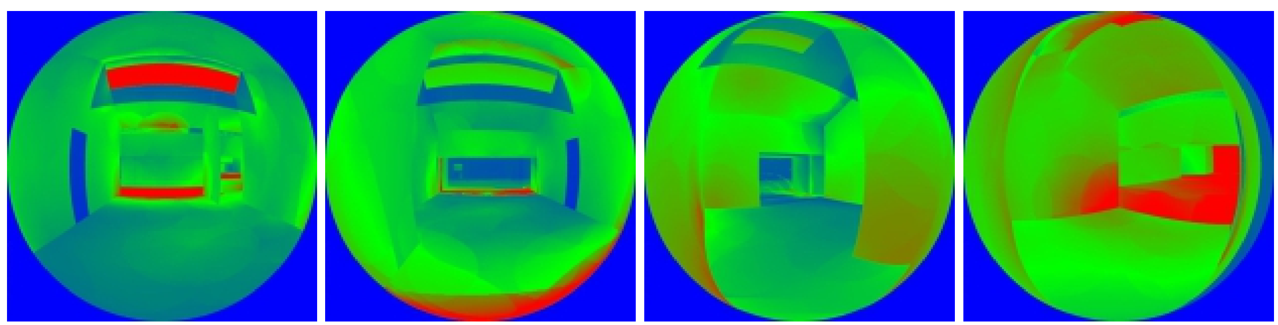


Fig.22 False Color Image

6B. CFD

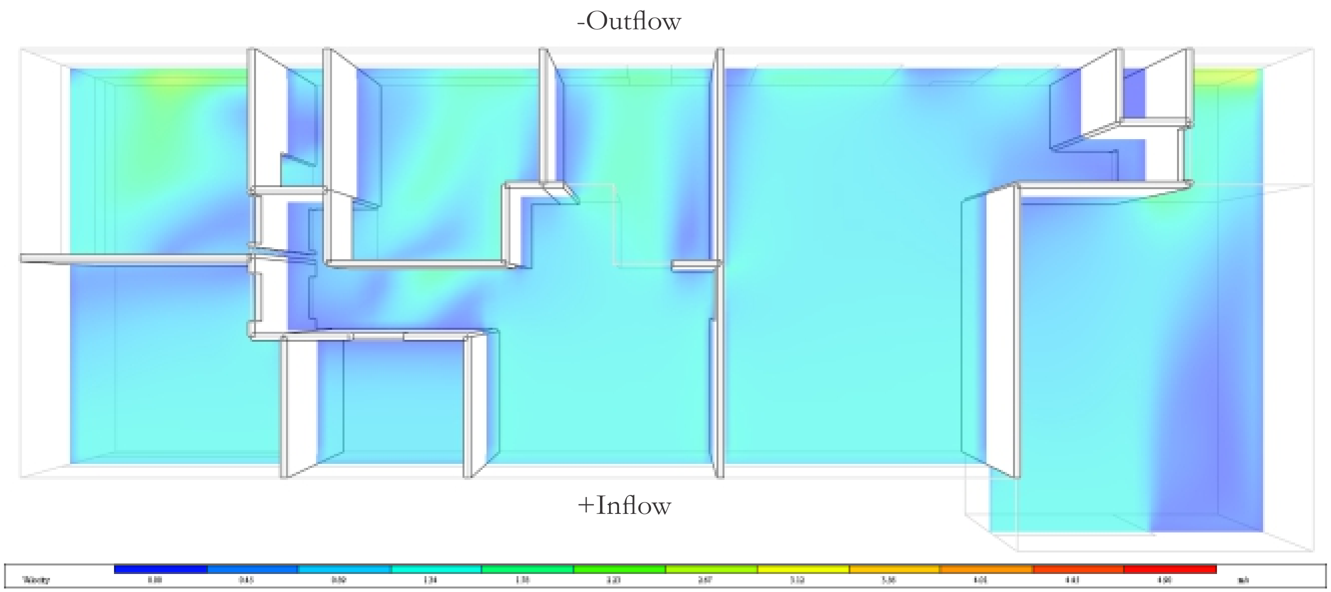


Fig.26 Velocity Contour at 1200 mm level from floor

Compared to baseline which had high wind velocity in dining area, a uniform wind flow distribution is achieved by introducing vents and at top and bottom part of interior walls. This arrangement addresses the positive pressure created on the wind ward side of the building and negative pressure on the leeward side.

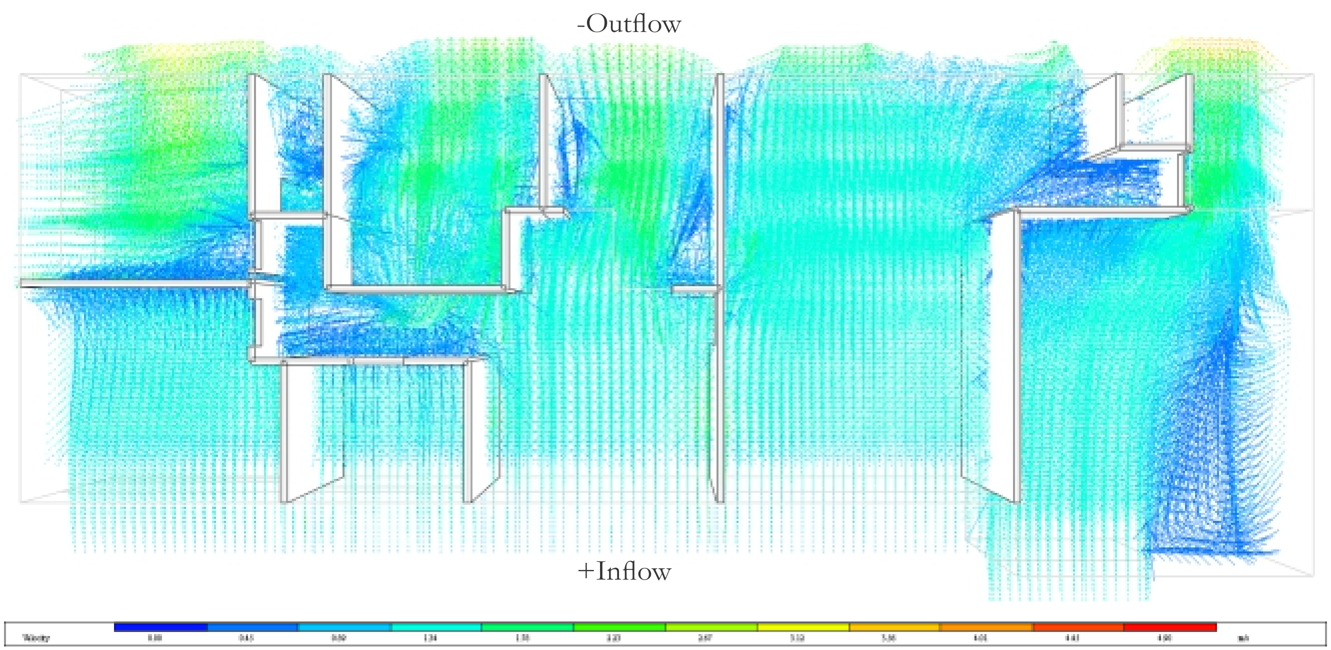


Fig.27 Velocity Vector at 1200 mm level from floor

Due to negative pressure, the building experience a pull effect. vents introduced at interior walls enhance this pull effect and helps in drawing more amount of air from the south and west sides, from where the prevailing wind approaches the house during summer months.

Fig.26 Velocity Vector showing bottom level vent in one of the Interior wall

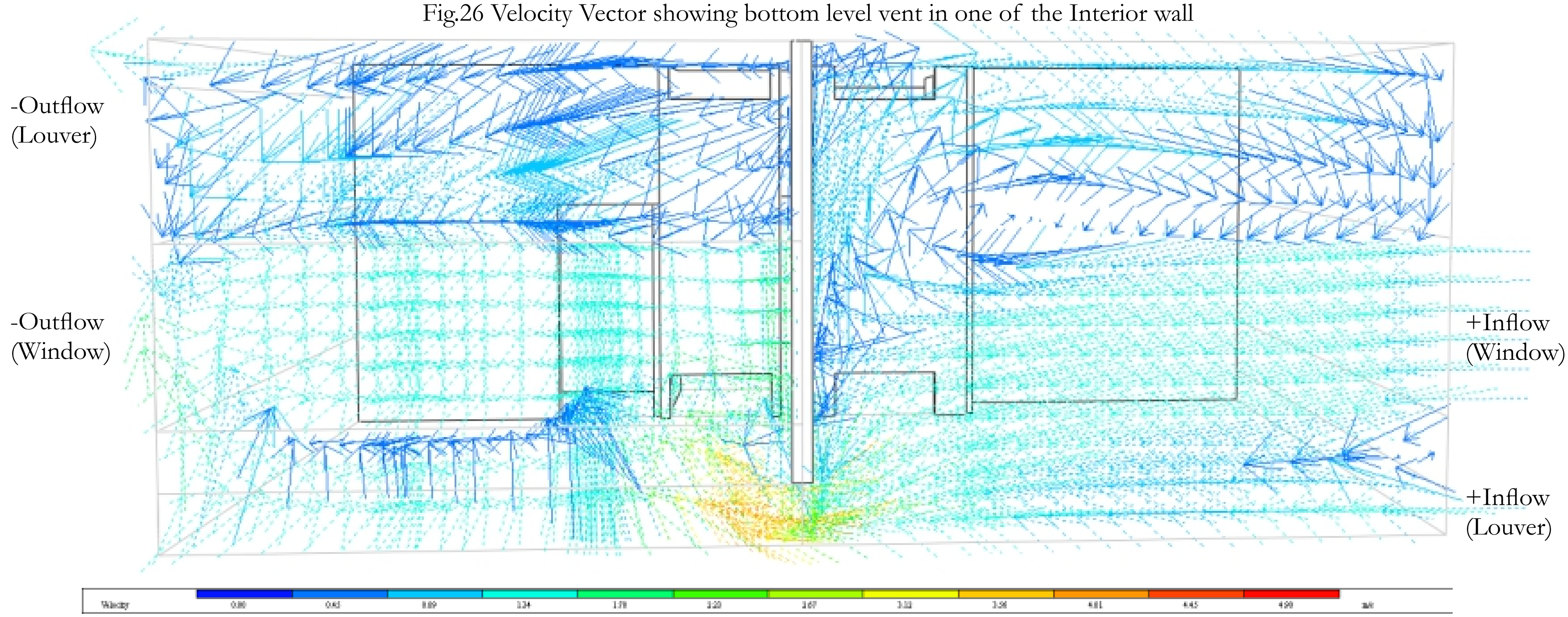
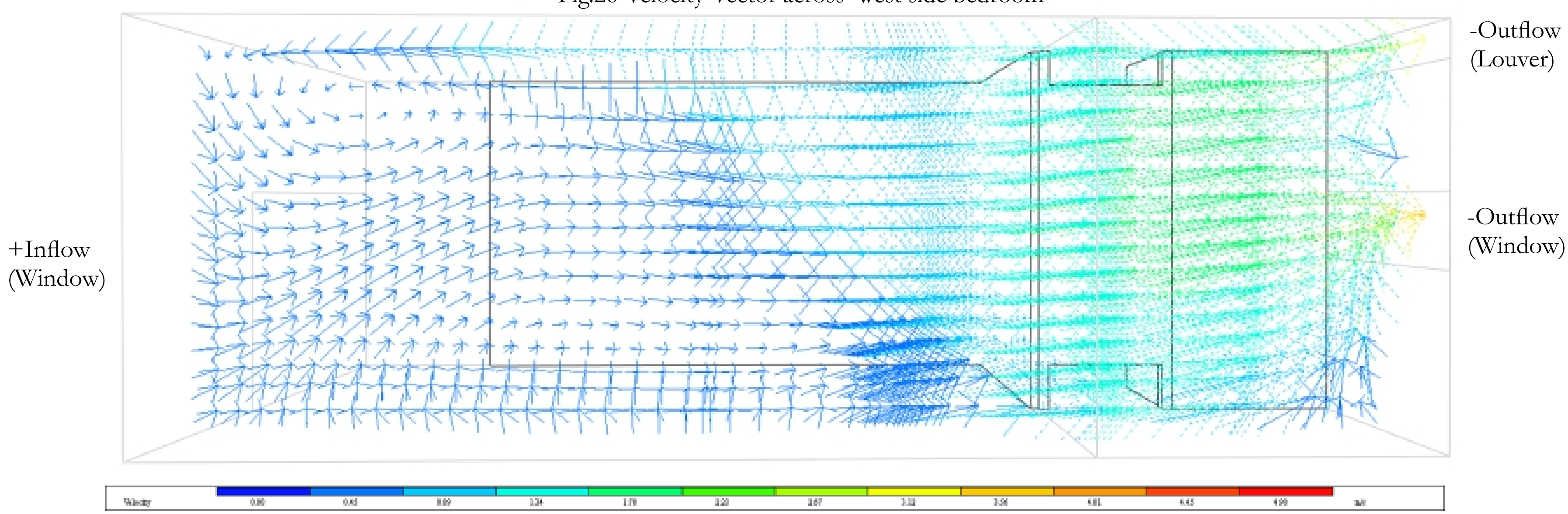
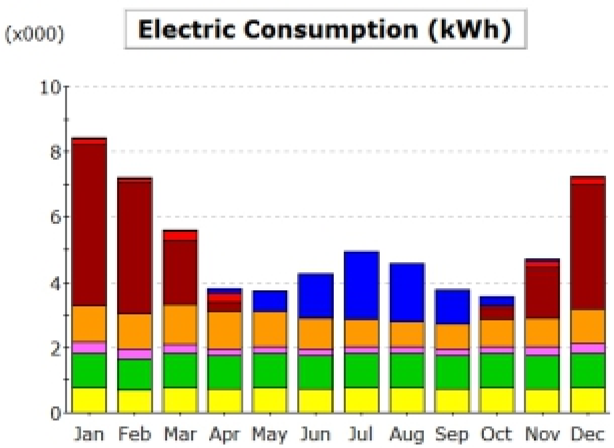


Fig.26 Velocity Vector across west side bedroom



6C. Energy Simulation



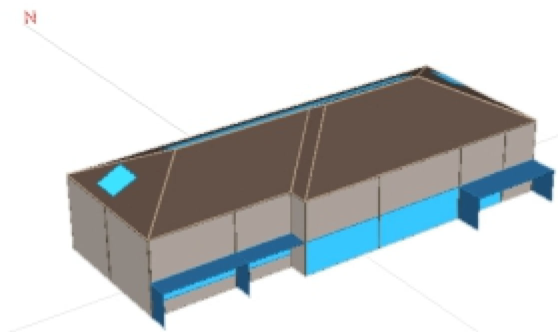


Fig.28 Energy Simulation Result
Annual Electricity Consumption (Kwh)

Since the changes made in design were primarily governed by daylight and CFD studies, the glass area and due to that the electricity consumption increased. in order to address the issue, and energy efficient glass (Pilkington Solar-E Plus A) was selected and technical specification were drawn form the manufacturer's website. This information was used to model glass layer in windows during energy simulation. This brought down electricity consumption from 79000 Kwh to 72000 Kwh.

Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.01	0.01	0.03	0.13	0.61	1.39	2.03	1.75	1.07	0.27	0.06	0.01	7.38
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	0.19	0.12	0.26	0.29	0.02	-	-	-	0.00	0.10	0.18	0.22	1.37
HP Supp.	4.92	4.02	1.97	0.27	0.00	-	-	-	-	0.34	1.56	3.81	16.88
Hot Water	1.14	1.10	1.22	1.15	1.07	0.92	0.84	0.78	0.75	0.82	0.89	1.04	11.73
Vent. Fans	0.34	0.31	0.28	0.22	0.21	0.21	0.22	0.22	0.21	0.23	0.27	0.34	3.06
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	1.05	0.95	1.05	1.02	1.05	1.02	1.05	1.05	1.02	1.05	1.02	1.05	12.41
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.76	0.69	0.76	0.74	0.76	0.74	0.76	0.76	0.74	0.76	0.74	0.76	8.95
Total	8.42	7.19	5.58	3.82	3.73	4.28	4.91	4.56	3.79	3.57	4.71	7.23	61.79

In addition to that, to improve the thermal resistance of building envelope, the wall construction information was changed from Plywood>Insulation board>Gypsum board (Outside>Inside) to Concrete>Minwool batt insulation>Brick (Outside>Inside). This further reduced the electricity consumption from 72000 Kwh to 62000 Kwh, providing approximately 20% reduction form baseline model.

7. Conclusion and Observations

During the process, in order to come up with all year successful energy saving strategy, several design iterations were performed. A serious back and forth information transfer loop had to be established between design environment (Sketchup) and simulation environment (Ecotect, IES-VE, eQuest). Integration of these environments would have significantly reduced the design development time, which in a real project can result into monetary savings. Increasing the glass area in facade improves the light levels in house, however, relatively more confident design decision can be taken if the analysis has been carried out for more scenarios throughout the year. In this exercise, there was no integration between CFD analysis and Energy Simulation. If temperature section from the house can be generated along with velocity contour, then the design iteration can be checked for its potential for human comfort. Also, energy consumption at zone level could be extremely helpful in making informed decisions, and with that, the rooms exposed to south facade and north facade could be investigated separately.