IMPACT OF MUTUAL SHADING ON ENERGY CONSUMPTION IN A MID-RISE RESIDENTIAL BUILDING

A DISSERTATION

Submitted in partial fulfilment of the requirements
For the award of the degree
of

MASTER OF ARCHITECTURE

By

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JUNE, 2019

CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in the dissertation entitled "IMPACT OF MUTUAL SHADING ON ENERGY CONSUMPTION IN A MID-RISE RESIDENTIAL BUILDING" in the partial fulfilment of the requirement for the award of the degree of Master in Architecture, submitted in the Department of Architecture and Planning, Indian Institute of Technology – Roorkee, is the authentic record of my own work carried out during the period from July 2018 to May 2019 under the guidance of Dr. Avlokita Agarwal, Department of Architecture and Planning, Indian Institute of Technology – Roorkee, India.

The Matter embodied in this report has not been submitted by me for the award of any other degree.

Date: June 2019

Place: Roorkee (Amandeep Singh)

This is to certify that the above statement made by the candidate Mr. Amandeep Singh is true to the best of my knowledge.

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Date: June 2019

Place: Roorkee

CERTIFICATE

Certified that report entitled **"IMPACT OF MUTUAL SHADING ON ENERGY CONSUMPTION IN A MID-RISE RESIDENTIAL BUILDING"** which has been submitted by **Amandeep Singh**, for partial fulfilment of the requirement for the award of the post graduate degree of Master of Architecture, in the Department of Architecture and Planning, Indian Institute of Technology, Roorkee, is the student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree to any other institute.

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Abstract

Human population increase and economic growth agendas (e.g. MBIE, 2015) increase the pressure on natural resources and ecosystems around the world (MEA, 2005). Even more, production needs to be realized from the same finite amount of natural resources. At the same time, environmental conditions need to be improved or at least maintained. One of the major natural resource for development is land. The land values around the urban areas, which has easy access to a number of resources for a comfortable lifestyle, are very high because the demand of land is much more then the supply. To solve this issue of land reduction, densely built urban spaces with multi-storeyed buildings started coming up, because more and more people are migrating to the urban areas in the need of a better life, resulting in the demand of more number of dwelling units. The buildings in these densely built urban spaces suffer lack of solar radiation due to shading from the adjacent buildings. This hugely impacts the energy consumption of a building. The study is sought to develop a systematic approach to quantify influence of mutual shading within a network of buildings, and what measures can be taken to optimize the building envelope for energy efficient design, keeping in mind the shading effect from adjacent buildings. The shaded areas of the building require different guidelines for lesser energy consumption as compared to areas that are not shaded, as these are prone to less amount of solar radiation throughout the day.

The guidelines provided for the energy efficient building design such as ECBC (in India), does not consider the impact of shading from the adjacent buildings. In the recent studies conducted by BEEP India while preparing the guidelines for Energy Efficient multi-storey residential buildings in Composite & Hot-Dry areas, the need for increasing the WWR for the rooms existing at the lower floors of the building is mentioned to meet the desired day light factor, as these floors are shaded by adjacent buildings and does not have direct solar access. In the guidelines, only WWR is talked about while there are other parameters that can be influenced as well.

There are several parameters which are to be considered while studying the impact of mutual shading on a building's energy consumption. These can be classified into two: 1. Building Exterior Parameters (Surrounding Environment), that impact the area of the building envelope exposed

to solar radiation & 2. The Building Envelope Parameters. Firstly these parameters are identified through in depth literature study. Then different building layouts of the adjacent buildings around the subject building are prepared and tested in different climates of India. Hot-dry climate is impacted by mutual shading the most. The further study is carried out for hot-dry climate. The simulations are carried out by varying the parameters for the selected network of buildings.

Based on the outcome of the simulations, recommendation and suggestions, considering mutual shading, for the building envelope parameters are provided for the energy efficient design of a building are provided. The recommended values of the envelope parameters are more lenient and easy to comply as compared to the general energy efficient design guidelines provided by BEEP India.

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Human population increase and economic growth agendas (e.g. MBIE, 2015) increase the pressure on natural resources and ecosystems around the world (MEA, 2005). Even more, production needs to be realized from the same finite amount of natural resources. At the same time, environmental conditions need to be improved or at least maintained [4]. One of the major natural resource for development is land. The land values around the urban areas, which has easy access to a number of resources for a comfortable lifestyle, are very high because the demand of land is much more then the supply. To solve this issue of land reduction, densely built urban spaces with multi-storeyed buildings started coming up, because more and more people are migrating to the urban areas in the need of a better life, resulting in the demand of more number of dwelling units.

1.1.1 Growth Profile of Indian Residential Sector

In rapidly urbanising India, population residing in urban areas is expected to reach 50% [6], which is going to add 441 million people to the urban population. To accommodate this huge increment in population, the urban household number is going to double by 2032 as per the 2011 census data of India. India would have to built an estimate of 700-900 million m^2 of commercial and residential spaces every year for the next 2 decades to meet the economic development, population increase and urbanisation demand [22]. Various studies by CEU and McKinsey predicted that the total residential floor area in going to much more than the total commercial floor area in India by 2030. As suggested by the data, by 2050, 15% of the floor space will be used for commercial purposes and 85% of the floor space will be used for residential purposes. There is an inclination towards development of multi-storey residential buildings to reduce suburban sprawl, and due to the scarcity and high cost of land in the core areas [6].

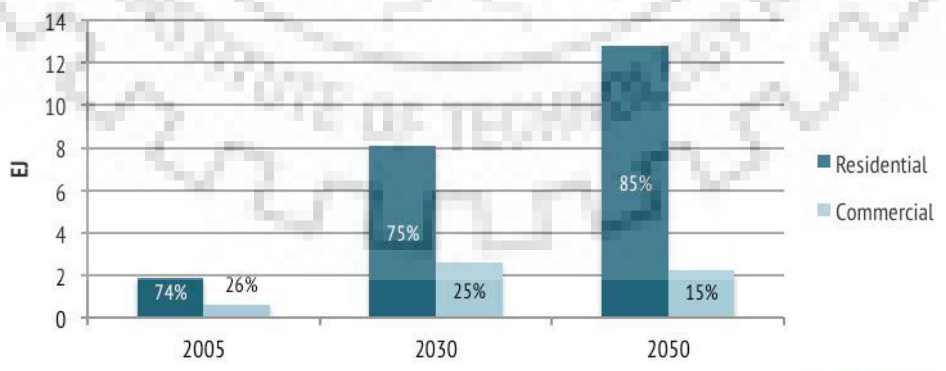


Fig. – 1 India's moderate efficiency scenario projected energy consumption of India's buildings in 2030 and 2050; percentages represent the ratio of residential and commercial buildings. Source: [9] Global building performance network (2014).

1.1.2 Energy Use in Residential Buildings

20.4% of the total electricity consumed in India for the year of 2012 [6], was by the residential sector. By the year 2032, residential sector will be using 36.5% of the total electricity consumed by the country. This will make it the largest electricity consuming sector in India. In the building sector, 75% of the total electricity consumption is used by the residential buildings. The gross electricity consumption in residential buildings increased from 50 TWh in 1995 to 220 TWh in 2015 [15], which is almost 4.5 times in the period of 20 years. The energy projection for the year 2030 shows it rising to anywhere between 600 to 900 TWh.

1.2 Study Area

To fulfill the need of housing requirement in the urban areas, densely built multi-storey residential townships started coming up.The buildings in these densely built urban spaces suffer lack of solar radiation due to shading from the adjacent buildings. This hugely impacts the energy consumption of a building. The study is sought to develop a systematic approach to quantify influence of mutual shading within a network of buildings, and what measures can be taken to optimize the building envelope for energy efficient design, keeping in mind the shading effect from adjacent buildings. The shaded areas of the building require different guidelines for lesser energy consumption as compared to areas that are not shaded, as these are prone to less amount of solar radiation throughout the day.

1.3 Research Gap

There are several guidelines provided for the energy efficient design of residential buildings such as Energy Conservation Building Code for residential buildings, Design guidelines for energy efficient multi-storey residential buildings, etc. All these guidelines do not consider the impact of shading from the adjacent buildings. In the recent studies conducted by BEEP India while preparing the guidelines for Energy Efficient multi-storey residential buildings in Composite & Hot-Dry areas, the need for increasing the WWR for the rooms existing at the lower floors of the building is mentioned to meet the desired day light factor, as these floors are shaded by adjacent buildings and does not have direct solar access. In the guidelines, only WWR is talked about while there are other parameters that can be influenced as well. There are several studies that prove that the impact of shading from adjacent buildings on a building's energy consumption is significant. The current set of guidelines are for the case where the building is fully exposed from all the sides and the attempt of the study is to come with the different set of recommendations for the shaded parts of a building which are prone to less solar radiation and hence can work with a little more lenient set of guidelines.

1.4 Research Questions

- How does shading from adjacent buildings impact the energy consumption?
- What are the different parameters that impact the shading from the adjacent buildings?
- In what terms can we measure the mutual shading, so that we can suggest the energy efficient guidelines?
- How does the impact of mutual shading change with respect to the climate?
- Can more lenient set of guidelines or recommendations be provided for the shaded portion of a building for energy efficient design?

1.5 Need for the Study

All the data mentioned in the previous sections of the report (1.1 & 1.3) prove the need for conducting the study in this particular field. The energy efficient guidelines in detailed format are only provided for the commercial buildings. While building construction in the residential sector is on a rise, and in the coming times it is going to exceed in number as compared to the buildings in the commercial sector. Also with the rise in economy, life style needs of an individual is increasing, resulting to more number of appliances in a residence, and hence more energy demand. There is an essential need to draw our focus towards providing energy efficiency guidelines for residential buildings as well. Recently a few sets of guidelines for the same are published. This study is basically an extension to those guidelines, as most of the these guidelines are for the multi-storey residential buildings and in multi-storey buildings there is a significant impact of mutual shading on a building's energy consumption as well. The study provides an extended set of suggestions and recommendations for energy efficient design of a multi-storey residential considering the impact of shading from adjacent buildings [6].

1.6 Aim

The aim is to analyse the impact of mutual shading from adjacent buildings on the energy consumption of a mid rise middle income group residential building for the purpose of providing alternate (more lenient) prescriptions for the energy efficient design of the building's envelope parameters for the mutually shaded facade.

1.7 Objective

- Identify the parameters of building surrounding environment which impact the shading from adjacent buildings.
- Identify the building envelope parameters which are affected by mutual shading.
- Analyse the impact of mutual shading in different Indian climatic regions to understand the impact of mutual shading in each region and to identify the climate where effect of mutual shading on the energy consumption is maximum.
- To give alternate suggestions and recommendations for the energy efficient design of a building's envelope for the surfaces shaded by adjacent buildings.

1.8 Scope and Limitation

- The base models are generated through data collected from literature study.
- All the possible layouts for a network of buildings are created hypothetically so that all the different scenarios, in which a building may exist in reality, are covered.
- The alternate recommendations are only provided for the hot-dry climate, as it has the maximum impact due to mutual shading.
- The impact on the building's heating and cooling loads are studied only, due its dominance in the overall energy consumption.
- The suggestions can only be implemented on multi-storeyed residential buildings existing in a township project.
- It is not applicable for plotted developments as in that case we don't have any control over the buildings existing in another plot.
- The base case will be developed using BEEP design guidelines for the energy efficient design of multi-storey residential buildings in a composite and hot-dry climate.

1.9 Methodology

Stage 1

- Literature study to identify various parameters of building surrounding environment which impact the shading from adjacent buildings. And to identify building envelope parameters.
- Literature study to identify the basic modelling data to develop base case. Like the plan form, zoning and form of the building and the simulation inputs.

Stage 2

- Create base models in design builder with respect to the data collected from the literature study.
- Developing various adjacent building's layouts in which it may exist around a subject building in a real scenario.
- Simulating each layout in all the five climate zones of India to understand the impact of mutual shading in each zone and to identify the climate experiencing maximum impacting from mutual shading.

Stage 3

- Identify the layouts with maximum impact from the selected climate zones.
- Develop different cases by trying combinations of the identified parameters and their respected different values.
- Simulate the final iterated models developed by the permutations and combinations of different layouts and parameter values and obtain energy consumption data.

Stage 4

- Observation and analysis of the data collected.
- Suggestions and recommendations for the better energy efficient design of buildings considering mutual shading.
- Report compilation.

METHODOLOGY CHART

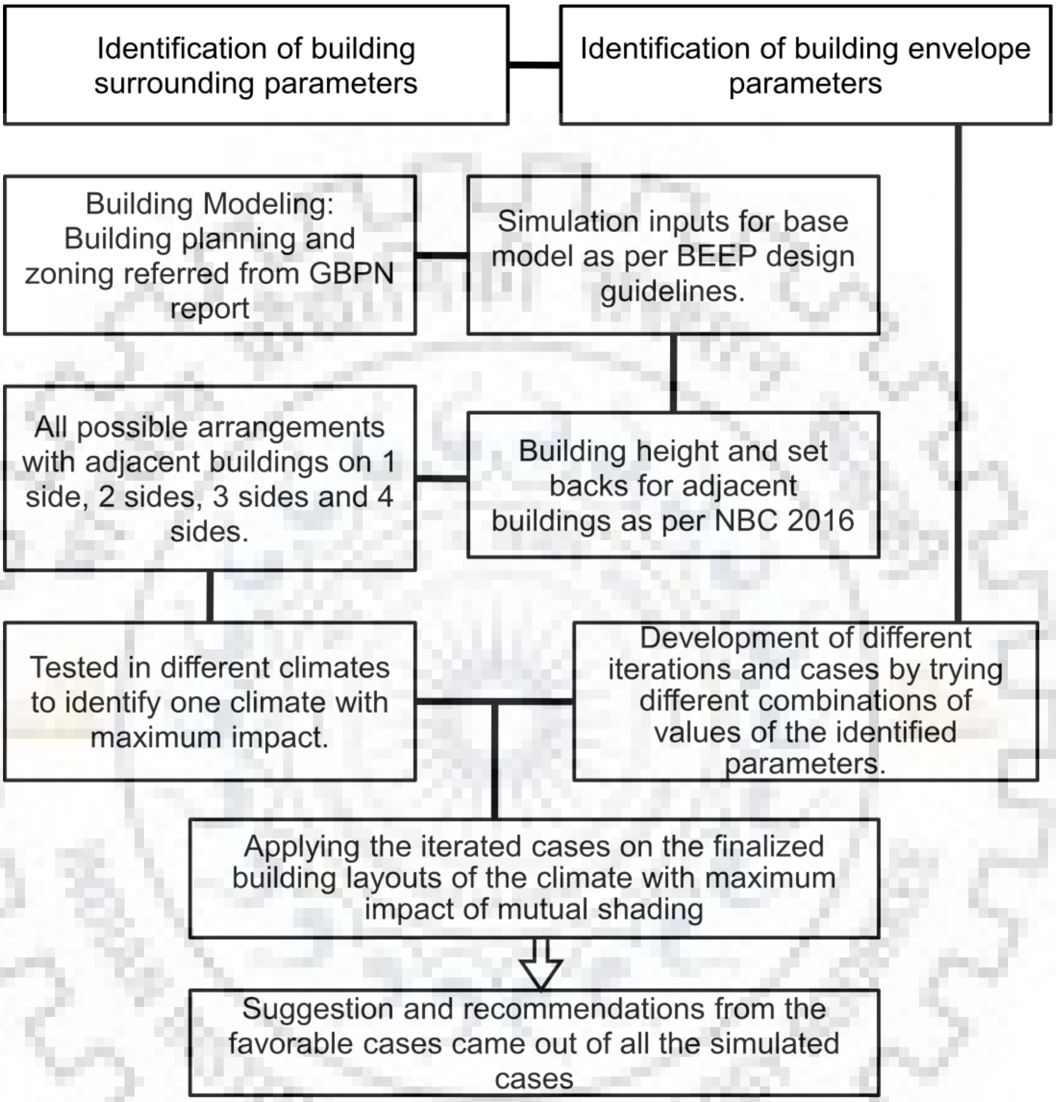


Fig. – 2 Research methodology flow chart.

CHAPTER 2

LITERATURE REVIEW

2.1 Building Envelope Parameters

2.2 Building Exterior (surrounding environment) Parameters

This chapter covers the basic factors that impact the mutual shading. Before moving to the parameters, there are other factors as well that impact the mutual shading in a built environment. That factor is the geographical location of the project. The sun path changes as we move up and down the latitude. Below 12° north, the impact of the sun can be seen on the northern façade of a building as well. Above that, the northern façade of a building remain unexposed to sun. Therefore the first and foremost factor to impact mutual shading is the sun path, which changes with respect to the latitude. After that, the other parameters that are required for the study can be classified in to two categories: 1.The Building Envelope Parameters& 2. Building Exterior Parameters (Surrounding Environment), thatimpact the area of the building envelope exposed to solar radiation.

2.1 Building Envelope Parameters

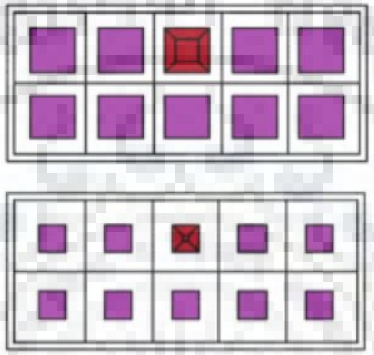
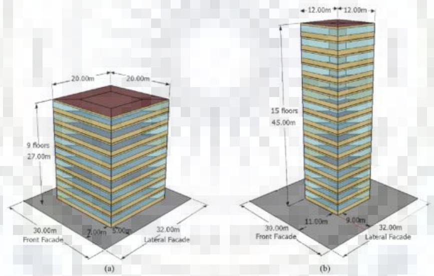
These are general building envelope parameters that are majorly being followed in the present for the energy efficient design of any building. These are the parameters that interact with the outdoor environment of the building and hence impacted by the solar radiation. The building exterior parameters control the amount of exposure to the solar radiation that a building faces and the envelope parameter are affected by the exposure, therefore varying the values of these parameters directly impact the energy consumption of the building.

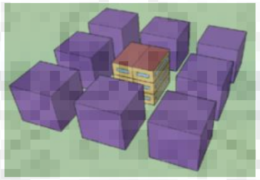
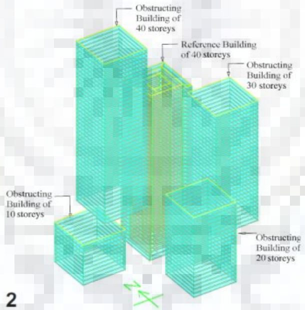
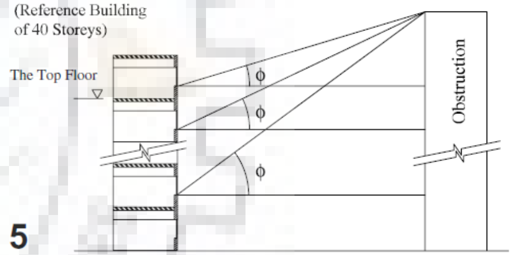
Any set of energy efficient guidelines follow these parameters to provide energy efficient design solutions. ECBC, NBC or BEEP, has similar set of building envelope parameters that are enlisted below.

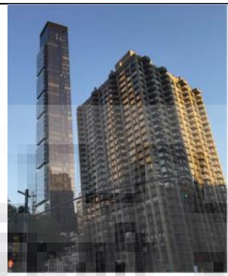
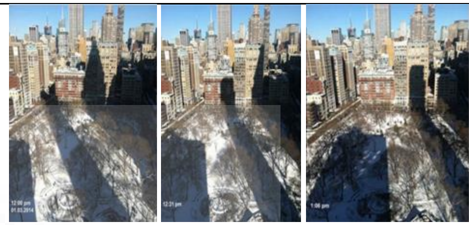
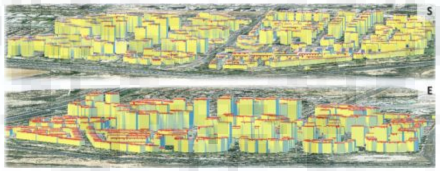
- Fenestration:
  - U-Factor
  - Solar Heat Gain Coefficient
  - Visual Light Transmittance
  - Window Wall Ratio
- Opaque External Wall:
  - U-Factor
- Roof Assembly:
  - U-Factor

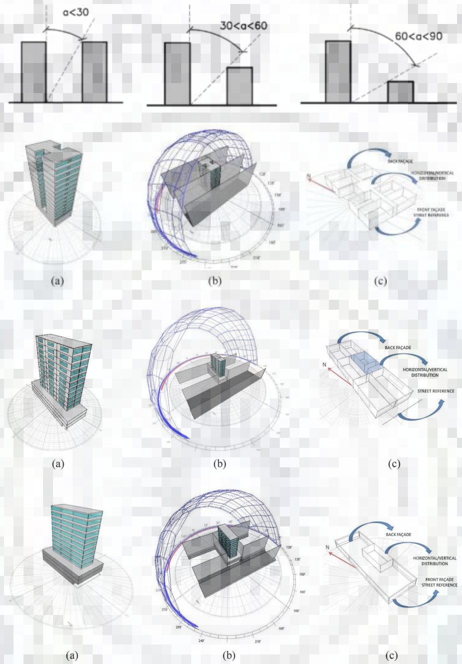
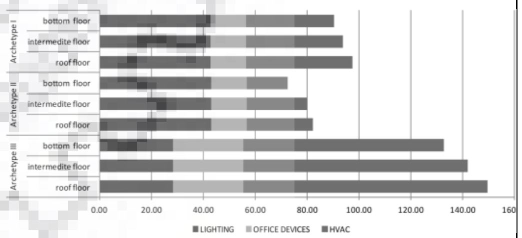
2.2 Building Exterior (surrounding environment) Parameters

The parameters that impact the mutual shading in a building are enlisted in this section. Varying these parameters will vary the amount of shading on a building. There are a number of factors that impact in the surrounding environment of a building that impact the mutual shading on a building. There is not much work done to identify and make a list of these parameters. Therefore, a detailed literature is done to find these parameters and understand how they impact the mutual shading effect. A number of research papers were studied and on the basis of that literature, 7 major parameters are identified. In the table given below, a brief summary of the findings from each studied paper is provided. After the summary table, the identified parameters are explained briefly.

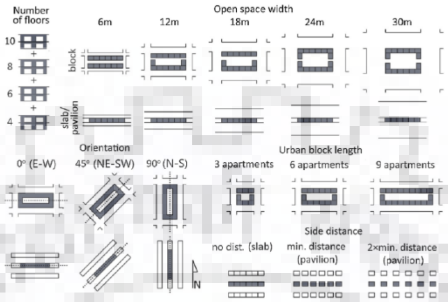
SUMMARY OF JOURNALS/RESEARCH PAPERS						
S. No.	JOURNAL	TITLE OF THE PAPER	SOFTWARE	DETAIL	RESULT & LEARNINGS FROM THE PAPER	STUDIED PARAMETER
1	Energy and Buildings	Estimating the impact of urban densification on high-rise office building cooling loads in hot and humid climate. | 2018 | Maceio, Brazil. *1 Citations*	EnergyPlus	Two cases for buildings and arrangements to be simulated are considered:   Solar reflectance from adjacent buildings is also considered by simulating 3 cases of varying WWR and reflectance.	<u>If the adjacent buildings have similar configuration as the subject building:</u> Shorter and bulkier buildings are more benefitted from mutual shading than taller and slender in terms of reducing cooling loads. There is less difference in the energy consumption between lower floors and upper floors in tall slender buildings, and more difference in the shorter bulkier buildings. Solar reflectance from the adjacent buildings, also impact the energy consumption of the subject building. Impact of solar reflectance is more than the WWR. Scenario with adjacent buildings having high WWR and less reflectance was more energy efficient	Form of the adjacent building Solar Reflectance from the adjacent buildings Setbacks

					than the scenario having less WWR and high reflectance.	
2	Applied Energy	Exploring mutual shading and mutual reflection inter-building effects on building energy performance. | 2015 | Perugia, Italy *16 Citations*	EnergyPlus	Quantified the impact of mutual shading by simulating test case(9 buildings cluster with H/W ratio = 2) in different climatic zones of USA. Building energy: a. Lighting b. Heating | c. Cooling. 	Two real cases in Italy are considered: a. In dense area | b. In open area The results were in the direction as observed in the test cases. 	Canyon Ratio
3	Applied Energy	Day lighting and energy implications due to shading effects from nearby buildings. | 2007 | Hong Kong, China. *72 Citations*	EnergyPlus	Study on commercial buildings. Impact due to adjacent building's height. 	 Angle between window sill for individual floors and the top of adjacent building.	Height of the Adjacent Building; Orientation.
4	The Real Estate Board of New York	The latest generation of towers: Tall, Slender and mostly Residential. | New York.	-	Impact due to form of the adjacent building. Shorter bulkier forms have more impact than tall and slender forms.		Form of the Adjacent Building

						
5	Energy and Buildings	Impacts of shading effect from nearby buildings on heating and cooling energy consumption in hot summer and cold winter zone of China. | 2016 | China. *7 Citations*	eQUEST	Five major cities in composite climate (3℃-30℃) studied. The canyon ratios studied were very low (W=.7H to 1.9H).  	Out of the five compared cities (Shanghai, Wuhan, Changsha, Chengdu and Chongqing), Shanghai and Wuhan showed no effect on annual energy consumption. The decrease in cooling load was equal to the increase in heating load. While the other 3 cities showed 10-13% savings in annual energy consumption.	Canyon Ratio
6	Energy and Buildings	Modeling the potential for PV installation in residential buildings in dense urban areas. | 2018 | Case study of Israel. *6 Citations*	R Open Source Code	 The study was demonstrated for a case study neighborhood in RishonLeZion, Israel, with diverse building typologies (varying building heights and canyon ratios).	The low-rise but dense typology in the south margin of the neighborhood (row houses) had the highest annual exposure to direct solar radiation (500kW h/m^2). The envelope of the high-rise apartment blocks (8–13 floors) and residential towers is exposed to comparatively less direct solar radiation (300kW h/m^2) per year.	Area of the exposed envelope surface; Building's Orientation; Location (relative).

7	Energy and Buildings	A methodology for estimating office building energy use baselines by means of land use legislation and reference buildings. | 2017 | Brazil. *5 Citations*	EnergyPlus	Three generations of high rise buildings discussed with respect to the revision in local byelaws. A new component with the name of Sky View angle Introduced.  	The buildings coming under the category of second generation were the most energy efficient, after that comes the first generation, and then the third generation. Electricity is majorly consumed for lighting in the first and second generations of the buildings, while for the third generation HVAC is the one that consumes the most of it. For a multistory building in any generation, the electricity consumption for HVAC increased for the upper floors, while for lighting and office devices it remained same.  	Parameters that varied in each generation: Building Height. Setbacks Design(form) Construction Material (less opaque surface and more glazed surface, hence increased WWR) Sky View Angle
8	Sustainable Cities	A parametric sensitivity analysis of the influence	EnergyPlus	Different types of building arrangements in an urban setting studied to see the impact on	The results generated were not studied in real setting. Hypothetical scenarios	No. of floors in a building (Height)

<table>
<tr>
<td></td>
<td>and Society</td>
<td>of urban form on domestic energy consumption for heating and cooling in a Mediterranean city. | 2016 | Thessaloniki, Greece.

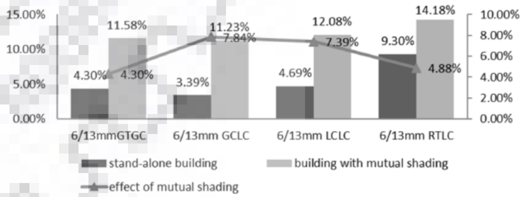
13 Citations</td>
<td></td>
<td>domestic energy consumption.

</td>
<td>created by varying the following parameters:

No. floors; Width of the open space; Orientation; Urban block length; Side distances/setbacks.

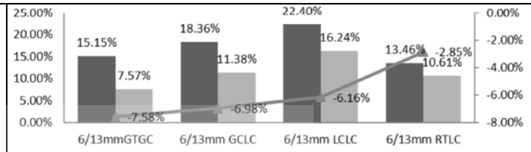
The final conclusion was that the compact forms are the most energy efficient.</td>
<td>Orientation

Setbacks

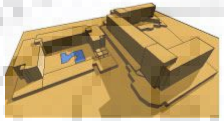
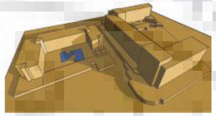
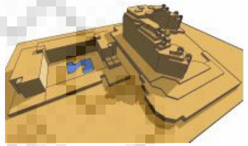
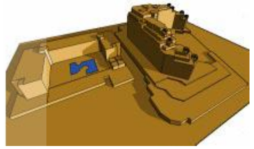
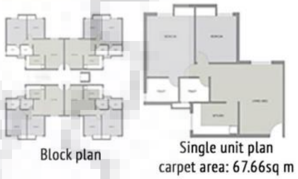
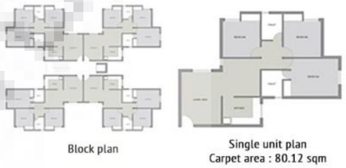
Cluster Size</td>
</tr>
<tr>
<td>9</td>
<td>Energy and Buildings</td>
<td>Energy efficient window retrofit for existing high rise residential buildings with the consideration of mutual shading. | 2018 | Hong Kong, China.</td>
<td>Design Builder</td>
<td>A 30 storey high rise building modeled as a base case with a WWR of 30%. The adjacent building of the same height is placed by maintaining a canyon ratio of H/W = 2.
4 different combinations of glazing:
<table>
<tr><th>Type</th><th>Name</th><th>External pane</th><th>Internal pane</th><th>U-value</th><th>SHGC</th></tr>
<tr><td rowspan="4">6/13mm double glazing with 13mm air filled</td><td>GTGC</td><td>6mm generic tint</td><td>6mm generic clear</td><td>2.66 W/m2•K</td><td>0.501</td></tr>
<tr><td>GCLC</td><td>6mm generic clear</td><td>6mm Low-e clear</td><td>1.91 W/m2•K</td><td>0.568</td></tr>
<tr><td>LCLC</td><td>6mm Low-e clear</td><td>6mm Low-e clear</td><td>1.35 W/m2•K</td><td>0.483</td></tr>
<tr><td>RTLT</td><td>6mm reflective tint</td><td>6mm Low-e tint</td><td>1.69 W/m2•K</td><td>0.122</td></tr>
</table>
were tested in 4 different climate zones of China:

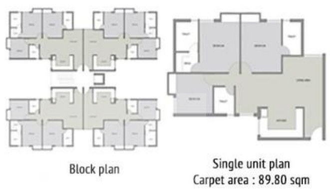
Mild summer & cold winter; Hot summer & warm winter; Hot summer & cold winter; Severe cold</td>
<td>Energy consumption in the Buildings existing in cold winter & mild summer climate was negligibly affected by the mutual shading. Buildings in hot summer & warm winter showed maximum impact, and in severe cold climate, the impact was –ive, i.e, the building consumed more energy due to mutual shading.


Hot summer & warm winter</td>
<td>Canyon Ratio</td>
</tr>
</table>

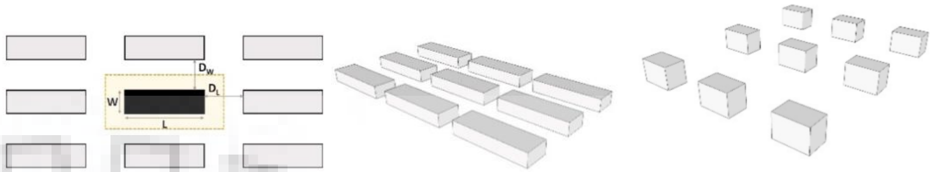
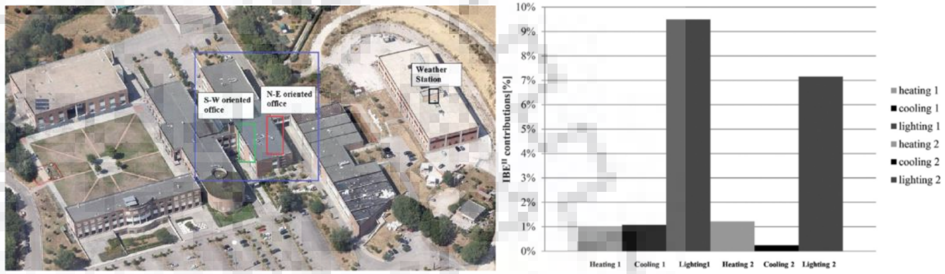
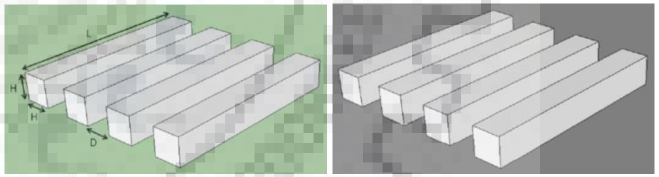
					 Severe Cold	
10	Energy and Buildings	Urban form and household electricity consumption: A multilevel study. | 2017 |Ningbo, China. *8 Citations*	Detailed Site Survey	Study of the electricity consumption data of the 3 different dwelling types in the Ningbo neighbourhood of China. 	<u>Just proved the validation of the research</u> Effect of neighbourhood density on residential electricity usage is different in different seasons. Impact of neighbourhood density on electricity consumption is more in summer months then in winter months. Tower and slab apartments showed more electricity consumption due to urban densification, as a result of UHI effect. Whereas single family houses proved to be more energy efficient in the dense setting due to mutual shading and less amount of exposed surface.	Simulated in real setting. Impact in terms of parameters not discussed.
11	Building and	Inter-building effect: Simulating the impact of	EnergyPlus	The base model developed for the analysis is closer to a real setting with 20 residential	<u>Just proved the validation of the research</u>	Simulated in real setting. Impact

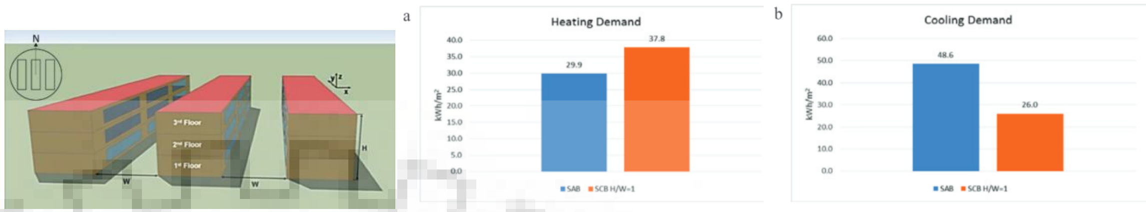
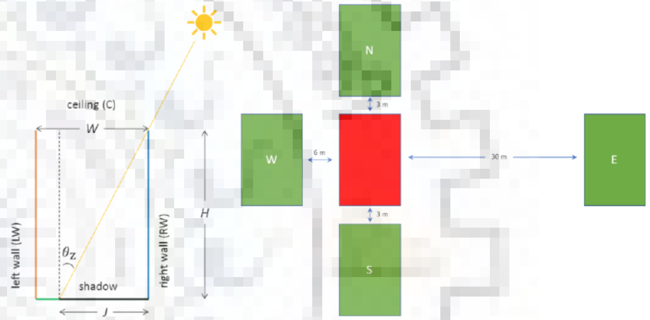
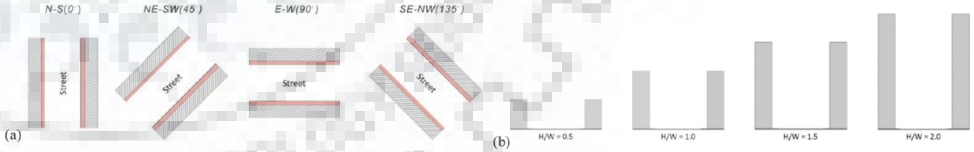
	Environment	a network of buildings on the accuracy of building energy performance predictions. | 2012 *62 Citations*		buildings. Double storey row houses with open space at the front and small setback at the rear side.  Two scenarios simulated: Single building scenario Network of buildings scenario	The main aim of the study was to expand the level of analysis for building energy modelling by including the impact due to the surrounding environment. The outcome revealed that: Monthly heating load in winters is underestimated up to 32%. And Monthly cooling load in summers is overestimated up to 58%.	in terms of parameters not discussed.
12	Energy and Buildings	Effect of external shading on household energy requirement for heating and cooling in Canada. | 2011 *39 Citations*	ESP-r Modeling	<u>Just proved the validation of the research</u> A double storey house is modelled of height 6.3 m. Shading from neighbouring houses (of similar configuration) and trees (evergreen and deciduous) studied. The setbacks were taken as per the development authority guidelines.	The heating and cooling energy requirements varied from region to region and the results supported the outcomes of the previous studies done. In the extreme scenario, the setbacks on all the three sides are reduced to 2.4 m, and the area of the house is increased to twice the size of the base case. It was noted that the cooling energy requirement is reduced by 90% for a house in Vancouver and heating energy requirement is increased by 10% for a house in Calgary.	Simulated in real setting. Impact in terms of parameters not discussed.

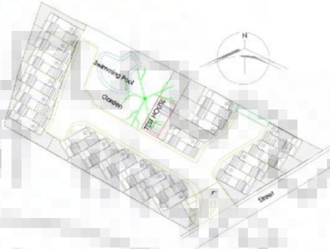
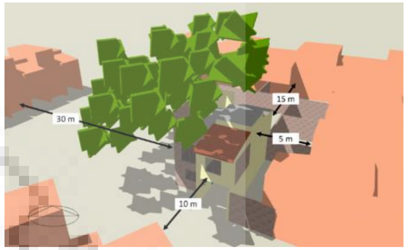
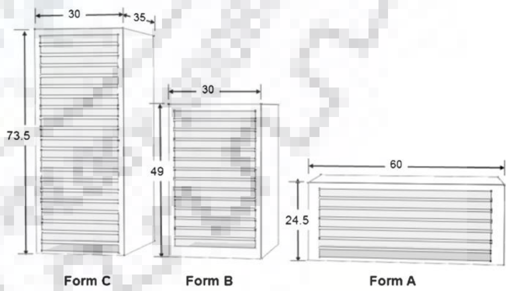
13	Analysis Software	Shading: Analyzing mutual shading among buildings. |2001 | Israel. *16 Citations*	CAD Tool (shading)	A case study of Israel, in which an existing building (Hotel Laguna) is shaded by the new upcoming building (Hotel Shva). As per the master plan the upcoming hotel was violating the solar rights of the existing hotel.  	A new design as per the F.A.R proposed, that didn't violated the solar rights. The developed CAD tool helped in the designing of the new form.  	Form of the Adjacent Building
14	GBPN Report	Residential buildings in India: Energy use projections and savings potentials. | 2014 | India.		Study conducted to provide quantitative information on residential building energy use and to determine the energy saving potentials in the sector. In total 777 houses surveyed from 4 different Indian cities, each representing different climatic zone of India. Based on the survey, a typical building floor plan was constructed for the modeling. The typical floor plan and clustering developed will help in developing the base models for the research.	  Single unit and clustering of 2BHK 	

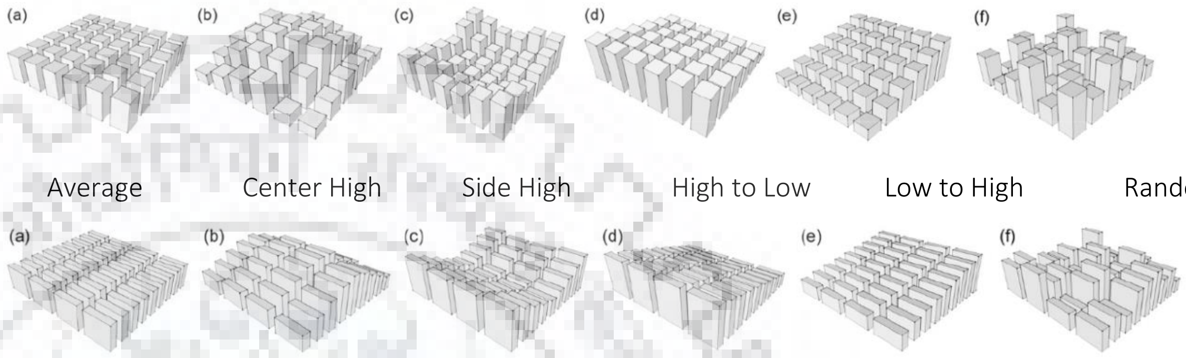
					 Single unit and clustering of 3BHK	
15	Guidelines by BEEP	Design guidelines for Energy-Efficient multi-storey residential buildings. | 2014 | Composite & Hot-Dry climate | India.	TRNSYS DIVA RELUXPro	Different typologies of multi-storey residential buildings: Tower; Linear; Linear Double Loaded Reduction in solar radiation due to mutual shading. Adjacent towers placement as per guidelines in NBC. Impact on energy consumption due to envelope parameters studied by applying different Energy Efficiency Packages (EEP) prepared for more energy efficient envelope design. Day light analysis conducted for zones on lower floors and upper floors separately.	Linear double loaded typology is the most energy efficient for east –west orientation. No effect of orientation on tower typology. 35% reduction in solar radiation exposure due to mutual shading for the tested case. Out of the envelope parameters varied to create the EEPs, the EEP with the external shutters on the windows for solar shading showed maximum savings. Zones in the lower floors required more WWR(30%) to achieve desired daylight factor then WWR(10%) on the upper floors.	Wall u-value. Glazing: u-value SHGC VLT WWR Building Orientation Building Form Building Setbacks

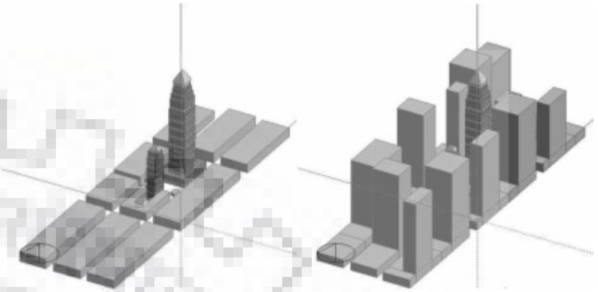
16	Guidelines by BEEP	Design guidelines for Energy-Efficient multi-storey residential buildings. | 2014 | Warm-Humid climate | India.	TRNSYS DIVA RELUXPro	Different typologies of multi-storey residential buildings: Tower; Linear; Linear Double Loaded Impact of surrounding buildings on the natural ventilation. Adjacent towers placement as per guidelines in NBC. Impact on energy consumption due to envelope parameters studied by applying different Energy Efficiency Packages (EEP) prepared for more energy efficient envelope design. Day light analysis conducted for zones on lower floors and upper floors separately.	Linear double loaded typology is the most energy efficient for east –west orientation. No effect of orientation on tower typology. Buildings should be placed at an angle of 45° to the direction of the wind to optimize natural ventilation. Out of the envelope parameters varied to create the EEPs, the EEP with the external shutters on the windows for solar shading showed maximum savings. Zones in the lower floors required WWR of 20% without overhang to achieve desired daylight factor. Whereas WWR of 10% is enough on the upper floors.	Wall u-value. Glazing: u-value SHGC VLT WWR Building Orientation Building Form
LESS INFORMATIVE JOURNALS						
17	Sustainable Cities and Society	Energy efficient neighbourhood design under residential zoning regulations in Shanghai. | 2017 | China.	EnergyPlus DAYSIM	Hypothetical Shanghai residential neighbourhood layout | Variation in *FAR* | Impact on energy due to elevators in high rise buildings.		

		3 Citations		
18	Energy and Buildings	Expanding inter-building effect modeling to examine primary energy for lighting. | 2014. *28 Citations*	EnergyPlus	2 Offices in a single building but different orientations simulated to calculate energy consumption data | Energy consumption for lighting is majorly impacted by the mutual shading. 
19	Energy and Buildings	Impact of radiation exchange between buildings in urban street canyons on space cooling demands of buildings.| 2015. *13 Citations*		Space cooling demand of standalone buildings is compared with buildings in urban street canyon configuration. *Soil property around the building | Solar reflectance from the adjacent buildings | Orientation | Canyon Ratio.* 
20	Energy	Influence of street canyon's microclimate on the energy demand of space cooling and heating		Impact on space cooling and heating demand due to neighboring buildings. Comparison between stand-alone building and building situated in a typical street canyon. (H/W=1)

		of buildings. | 2016 | Rome. *4 Citations*		 Heating demand increases in winters | cooling demand decreases in winter | annual energy savings
21	Solar Energy	Using solar availability factors to adjust cool-wall energy savings for shading and reflection in neighboring buildings. | 2019 *0 Citations*	eQuest and EnergyPlus	Difference in the Solar Availability Factor (ratio of sunlight incident on the wall of the subject building in the presence of adjacent building to the absence of adjacent building) with respect to varying <u>*canyon ratios*</u> (.2, 1, 2 & 10) is studied for 17 cities in USA. SAF values varied from .06 to .24. 
22	Energy and Buildings	Impact of street canyon typology on building's peak cooling energy demand: a parametric analysis using orthogonal experiment. | 2017 | Taipei, Taiwan. *3 Citations*	EnergyPlus and ENVI-met	Variable <u>*canyon ratios and orientations*</u> studied to analyze its impact on the streets microclimate and the energy consumption on the lower 3 floors in a building.  Wider canyons require trees plantation for better microclimate then narrow canyons. Buildings in NE-SW oriented canyons are more energy efficient.

23	Energy and Buildings	Tree and neighboring buildings shading effects on the thermal performance of a house in a warm sub-humid climate. | 2015 | Mexico. *3 Citations*	EnergyPlus	The impact is studied in a non air conditioned building. Indoor temperature difference of 2.3℃ less is noted while considering mutual shading.  
24	Energy Conservation and Management	Shading effects due to nearby buildings and energy implications. | 1999 | Hong Kong, China. *43 Citations*		Total 120 commercial buildings surveyed in the business districts of Hong Kong. Shading from the adjacent buildings ranged from 25% to 31%. The study showed that total building cooling load is overestimated by about 2% and more attention to be given towards building's internal loads then the gains through building's envelope.
25	Energy Policy	The role of urban form as an energy management parameter. | 2013 | London | U.K. *17 Citations*	Virtual Environment (VE)	Three types of office building forms are tested in a street of London. In the stand alone case, the energy consumption pattern showed no variation. But when placed in an urban setting, the form C consumed maximum energy for cooling, while Forms B & C showed similar results. 
26	Building	The study of the effects	ENVI-met	12 different types of building arrangements studied, with 6 for point type building structure and 6 for slab

	and Environment	of building arrangement on microclimate and energy demand of CBD. | 2016 | Nanjing, China. *6 Citations*	HTB2	type building structure. The building's shape and arrangement affects the energy demand in cooling the rooms.  Buildings in point shape shows more potential for saving the energy. Buildings in random and center low arrangements have a worse performance in energy use while the buildings in average and center high arrangements show a better energy performance.
27	Energy and Buildings	The effect of urban densification on energy consumption and solar gains: the study of Abu Dhabi's neighborhood. | 2017 | Abu Dhabi U.A.E *1 Citation*		Variation in <u>*the no. of floors (building height) and the setbacks*</u> around the building is studied for a hot and dry climate of Abu Dhabi. The set back varied from 5 to 15 meters and the no. of floors from 1 to 3.  For the setback of 5 meters, 1 storey villa shows the reduction of solar gains by 19%, 2 stories villa 29.2% and 3 stories villa 36.6%. Cooling demand reduced by around 5% for 1 storey, 5.8% for 2 stories and 7.2 for 3 stories villa.
28	Urban Technology	Simulating the thermal energy performance of	EnergyPlus	2 buildings (1 Commercial B1 and 1 Residential B2) in New York are studied to analyzethe inter building effect (IBE). Both the buildings were first simulated without the surroundings, then with the surroundings. The

		buildings at urban scale: Evaluation of inter-building effects in different urban configurations. |2014 | New York. *12 Citations*		surrounding density varied in 3 levels: Non-dense urban area; dense urban area and very dense urban areas.  The results were as follows: The analysis showed in IBE of 9.6%, 20.8% and 50.8% for office building, and 27.9%, 34.3% and 71.9% for the residential building, corresponding to the 3 growing levels of the urban density. The difference in solar gains of 24% in B1 and 77% in B2 was noticed, when individual building is compared in a real scenario. These differences were up to 75% and 78% when the analysis is focused on the lower floors of B1 and B2 respectively.

The following (2.2.1 to 2.2.7) are the final parameters identified from the literature studied above.

2.2.1 Form of the adjacent building

In a study conducted in [26], a hypothetical arrangement of buildings is modelled. In the first case they modelled shorter and squatter building and in the second case they modelled taller and thinner buildings, on the same plot.

Fig. – 3 Impact of adjacent building's form on mutual shading (1).
Source: [26] Izabella Lima, Veridiana Scalco and Roberto Lamberts (2018).

The results showed that, Shorter and bulkier buildings are more benefitted from mutual shading than taller and slender in terms of reducing cooling loads as they cast more shadow more longer period of time at a single location. There is less difference in the energy consumption between lower floors and upper floors in tall slender buildings, and more difference in the shorter bulkier buildings. The same analysis was written by the real estate board of New York [2] in there publication on the solar rights in a mega city. The images shown below are from the publication that shows the shadow casted by two different towers in a park adjacent to them.

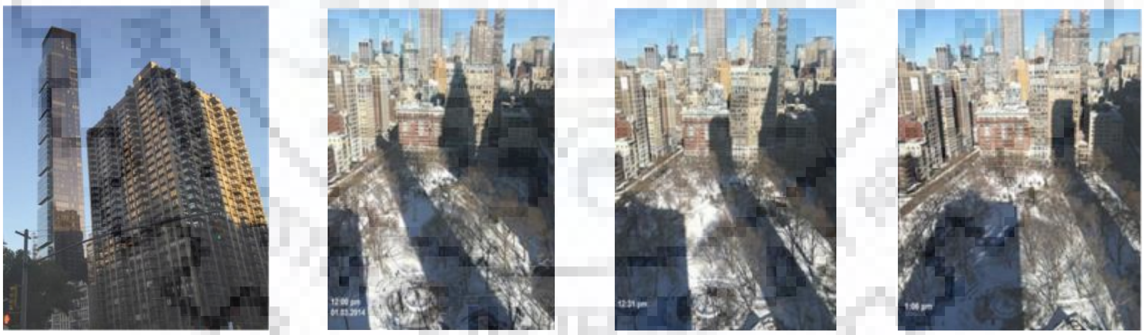


Fig. – 4 Impact of adjacent building's form on mutual shading (2). Source: The real estate board of New York

In another research [29], a case study of Israel, in which an existing building (Hotel Laguna) is shaded by the new upcoming building (Hotel Shva). As per the master plan the upcoming hotel was violating the solar rights of the existing hotel. A new design as per the F.A.R proposed, that didn't violated the solar rights. The new form of the hotel was so designed that it does not violate the solar rights of the existing hotel.

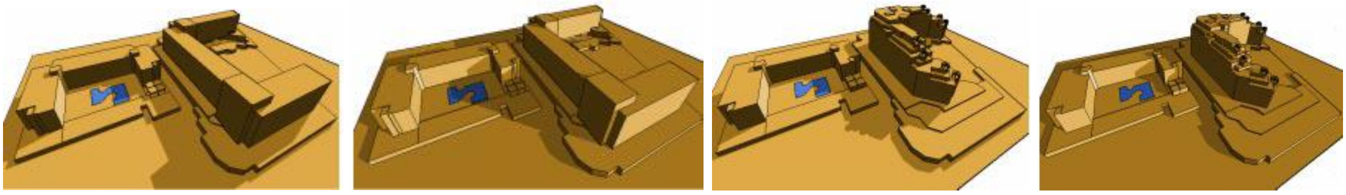


Fig. – 5 Impact of adjacent building's form on mutual shading (3). Source: [29] Dr. A. Yezioro and Prof. E. Shaviv (1994).

2.2.2 Height of the adjacent building

This is one of the most important parameter that impacts the mutual shading. The height of the adjacent building decides the reach of its shadow. If the adjacent building is taller than our building, then it might remain shaded for the entire day. Lesser height of the adjacent building means that our building will be exposed to the solar radiation for maximum time of the day. There are various studies conducted in which the impact of the adjacent building's height is studied on a building's shading. In study [2], buildings with four different heights are placed around the test building in a hypothetical environment, and then its impact is accessed. The height of the adjacent building is measured in terms of angle of obstruction i.e. the angle between the window sill on a floor and the top of the building in front of it.

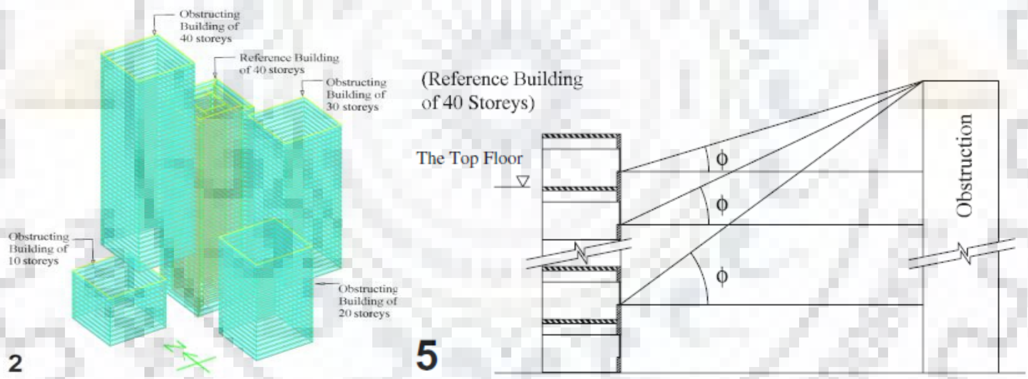


Fig. – 6 Impact of adjacent building's height on mutual shading. Source: [2] Danny H.W. Li and S.L. Wong (2007).

2.2.3 Orientation

The orientation of the network buildings is another factor that impacts the mutual shading. The suns position is different at different cardinal points. [3] Sun's azimuth is more on the south side as compared to east and west sides. And the north side is not at all exposed to the sun for the cities above latitude 12° north. Therefore, if the adjacent building is present at east or west orientation, it will block maximum amount of solar radiation. The northern facades are less affected by the presence of adjacent building, as there isn't any solar radiation to block.

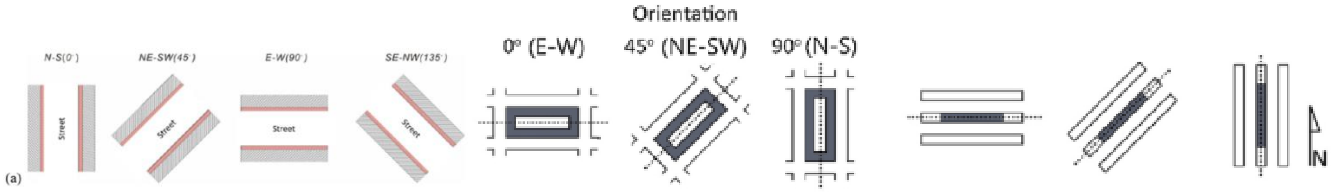


Fig. – 7 Impact of building cluster's orientation on mutual shading. Source: [34] Kuo-Tsang Huang and Yi-Jhen Li (2017).

2.2.4 Canyon ratio

Canyon ratio is the most researched parameter among all the other parameters. But the impact of canyon ratio is analysed for Urban Heat Island effect majorly. It does have the impact on mutual shading as well. A single term canyon ratio covers two major parameters that impact the mutual shading; these are, the distance between the two buildings and the height of the two buildings. It does not only impact the microclimate of a surrounding, but also the energy consumption of the buildings in that particular environment. In various studies carried out [28] [36], it was observed that more compact the surrounding environment was the more energy efficient the buildings were in that environment. This is because the compact arrangement blocked the solar radiation, kept the adjacent buildings shaded, and hence resulted in lower cooling loads. But the case was opposite in cool environments, here the obstruction in solar radiation due to shading by adjacent buildings lead to higher heating loads.

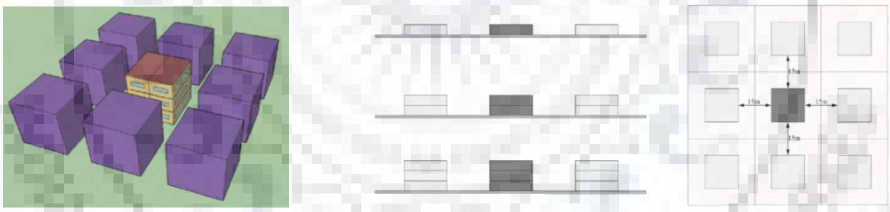


Fig. – 8 Impact of canyon ratio on mutual shading (1). Source: [28] Yilong Han, John E. Taylor and Anna Laura Pisello (2015).

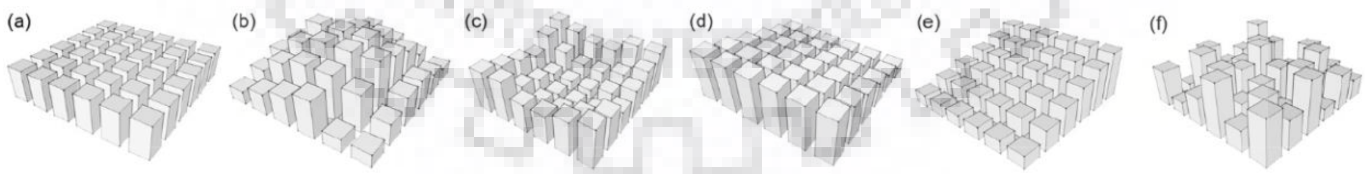


Fig. – 9 Impact of building cluster's orientation on mutual shading (2).
Source: [37] Ji-Yu Deng, Nyuk Hien Wong and Xin Zheng (2016).

2.2.5 Solar reflectance from adjacent buildings

While studying various research papers in search of parameters, some papers came across in which the solar reflectance from adjacent buildings is also considered as a parameter that impacts the mutual shading. In a few studies in which very detailed models are prepared for the analysis, it was observed that solar reflectance from adjacent buildings add to exposure intensity of on the building. High reflectance materials reduced solar gains in the building they are applied to, but solar radiation reflected from the building surface adds to the solar gains of its adjacent building. A study was conducted [12], in which the adjacent buildings were modelled with different compositions on glazing. From high WWR to low WWR and from high reflectance glass to low reflectance glass was tested to check the impact of the solar reflectance of the adjacent building on energy consumption of the building. It was observed that the impact of solar reflectance is more than the WWR. Scenario with adjacent buildings having high WWR and less reflectance was more energy efficient than the scenario having less WWR and high reflectance.

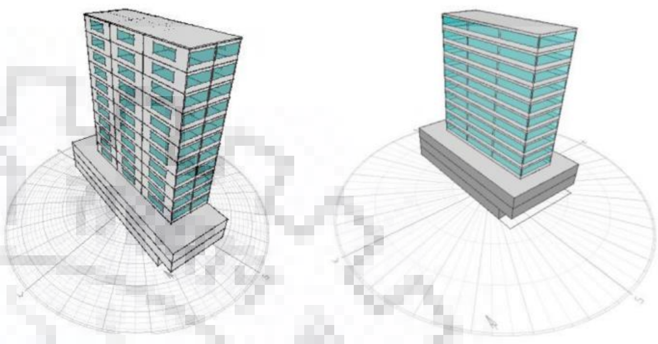


Fig. – 10 Impact of solar reflectance from adjacent building on mutual shading. Source: [12] Tatiana Alves, Luiz Machado, Roberta Gonc¸ alves de Souza and Pieter de Wilde (2017).

2.2.6 Setbacks around building

Like canyon ratio, this parameter is also related to the distance between the buildings. But canyon ratio only talks about the street widths, not the side opens spaces left around a building. In almost all of the cases setback distances are directly proportional to the height of the building, the taller building, more the setback will be. Setbacks are also provided as per fire and safety norms, so that in the case of emergencies like fire, relief providing vehicles can easily access the each side of the building. Another purpose of the setback is to provide enough space around building that it can full its natural lighting and ventilation needs. This parameter has guidelines for the provision provided by the local authorities which are mandatory to follow, and its purpose is to make sure that the buildings are not fully shading each other. This parameter is very generally tested in a research papers [12] [28] regarding mutual shading.

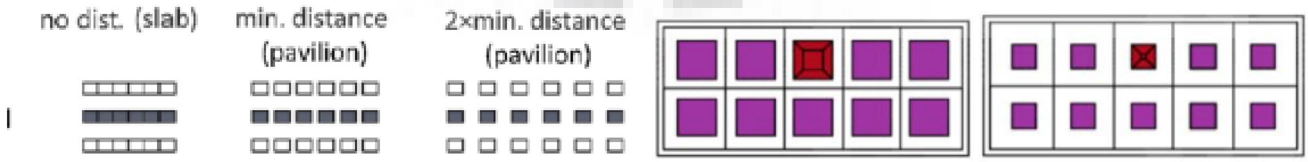


Fig. – 11 Impact of setbacks around building on mutual shading.
Source: [26] Izabella Lima, Veridiana Scalco and Roberto Lamberts (2018).

2.2.7 Modelling and Simulation of a real scenario

In most of the cases studied, either hypothetical scenarios were created to study the impact of the parameter, or data from the real locations were collected, and then modelled to see the impact of the surrounding environment on the buildings' energy consumption [4] [30] [32]. In the study of real scenario, the common pattern observed was, first phase included the data collection form the site for modelling. After data collection a replicated model of the real scenario is developed, and then simulations are carried out on a single building existing in that environment. After that same building is simulated after removing the surrounding environment and then the test results for the two cases are compared. That is how the impact of mutual shading is analysed for a real scenario.

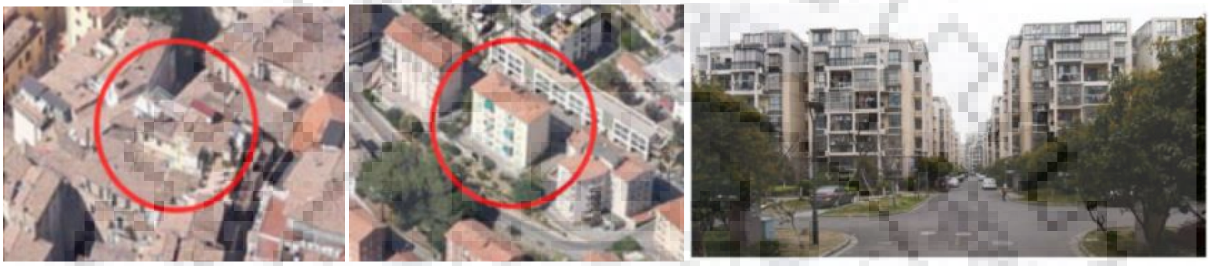


Fig. – 12 Real scenarios studied for mutual shading. Source: [30] Chaosu Li, Yan Song and Nikhil Kaza (2017).

CHAPTER 3

SIMULATION DATA

3.1 Description of Base Model

3.2 Building Network Layouts

The impact of mutual shading varies from region to region as the climate changes. As India has five different climatic zones, therefore, first there is a need to analyse how mutual shading impact the energy consumption of a building existing in these different climates. To understand this, energyplus simulation tool is used to access the energy data of the subject building (the building on which the impact of mutual shading is to be studied) for different climatic conditions and layouts. A base model of the subject building is developed and then neighbouring buildings are placed adjacent to it. Different cases are made out of the possible arrangements of the adjacent buildings around the subject building. All these cases are modelled in design builder for each climate and then simulated to get the annual energy consumption data.

3.1 Description of Base Model

The base case is a simple stand alone (with no adjacent buildings) multi-storey residential building exposed on all the sides. The energy consumption of the base model is compared with the buildings with mutual shading to see the difference in energy data.

3.1.1 Plan and form of the building

The building forms usually considered are very geometric in shape, which is not the case in real scenario, particularly in the case of residential buildings. In multi-storey residential buildings, the plan form of a building is usually evolved from the function of the spaces it has. Also, various studies conducted have proved that a building's form has a crucial impact on its energy consumption. The basic factors that have the impact are: the compactness of the building form and self shading due to the shape of the building. Now, there can be uncountable ways in which a building can be planned, but each plan is based on a common idea.

In a report compiled by GBPN on Residential buildings in India: Energy use projection and savings potentials, a very exhaustive study has been conducted on the plan form of a multi-storey residential building. In the study, total 777 houses were surveyed from 4 different Indian cities, each representing different climatic zone of India. Based on the survey, a typical form of the building floor plan is evolved after carefully observing the repetitive features of the layout plans. A general layout of Indian residential building plan was prepared for 1bhk units, 2bhk units and 3bhk units.

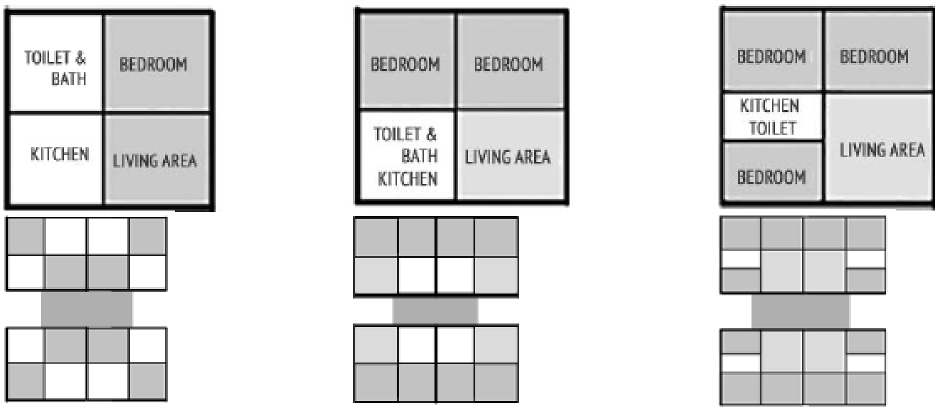


Fig. – 13 Indian residential plan general layout. Source: [9] Global building performance network (2014).

For the base model, the floor plan and clustering layout of 3bhk floor plan is considered, as the study is targeting more towards the middle income group housing. As per the GBPN report, the suggested floor plan and cluster layout is shown in the figure below.

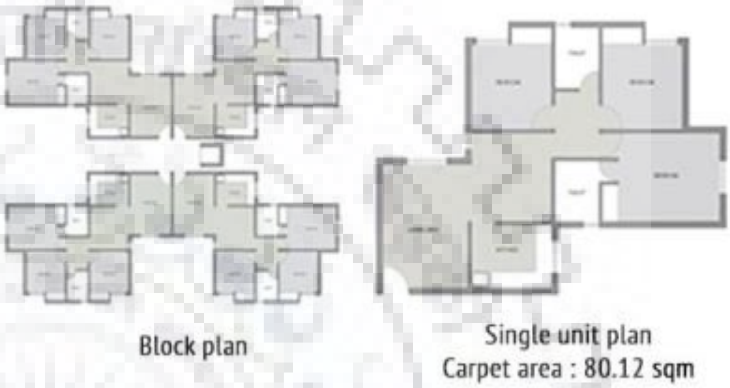


Fig. – 14 Building plans for building energy modelling. Source: [9] Global building performance network (2014).

3.1.2 Building zones

Unlike office buildings, residential buildings have different zones which operate throughout the 24 hours cycle. In office buildings, cooling loads are majorly dominated by internal heat gains (lighting, computers, people etc.), while in residential buildings most of the cooling load emerges from heat gains through building envelope. A major part of an office space has similar operation being performed in it. A typical residential building has 5 different zones; bedroom, living room, kitchen, toilet and common circulation spaces like staircase lobby. Each zone is in operation at a specific time during the 24 hours cycle for a specific task. The zones with the maximum hours of occupancy are living rooms and bedrooms, hence contributes majorly towards the total energy consumption of a single dwelling unit. Living rooms are occupied during day time while bedrooms are occupied during the night.

Fig. – 15 Zones distribution in the modelled building plan.

To get more precise results for the energy consumption of the modelled building, it is divided into 4 zones, two zones for the bedroom and two zones for the living room, with proportionate floor area distribution. Each facade of the building has equal area distributed to the bedroom and to the living room.

3.1.3 Building height

As per NBC 2016, the minimum clear height of a habitable room should be 2.75 meters. Adding to that number, the average thickness of flooring is 0.4 meters, the total floor to floor height in the building thus came out to be 3.15 meters. A medium rise building has different definition for different cities. In major metro cities like Delhi and Mumbai in India, any building between 4 to 12 stories is considered to be a mid rise building. For the purpose of the study, the building modelled has 12 stories, which gave us the total height of 37.8 meters.

Fig. – 16 Base case: 12 floors high standalone building.

3.1.4 Simulation Inputs

Detailed simulation inputs for the base model are taken as per the guidelines for the energy efficient design of a multi-storey residential building provided by BEEP India. This way we can better analyse how an already energy efficient building, designed as per guidelines, is affected by the mutual shading. Our aim is to come up with an extended set of guidelines for a building's envelope design, which are more lenient as compared to generic ones, for the portions that are shaded by an adjacent building. The idea is to match the energy performance of the building designed as per lenient guidelines to the energy performance of the building designed as per generic guidelines in a standalone scenario. The table provided below shows various simulation inputs for the base model.

S. No.	Material	SHGC	VLT	U-Value
1	Double Glazing, clear, no shading	0.697	0.781	2.708
2	Wall: Brick mineral insulation thermolite block and l/w plaster			0.403
3	Roof: Projected flat roof			2.5
4	Window to Wall Ration : 20%			
5	HVAC with split no fresh template			

Table – 1 Simulation inputs in the model

3.2 Building Network Layouts

After creating and simulating the base model with a simple stand alone building, different possible layouts of single and multiple buildings arrangements around the subject building are developed. In total 15 layouts of building clusters are developed, which are the typical cases in which buildings may exist. All these cases are explained in detail in 3.2.

3.2.1 Description of adjacent building

The role of the adjacent building is to shade the subject building from the incident solar radiation. This building will not be simulated as we do not require its energy consumption data. It is only a dummy building. Therefore its detailed modelling is not required. It is just a single zone building, with the similar form, floor area and height as of the base model building. This building is modelled like a component block. Its number and orientation around the subject building is iterated to develop different cases which we are talking about.

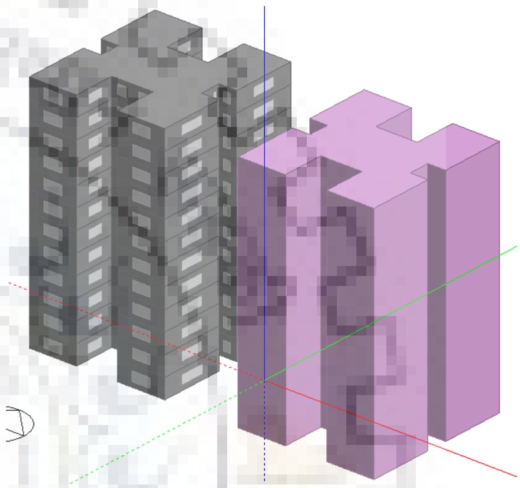


Fig. – 17 Base case with another adjacent building Of same height placed at a distance of 12 meters.

3.2.2 Different possible cases

The subject building that we have modelled has 4 sides; that means it is exposed to solar radiations from those four different sides. Presence of an adjacent building on a side will shade the subject building, and protect it from direct incident solar radiation on that particular side. These different cases are evolved from 2 basic logics: 1. the number of sides where adjacent building is present and 2. the orientation of the mutually shaded/exposed sides. In this way the total number of cases came out like following:

a. Adjacent building on one side: East, West, North and South. (4 Cases)
b. Adjacent building on two sides: South-East, North-East, East-West, South-West, North-South and North-West. (6 Cases)
c. Adjacent building on three sides: North-South-East,

East-West-North, East-West-South and North-South-West. (4 Cases)

d. Adjacent building on four sides: East-West-North-South. (1 Case)

Total number cases = 15 Cases

The above mentioned cases are just the possible arrangements of the building. All these 15 cases are modelled and simulated for the 5 different climatic regions of India. This gives us the total number of 75 cases to be simulated. The adjacent table shows cities representing each of the climatic regions. The weather data files of these cities are used for the simulation purpose.

Climate	City
Composite	New Delhi
Hot-Dry	Jodhpur
Warm-Humid	Guwahati
Cold	Shillong
Temperate	Bangalore

CHAPTER 4

MUTUAL SHADING ANALYSIS

4.1 Impact on Different Cases

4.2 Impact With Respect to Climate

4.3 Annual Cooling Loads

4.4 Annual Heating Loads

The simulation results are compared at various levels. First a case to case comparison is done to see the impact of the adjacent buildings' arrangement on the subject building's energy consumption. Second comparison is done on the bases of the impact of different climate. It is carefully observed that in which climate mutual shading has the maximum benefit or loss or does not have an impact at all. Third one is the climate wise comparison on the annual cooling load and the last but not the least is the climate wise comparison on the annual heating load.

4.1 Impact on Different Cases

The case to case comparison helps in better understanding the impact of the adjacent buildings and its arrangements on the energy consumption in the subject building.

The graph given below shows how the total annual energy consumption is varying from cases to case and climate to climate. The numbers on the left side shows total annual energy consumption in kWh, the bars represent different climatic zones, the x-axis represents different cases in which the adjacent building is present and at which orientation. The numbers on the right side shows the percentage difference in energy consumption for different cases and climates.

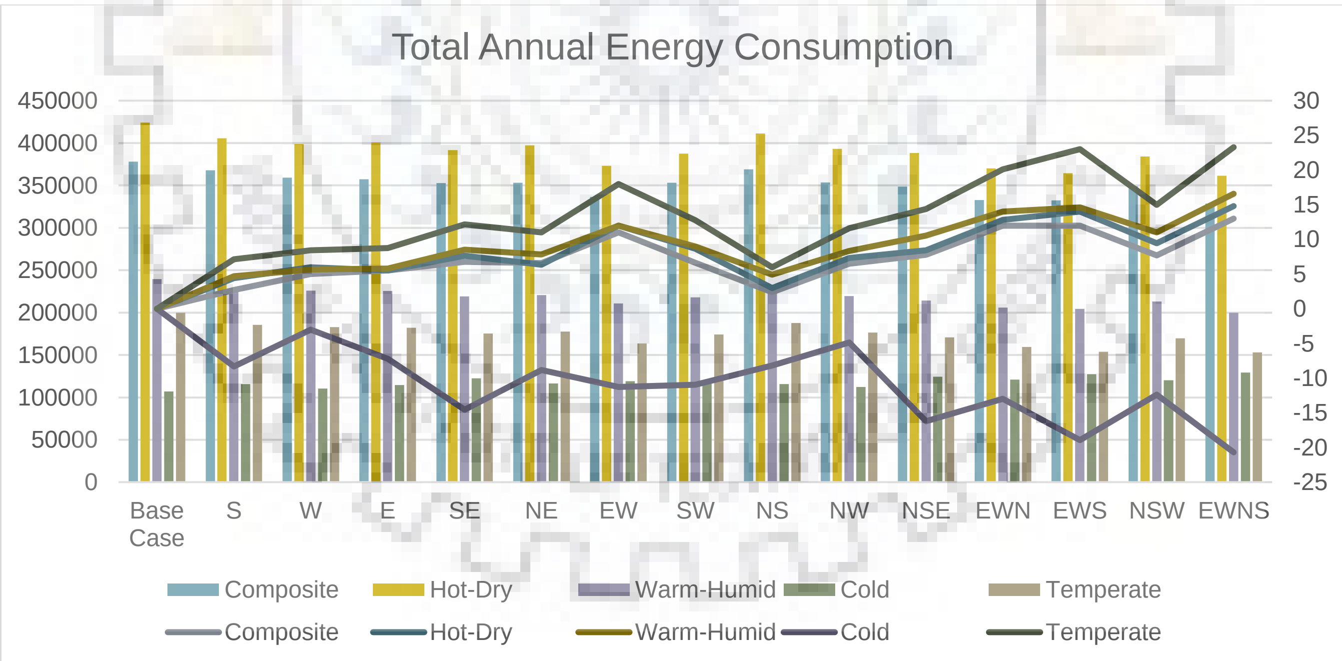


Fig. – 18 Variation in total energy consumption for different climates and layouts.

As observed, the energy consumption in the base case is reduced by the presence of an adjacent building. However, the energy savings is not directly proportional to the number shaded sides. In the case of shading from North-South, the energy savings is lesser than the cases in which building is shaded from west side and east side. For the North-South shading, the energy is similar to that of south shading. The best case out of the adjacent buildings on two sides with the maximum energy savings is the East-West shaded case. The energy savings for it is similar to that of the energy savings in adjacent building on three sides case of East-West-North shaded and East-West-South shaded. Shading from all the four sides has the maximum energy savings, as the exposure to solar radiation in minimum in this case due to presence of adjacent buildings at all the four sides. From the above comparison it is observed that the orientations with the maximum impact are East and West sides. Mutual shading due to presence of adjacent building on these sides has the maximum potential of energy savings.

4.2 Impact With Respect to Climate

It is observed that mutual shading has some amount of impact in each in each climatic condition. The overall impact is positive for composite, hot-dry, warm-humid and temperate climates, accept the cold climate. In the other 4 climates, the cooling load is the dominant factor in the overall energy consumption of a building and shading from the adjacent buildings causes reduction in the cooling loads. Therefore for these four climates, the impact of mutual shading is positive.

Savings in Building's Annual Energy Consumption					
*The numbers represents energy in kWh saved for that case from the base case.					
Cases	Composite	Hot-Dry	Warm-Humid	Cold	Temperate
Standalone Building					
Case 1	0	0	0	0	0
Adjacent Building on One side					
S	10303.88	18806.18	11209.39	-8875.08	14241.69
W	18885.79	25286.9	13614.62	-3297.3	16851.4
E	20971.21	23472.9	13868.45	-7706.45	17475.39
Adjacent Building on Two Sides					
SE	25529.65	32474.15	20368.49	-15577.49	24265.51
NE	24922.22	26901.95	18794.53	-9453.9	22015.29
EW	41508.94	51010.58	28806.74	-12075.92	35923.19
SW	25184.52	36661	21497.72	-11743.55	25531.81
NS	8986.38	12806.05	11758.86	-8750.83	12012.56
NW	24644.92	31107.39	19974.36	-5227.01	23232.3
Adjacent Building on Three Sides					
NSE	29434.43	35885.92	25249.36	-17372.21	28772.11

EWN	45354.78	54332.56	33590.76	-13921.99	40156.99
EWS	45648.08	59662.91	35014.06	-20256.77	45943.91
NSW	29115.4	40039.03	26374.54	-13234.65	29999.55
Adjacent Building on Four Sides					
EWNS	493434.6	62948.97	39745.13	-22149.07	46520.28

Table – 2 Savings in building's energy consumption due to mutual shading for different climates and layouts.

Whereas on the other hand, in cold climate, heating loads are the dominant factor in the overall energy consumption of a building. Mutual shading in this climate reduces the exposure of the subject building to the incident solar radiations, because of which increase in annual heating load is observed. Therefore mutual shading has negative impact on the energy savings in cold climate.

For the rest of the four climates, while looking at the percentage saving, it was observed that the increase and decrease in the energy savings for different cases is in a similar pattern. Bigger number for the percentage of energy saved is observed in temperate climate and lowest in composite climate. Whereas if we look at the absolute values, the units of energy saved is maximum in Hot-Dry climate and least in Warm-Humid climate.

4.3 Annual Cooling Loads

As discussed above, cooling load is the dominant factor in the overall energy consumption for the four climates. Cooling loads are the highest in Hot-Dry and composite climates, with maximum being in the Hot-Dry climate. The cooling load values are almost negligible for the cold climate as compared to the other climates.

The case to case percentage differences of cooling loads for different climates are in the similar range accept the cold climate. In cold climate the absolute values are very small and hence the percentage difference is very high. Now if we look at the absolute values, Hot-Dry climate gives us the maximum savings out of all the climates. The annual cooling load savings for the best case i.e. shaded for four sides (EWNS) is: 64,252.86 kWh for Hot-Dry, 54,979.85 kWh for Composite, 46,520.19 kWh for Temperate, 40,790.45 kWh for Warm-Humid and 835.05 for Cold climate.

For decreasing building's cooling load, placing the adjacent building on East and West sides gave the best positive results. Therefore, to achieve maximum savings in the cooling load, it is best suggested to mutually shade a building from east and west sides.

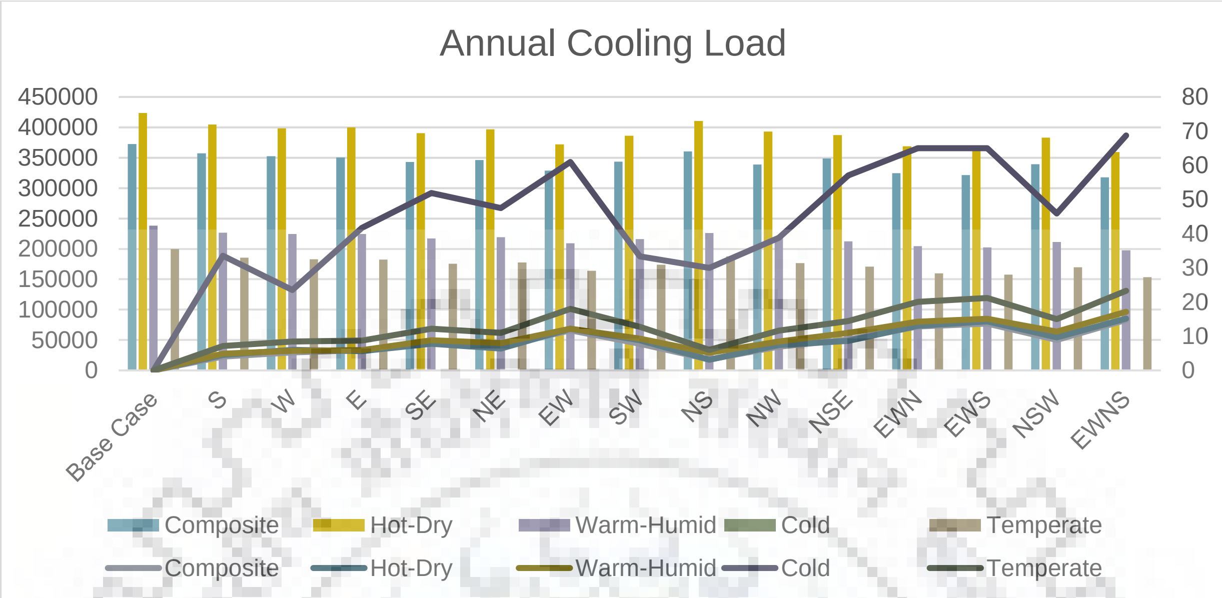


Fig. – 19 Variation in annual cooling loads for different climates and layouts.

4.4 Annual Heating Loads

The heating loads are very high in cold climate. The actual impact of mutual shading on annual heating loads can only be seen in cold climate. Composite climate also shows some influence but it is heavily dominated by cold climate. Mutual shading increases a building's heating load. Mutual shading's impact on heating load is opposite to the impact of cooling load.

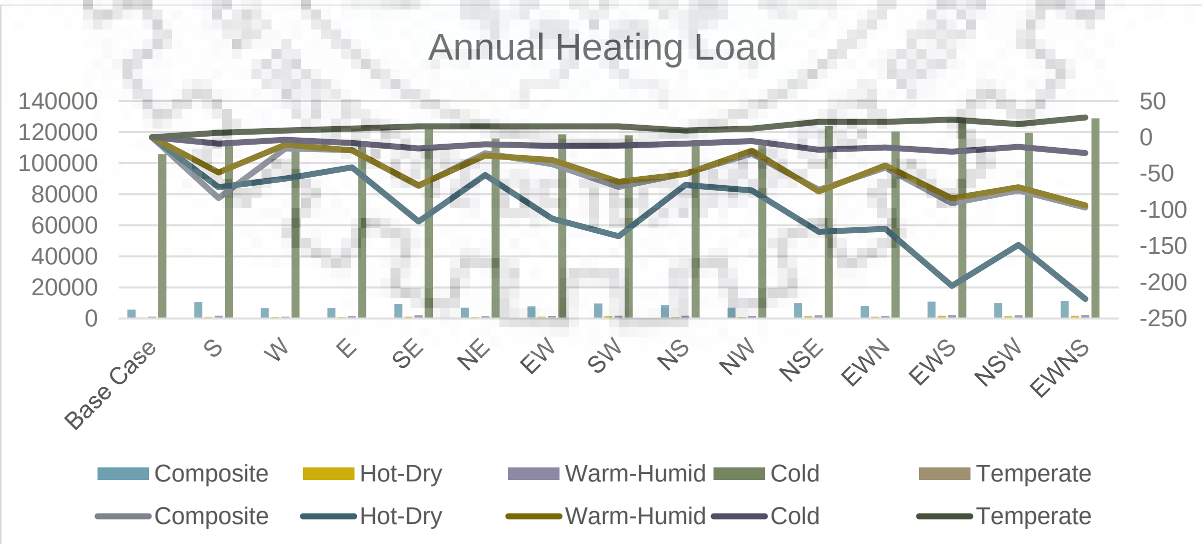


Fig. – 20 Variation in annual heating loads for different climates and layouts.

Mutual shading increases a building's heating load. For building's cooling load it was observed that mutual shading from East and West sides was showing high difference in energy consumption as compared to other sides. But for a building's heating load, shading from south and east has the maximum impact. It increases the building's energy consumption by a significant number.

Therefore, for cold climate, placing adjacent building should be avoided on the southern and eastern sides, as mutual shading from those sides has the maximum negative impact.

Out of all the climates studied, maximum energy savings due to mutual shading is observed in Hot-Dry climate. Therefore for the further study, Hot-Dry climate will be worked upon in detail.

Savings in Building's Annual Heating Load					
*The numbers represents energy in kWh saved for that case from the base case.					
Cases	Composite	Hot-Dry	Warm-Humid	Cold	Temperate
Standalone Building					
Case 1	0	0	0	0	0
Adjacent Building on One side					
S	-4813.82	-402.26	-583.58	-9282.16	0.02
W	-890.19	-333.75	-122.37	-3582.61	0.03
E	-1005	-242.31	-215.74	-8212.55	0.04
Adjacent Building on Two Sides					
SE	-3852.01	-680.27	-795.35	-16208.21	0.05
NE	-1263.07	-305.67	-298.87	-10030.75	0.05
EW	-2113.72	-655.65	-377.22	-12816.27	0.05
SW	-3909.38	-797.6	-734.92	-12150.48	0.05
NS	-2862.96	-383.78	-606.12	-9114.4	0.03
NW	-1294.85	-429.21	-222.39	-5699.01	0.04
Adjacent Building on Three Sides					
NSE	-4151.95	-762.39	-894.22	-18063.82	0.07
EWN	-2409.24	-738.84	-467.74	-14712.38	0.07
EWS	-5205.61	-1198.38	-1012.92	-21046.13	0.08
NSW	-4191.44	-867.99	-823.32	-13792.6	0.06
Adjacent Building on Four Sides					
EWNS	-5545.25	-1303.89	-1125.31	-22984.1	0.09

Table – 3 Impact on building's annual heating loads due to mutual shading for different climates and layouts. (The minus sign shows that impact was negative, the overall heating loads for the cases increased by the respected numbers mentioned)

Savings in Building's Annual Cooling Load					
*The numbers represents energy in kWh saved for that case from the base case.					
Cases	Composite	Hot-Dry	Warm-Humid	Cold	Temperate
Standalone Building					
Case 1	0	0	0	0	0
Adjacent Building on One side					
S	15117.8	19208.44	11792.97	407.09	14241.67
W	19775.98	25620.65	13736.99	285.32	16851.37
E	21976.21	23715.21	14084.2	506.11	17475.36
Adjacent Building on Two Sides					
SE	29381.64	33154.42	21163.85	630.74	24265.47
NE	26185.3	27207.62	19092.41	576.78	22015.25
EW	43622.66	51666.23	29183.97	740.35	35923.14
SW	29093.9	37458.6	22232.64	406.94	25532.27
NS	11849.34	13189.84	12364.98	363.57	12012.53
NW	25939.77	31536.6	20196.76	472.01	23232.27
Adjacent Building on Three Sides					
NSE	33586.38	36648.31	26143.59	692.61	28771.78
EWN	47764.02	55071.4	34058.53	790.4	40156.67
EWS	50853.7	60861.29	36026.98	789.37	42343.83
NSW	33306.84	40907.02	27197.86	557.94	29999.5
Adjacent Building on Four Sides					
EWNS	54979.85	64252.86	40970.45	835.04	46520.19

Table – 4 Savings in building's energy consumption due to mutual shading for different climates and layouts.

CHAPTER 5

ITERATIONS/CASES

5.1 Adjacent Building's Layout

5.2 Angle of Obstruction (Building Exterior Parameter)

5.3 Building Envelope Parameters

5.4 Final Number of Cases

From the previous chapter, maximum amount of energy savings is observed in Hot-Dry climate. In this chapter, further cases and iterations to be studied to come up with the final set of guidelines for the mutually shaded facades of a building existing in Hot-Dry climate are discussed.

5.1 Adjacent Building's Layout

For the mutual shading analysis done in the previous chapter, 15 cases for each climate were studied. Due to time restriction, it won't be possible to simulate and test all the 15 cases in the further study. Therefore, best energy efficient cases from each set of arrangements (adjacent building on 1 side, 2 sides, 3 sides and 4 sides) are taken up and further iterations are made in those cases only. The 3 cases from the top 5 overall most energy efficient cases were from the same set of arrangements. That is why, to get the better understanding for all the set of arrangements, best case from each set is considered.

Overall Best Cases		
Cases	Energy Consumption	Savings from Base Case
Standalone Building		
Base Case	424304.75	Unit Difference
Adjacent Building on Two Sides		
EW	373294.17	51010.58
Adjacent Building on Three Sides		
EWN	369972.19	54332.56
EWS	364641.84	59662.91
NSW	384265.72	40039.03
Adjacent Building on Four Sides		
EWNS	361355.78	62948.97

Best Cases From Each Set of Arrangements		
Cases	Energy Consumption	Savings from Base Case
Standalone Building		
Base Case	424304.75	Unit Difference
Adjacent Building on One side		
W	399017.85	25286.9
Adjacent Building on Two Sides		
EW	373294.17	51010.58
Adjacent Building on Three Sides		
EWS	364641.84	59662.91
Adjacent Building on Four Sides		
EWNS	361355.78	62948.97

Table – 5 Best cases with maximum energy savings (overall and best from each set of arrangements)

In all the cases analysed, the energy consumption is reducing from top floor to the bottom floor due to mutual shading. Till a particular floor from the ground floor, the energy consumption is constant, these are the floors that are constantly shaded. Above this floor, the energy consumption is gradually increasing as the mutual shading is reducing. From the table provided below it is observed that the change in energy consumption is visible from same floor level i.e. the seventh floor level, for all the cases with mutual shading. In base case (stand alone building), the energy change is noticed on the eleventh floor level, below that the energy consumption for each floor is constant.

Reduction in Energy Consumption (kWh) From Top Floor to Bottom Floor					
Floor Lvl.	Base Case	W	EW	EWS	EWNS
1	32418.33	29235.89	26300.64	25407.01	25102.92
2	32493.43	29242.7	26305.63	25409.77	25103.31
3	32495.67	29260.73	26306.36	25411.62	25105.83
4	32540.4	29270.72	26315.74	25414.96	25106.32
5	32571.21	29273.41	26316.41	25417.73	25107.36
6	32671.12	29274.34	26317.35	25425.96	25111.21
7	32793.97	29275.3	26320.22	25429.86	25311.89
8	33177.63	30572.98	28046.01	27407.23	27150.19
9	33265.85	32258.32	30309.62	30035.78	29308.77
10	33272.97	34816.93	33381.03	33041.05	31788.08
11	41164.78	40439.22	39577.28	39332.83	39333.4
12	55231.35	56862.17	56460.83	56334	56227.44

Table – 6 Energy consumption reduction pattern from top floor to bottom floor for the base case and other layouts.

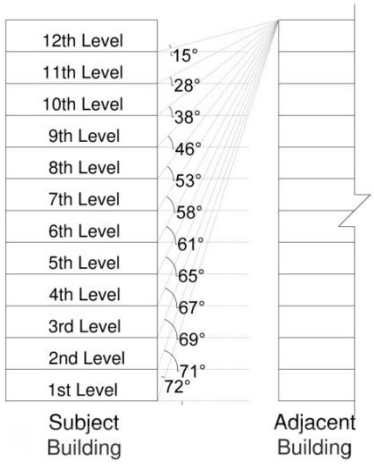


Fig. – 21 Angle of Obstruction Values for each floor.

For the study, each floor level is identified by its angle of obstruction as shown in the figure above.

5.2 Angle of Obstruction (Building Exterior Parameter)

The angle of obstruction represents both height of the adjacent building and the distance between the two buildings. If we say angle of obstruction as θ, then it is the angle between the floor level of the subject building and the topmost level of the adjacent building. The solar radiation exposure on the building façade varies from top (high insolation) to bottom (less insolation). In the presence of an adjacent building, till certain height, the building remains shaded throughout the day. These floors that remain constantly shaded exist beyond the θ_{max}, which is the maximum angle of obstruction. Above θ_{max} variation in energy consumption per floor is not observed due to mutual shading. Similarly, after certain height, the façade is not affected by the shadow, it remains fully exposed to the sun. These floors that are fully exposed to the solar radiation exist below θ_{min}, which is the minimum angle of obstruction. Below θ_{min} energy consumption per floor is maximum and constant. The constant variation in energy consumption per floor is observed between θ_{max} and θ_{min} as the shadow pattern is changing as we move up the floors.

In the study of angle of obstruction, it was observed that θ_{max} and θ_{min} for each variable case is the same. To check this, adjacent building with variable heights is placed at variable distances from the subject building and then insolation analysis on the shaded facade of the subject building is carried out in Ecotect. The outcome of the analysis done for the southern facade is shown in the figures below. The numbers in the first figure represents the Total Radiation (Wh) values on the particular floor.

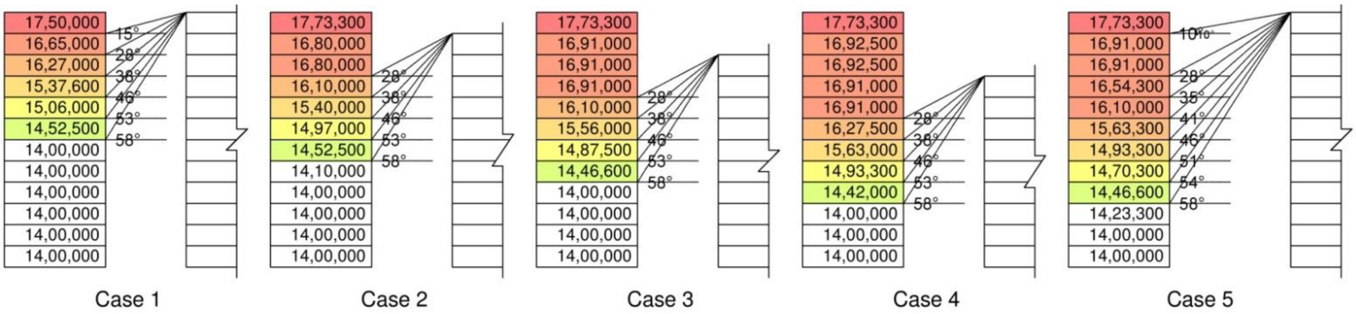


Fig. – 22 Total solar radiation values for different cases and angles of obstruction.

It can be seen from the figure above that with the changing cases, total radiation (TR) values for floor number is changing, but angle of obstruction at which the TR value is changing is constant in all the cases. The θ_{max} and θ_{min} are same for each case and similar are the varying TR values at each angle of obstruction between θ_{max} and θ_{min}. This proves that the impact of mutual shading at a particular angle of obstruction will be similar for different possible cases formed by varying the adjacent building's height and by varying the distance between the subject building and the adjacent building.

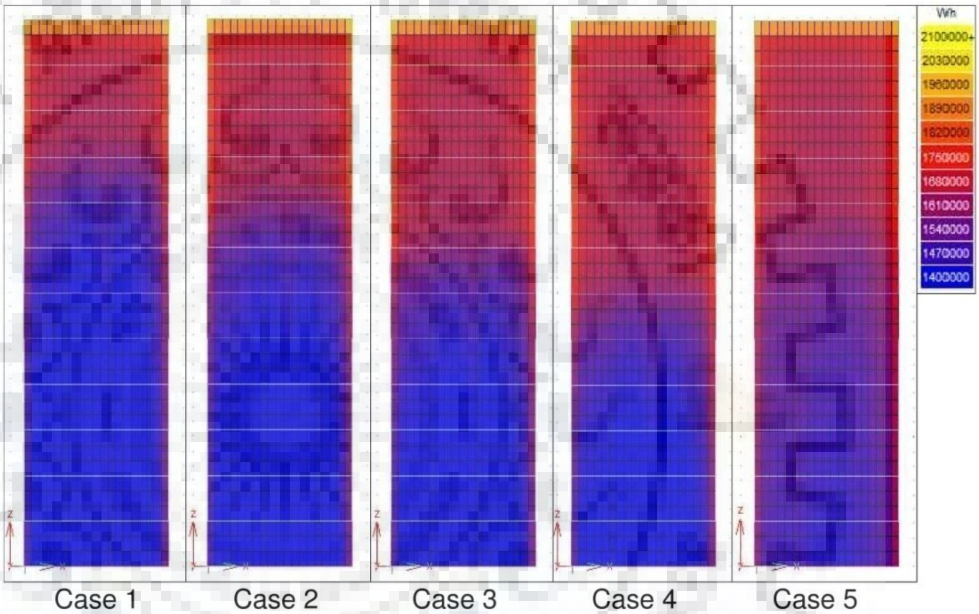


Fig. – 23 Total incident solar on the facade of the subject building for different cases.

That is why it is appropriate to mention floor level by its angle of obstruction because the recommendations suggested in the end for an angel θ, will be applicable on various arrangements that can be possible due to iterations in the adjacent building's height and the distance between the building values.

For our case, θ_{max} and θ_{min} came out to be on 7th floor i.e. 58° and 11th floor i.e. 28° respectively. The variation in energy consumption is observed in increasing order from 7th to 11th, therefore the final floors and angles of obstruction came out to be 7th, 8th, 9th, 10th & 11th floors and 58°, 53°, 46°, 38° and 28° respectively.

5.3 Building Envelope Parameters

Alternate construction materials for walls and fenestrations with varying thermal properties are used for the study. The properties of the alternate construction materials used vary between that of the generic material used for the common practice and the materials with the properties as per the design guidelines provided by BEEP India. In total 4 materials for each wall type and glazing type is selected. One material for both the cases is the prescribed material as per the best practice. The other 3 has properties slightly less efficient than the best practice, but better then the generic materials that are used in common practice. For the floors with mutual shading, that has less energy consumption than the floors exposed to solar radiation, best practice materials are replaced with one of the other 3 materials to bring the energy consumption for that floor similar to that of the exposed floor. This way, mix and match of various construction components will be tested and out of all those tests, best suited recommendations will be suggested in the end.

5.3.1 Glazing Type

The four different glazing types selected on the basis of its u-values are mentioned in the table below. Commonly used single glazed 6mm thick clear glazing has a u-value of 6.12 W/m²K. The glazing types selected has better thermal performance with u-value varying between 2.708 W/m²K to 5.447 W/m²K, with similar difference between each value. The materials selected have the SHGC and VLT values within the prescription range of ECBC 2017.

Glazing Type				
S.No.	Glazing Description	U-Factor	VLT	SHGC
G_1	Double Glazing Clr No shading	2.708	0.781	0.697
G_2	Single LoE (e=0.2) Clr 6mm	4.233	0.811	0.71
G_3	Single LoE (e=0.4) Clr 6mm	4.945	0.85	0.775
G_4	Single Ref-B-H Clr 6mm	5.447	0.301	0.357

Table – 7 Properties of different glazing types to be tested.

5.3.2 Wall Type

Four different construction styles of wall selected for the study are mentioned in the table below. The u-value of a generic brick wall commonly used is 2.1 W/m²K. The wall types selected has better thermal performance with u-values varying between 0.403 W/m²K to 1.562 W/m²K.

Wall Type		
S.No.	Wall Description	U-Factor
W_1	Brick mineral insulation thermolite block and l/w plaster.	0.403
W_2	Brick air b/w concrete block and phenolic foam and l/w plaster.	0.825
W_3	Brick air b/w concrete block and l/w plaster	0.95
W_4	Brick cavity with dense plaster	1.562

Table – 8 Properties of different wall types to be tested.

5.3.3 Window Wall Ratio

The maximum permissible WWR as per ECBC 2017 is 40%, as per NBC 2016 it is 60%. For appropriate natural ventilation in a building, as per NBC 2016, the WWR should be kept more than or equal to 20%. Keeping in mind the range of the WWR as suggested by various guidelines, the variations in WWR considered for the study are: 20%, 30%, 40%, 50% and 60%.

5.4 Final Number of Cases

Four cases of building layouts are selected from each set of arrangements: East-West-North-South, East-West-South, East-West and West. Then variation in energy consumption pattern from lower floor to the top floor is observed for each case to finalize the angles of obstruction for the mutually shaded areas. For each case, the variation in energy consumption due to mutual shading is noticed on the same floor levels. Therefore the angles of obstruction for all the cases are same.

Adjacent Building's Layout		Angle of Obstruction θ		WWR		Glazing Type		Wall Type	Total Cases
		58°		20%		G_1		W_1	
		56°		30%	X	G_2	X	W_2	
EWNS	X	46°	X	40%		G_3		W_3	320
		38°		50%		G_4		W_4	
		28°							
		58°		20%		G_1		W_1	
		56°		30%	X	G_2	X	W_2	
EWS	X	46°	X	40%		G_3		W_3	320
		38°		50%		G_4		W_4	
		28°							
		58°		20%		G_1		W_1	
		56°		30%	X	G_2	X	W_2	
EW	X	46°	X	40%		G_3		W_3	320
		38°		50%		G_4		W_4	
		28°							
		58°		20%		G_1		W_1	
		56°		30%	X	G_2	X	W_2	
W	X	46°	X	40%		G_3		W_3	320
		38°		50%		G_4		W_4	
		28°							

Fig. – 24 Schematic representation of the different cases to be simulated formed for each layout.

There are five angles representing each floor: 28°, 38°, 46°, 56° and 58°. Then there are building envelope parameters. Varying these parameters is actually going to change the energy consumption of the floor. There are four variations selected for each of the building envelope parameters: Wall, Glazing and WWR. The total number of cases formed after doing the permutations and combinations of the above mentioned cases and iterations are 1280. The alternate set of guidelines for the energy efficient design of the shaded areas in a multi-storey residential building will be suggested out of the best cases from the above mentioned 1280 cases. A schematic diagram to explain the cases and iterations is provided below.

CHAPTER 6

DATA ANALYSIS

For the purpose of the study, the 1280 cases formed in the previous chapter are simulated. A number of observations are noted. The analysis of these observations is discussed in detail in this chapter.

6.1 Simulated Cases

In total 1280 cases were formed by varying the values of the parameters identified. The variations in the set of building envelope parameters were formed within the range of the best energy efficient guidelines by BEEP India and the generic material used in the common practice. The building envelope parameters were: wall type, glazing type and the proportion between the wall and window, which is the window wall ratio. In the cases formed, first the proportion of the window to wall is set and then their respective properties are changed. While simulating the cases, it was observed that for a particular WWR value, the energy consumption of the subject building starts exceeding the energy consumption of the base model. That particular WWR value varied from case to case. As the purpose of our study is to come up with a set of recommendations for the envelope parameters of the shaded facade, by applying which, we could get energy consumption values as that of the facade exposed to the solar radiations.

Simulated Cases for Building Shaded from EWNS Sides							
Angle of Obstruction		WWR		Glass Types		Wall Types	Total Cases
58°	X	20%	X	G_1	X	W_1	49
		30%		G_2		W_2	
		40%		G_3		W_3	
				G_4		W_4	
58°	X	50%	X	G_1	X	W_1	
56°	X	20%	X	G_1	X	W_1	49
		30%		G_2		W_2	
		40%		G_3		W_3	
				G_4		W_4	
56°	X	50%	X	G_1	X	W_1	
46°	X	20%	X	G_1	X	W_1	33
		30%		G_2		W_2	
				G_3		W_3	
				G_4		W_4	
46°	X	40%	X	G_1	X	W_1	
38°	X	20%	X	G_1	X	W_1	17
				G_2		W_2	
				G_3		W_3	
				G_4		W_4	
38°	X	30%	X	G_1	X	W_1	
28°	X	20%	X	G_1	X	W_1	17
				G_2		W_2	
				G_3		W_3	
				G_4		W_4	
28°	X	30%	X	G_1	X	W_1	
Total Number Cases Simulated							165

Simulated Cases for Building Shaded from EWS Sides							
Angle of Obstruction		WWR		Glass Types		Wall Types	Total Cases
58°	X	20%	X	G_1	X	W_1	64
		30%		G_2		W_2	
		40%		G_3		W_3	
		50%		G_4		W_4	
56°	X	20%	X	G_1	X	W_1	64
		30%		G_2		W_2	
		40%		G_3		W_3	
		50%		G_4		W_4	
46°	X	20%	X	G_1	X	W_1	34
		30%		G_2		W_2	
				G_3		W_3	
				G_4		W_4	
46°	X	40%	X	G_1	X	W_1	
						W_2	
38°	X	20%	X	G_1	X	W_1	8
				G_2		W_2	
						W_3	
						W_4	
28°	X	20%	X	G_1	X	W_1	9
				G_2		W_2	
						W_3	
						W_4	
28°	X	20%	X	G_3	X	W_1	
Total Number Cases Simulated							179

Table – 9 and 10 Representation of the total number of cases finally simulated of EWNS and EWS side respectively.

Therefore, after observing that the energy consumption of the subject building is exceeding the required value after applying that WWR value, the further iterated cases for that wall and window proportion are not simulated. The final cases simulated after observing the above mentioned outcomes are 695 cases.

Out of these cases, the final sets of recommendations are formed. Case wise, the total number of simulations performed is explained in the tables below.

Simulated Cases for Building Shaded from W Sides							
Angle of Obstruction		WWR		Glass Types		Wall Types	Total Cases
58°	X	20%	X	G_1	X	W_1	64
		30%		G_2		W_2	
		40%		G_3		W_3	
		50%		G_4		W_4	
56°	X	20%	X	G_1	X	W_1	61
		30%		G_2		W_2	
		40%		G_3		W_3	
				G_4		W_4	
56°	X	50%	X	G_1	X	W_1	
				G_2		W_2	
				G_3		W_3	
						W_4	
56°	X	50%	X	G_4	X	W_1	
46°	X	20%	X	G_1	X	W_1	17
				G_2		W_2	
				G_3		W_3	
				G_4		W_4	
46°	X	30%	X	G_1	X	W_1	
38°	X	20%	X	G_1	X	W_1	17
				G_2		W_2	
				G_3		W_3	
				G_4		W_4	
38°	X	30%	X	G_1	X	W_1	
28°	X	20%	X	G_1	X	W_1	17
				G_2		W_2	
				G_3		W_3	
				G_4		W_4	
28°	X	30%	X	G_1	X	W_1	
Total Number Cases Simulated							176

Simulated Cases for Building Shaded from EW Sides							
Angle of Obstruction		WWR		Glass Types		Wall Types	Total Cases
58°	X	20%	X	G_1	X	W_1	64
		30%		G_2		W_2	
		40%		G_3		W_3	
		50%		G_4		W_4	
56°	X	20%	X	G_1	X	W_1	64
		30%		G_2		W_2	
		40%		G_3		W_3	
		50%		G_4		W_4	
46°	X	20%	X	G_1	X	W_1	33
		30%		G_2		W_2	
				G_3		W_3	
				G_4		W_4	
46°	X	40%	X	G_1	X	W_1	
38°	X	20%	X	G_1	X	W_1	5
						W_2	
						W_3	
						W_4	
38°	X	20%	X	G_2	X	W_1	
28°	X	20%	X	G_1	X	W_1	9
				G_2		W_2	
						W_3	
						W_4	
28°	X	20%	X	G_3	X	W_1	
Total Number Cases Simulated							175

Table – 11 and 12 Representation of the total number of cases finally simulated of W and EW side respectively.

The maximum number of cases (179 cases) simulated are for the case of EWS shaded building and the least number of cases observed are 165, for EWNS shaded building.

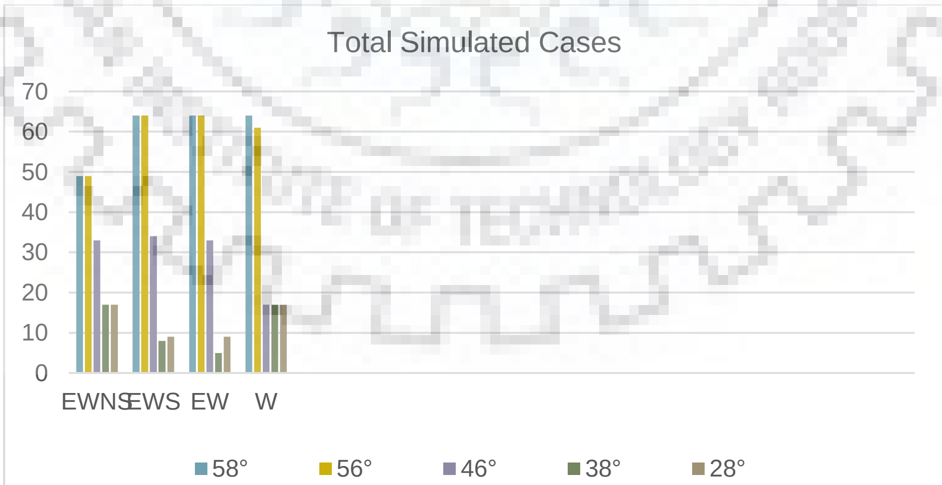


Fig. – 25 Total number of cases simulated for each layout and each angle of obstruction.

6.2 Annual Energy Consumption Analysis

All the finally mentioned 695 cases were simulated, out of which 91 cases are the ones which can be considered for the final set of recommendations. All the remaining 604 cases are unfavourable cases. All the variations and values are tested on the subject building for different layouts. The unfavourable cases are the ones in which the annual energy consumption value of the subject building did not match with the base case building. The energy consumption is matched for the same. There are further two types of unfavourable cases: one with less energy consumption then the subject building and the other with more energy consumption than the subject building. Amongst the unfavourable cases, the number of cases with less energy consumption is very high. There are in total 460 cases for the less energy consumption and 144 for the higher energy consumption. This is because a large set of cases with higher energy consumption were predicted at earlier stage and not simulated. The number of favourable cases varied from layout to layout and within thise layouts it varied for different angle of obstructions.

6.2.1 Annual energy consumption variations for EWNS layout

In the EWNS layout, the subject building is surrounded by adjacent building at all the four sided. As all the sides are mutually shaded, the properties of the envelope parameters are varied on all the 4 sides. So, for the cases of EWNS shaded building parameter values shown in the table in the Annex II are applied on all the 4 sides.

The graph shown below represents the annual energy consumption of each variation for an angle of obstruction. The small dots represent the annual energy consumption (AEC) of different cases. These cases are in a serial order with prescriptive envelope parameter values first and gradually moving towards more lenient values with generic values in the last. Each shade in the graph represents an angle of obstruction, and the solid line segment marks the energy consumption of the base case for that angle. The dots for the staring case falls under the line of base case's AEC. These are the cases with strict parameter values. For higher angle of obstruction value, i.e. the lower floor of the building, the cases with less energy consumption are more, as these floors are mutually shaded by the adjacent building. Here for the angle 58° and more we can use generic construction materials for walls and glazing till WWR 30% and still achieve AEC values similar to that of a stand building designed with special construction materials of best properties as per the BEEP guidelines. We can go up to 50% WWR by using wall and glazing type of properties as the recommendations of the guidelines.

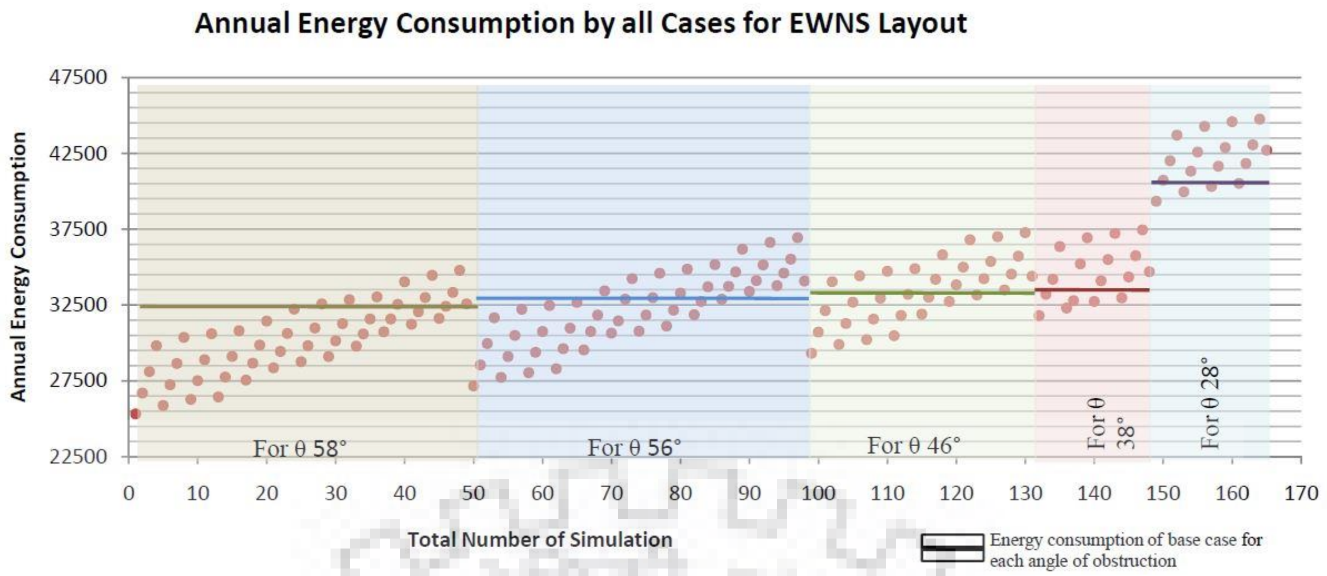


Fig. – 26 Annual energy consumption for each case simulated for EWNS layout.

Here the points are more scattered because the variations in the parameters are done for all the sides. The envelope of the building is completely changed in this case, resulting in the huge difference in the values of each case. As we are moving towards upper floors, the impact of mutual shading is reducing, resulting in higher energy consumption, the simulated cases values have gone up the base case's energy bar. Resulting in many cases with AEC less than the base case. The favourable cases for EWNS that has AEC values similar to that of the base case are summarised in the table below.

Recommendations For Building Shaded From EWNS Sides						
S. No.	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption	Base Case Energy Consumption
1	58°	30%	G_2	W_4	32219.14	32793.97
2		30%	G_3	W_4	32564.89	
3		30%	G_4	W_4	32840.92	
4		40%	G_1	W_4	33021.3	
5		40%	G_2	W_3	32540.41	
6		40%	G_3	W_3	32980.78	
7		40%	G_4	W_2	32408.41	
8		50%	G_1	W_1	32564.77	
9	56°	30%	G_1	W_4	33422.85	33177.63
10		30%	G_2	W_3	32871.98	
11		30%	G_3	W_3	32979.26	

12		30%	G_4	W_3	33269.25	
13		40%	G_2	W_1	32879.45	
14		40%	G_3	W_1	33386.86	
15	46°	20%	G_3	W_3	32948.87	33265.85
16		20%	G_4	W_3	33190.86	
17		30%	G_1	W_2	33005.05	
18		30%	G_3	W_1	33158.96	
19		30%	G_4	W_1	33482.41	
20	38°	20%	G_1	W_2	33194.99	33272.27
21		20%	G_4	W_1	32967.81	
22	28°	20%	G_1	W_2	40719.87	41164.78
23		20%	G_2	W_2	41313.43	
24		20%	G_4	W_1	40510.92	

Table – 13 List of favourable cases for building shaded from EWNS sides.

6.2.2 Annual energy consumption variations for EWS layout

In this layout, the building is mutually shaded from East-West-South sides. Only the north side is exposed, that is why it has minimal difference from the case of EWNS layout.

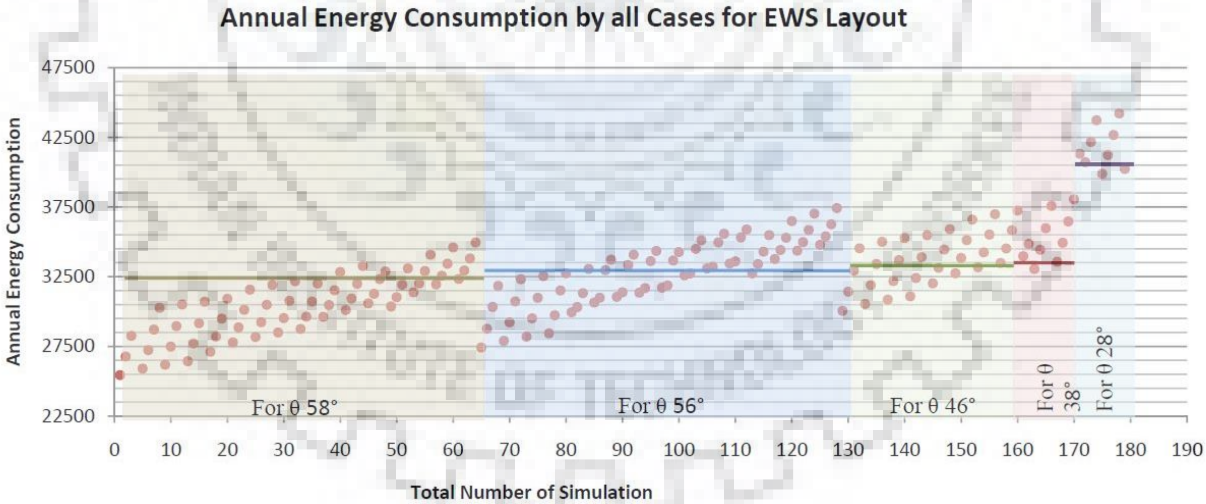


Fig. – 27 Annual energy consumption for each case simulated for EWS layout.

Here also the trend is similar. For the angle of obstruction 56°, 50% of the cases have less energy consumption then the base case and 50% has more energy consumption then the base case. For the angle of obstruction 38° and above, the numbers of cases below the base case's energy consumption are almost negligible. Therefore for these cases we have less number of alternate recommendations. It can be best understood from the table provided with the favourable cases, which are the alternate recommendations for this layout.

Recommendations For Building Shaded From EWS Sides						
S. No.	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption	Base Case Energy Consumption
1	58°	40%	G_2	W_4	32830.77	32793.97
2		40%	G_3	W_4	33266.75	
3		40%	G_4	W_4	32866.25	
4		50%	G_1	W_4	33086.64	
5		50%	G_2	W_3	32892.51	
6		50%	G_3	W_2	32555.36	
7		50%	G_4	W_2	32937.16	
8	56°	30%	G_1	W_4	33044.92	33177.63
9		30%	G_2	W_3	32965.04	
10		30%	G_3	W_3	33335.16	
11		30%	G_4	W_3	33612.21	
12		40%	G_1	W_3	33650.02	
13		40%	G_3	W_2	33208.03	
14		40%	G_4	W_1	33436.38	
15		50%	G_1	W_2	33393.84	
16	46°	20%	G_1	W_3	32936.4	33265.85
17		20%	G_2	W_3	33407.72	
18		20%	G_3	W_3	33685.14	
19		30%	G_1	W_2	33129.57	
20		30%	G_3	W_1	33170.16	
21		30%	G_4	W_1	33472.73	
22	38°	20%	G_1	W_1	33041.05	33272.27
23		20%	G_2	W_1	33562.79	
24	28°	20%	G_1	W_1	41319.83	41164.78
25		20%	G_2	W_2	41217.87	

Table – 14 List of favourable cases for buildings shaded from EWS sides.

6.2.3 Annual energy consumption variations for EW layout

In this layout, the subject building is shaded from 2 sides. Out of all the layouts studied for 2 adjacent buildings, EW layout was the most impact full. The lowest energy consumption value for the layout i.e. with the first set of the different cases followed is still in the similar range of the EWNS layout's lowest energy consumption. But here, AEC for most of the cases studied is less than the base case's AEC. That is because for this case, the changes in the material properties is done only on the two facades which are shaded the rest of the facades which are exposed are left unchanged.

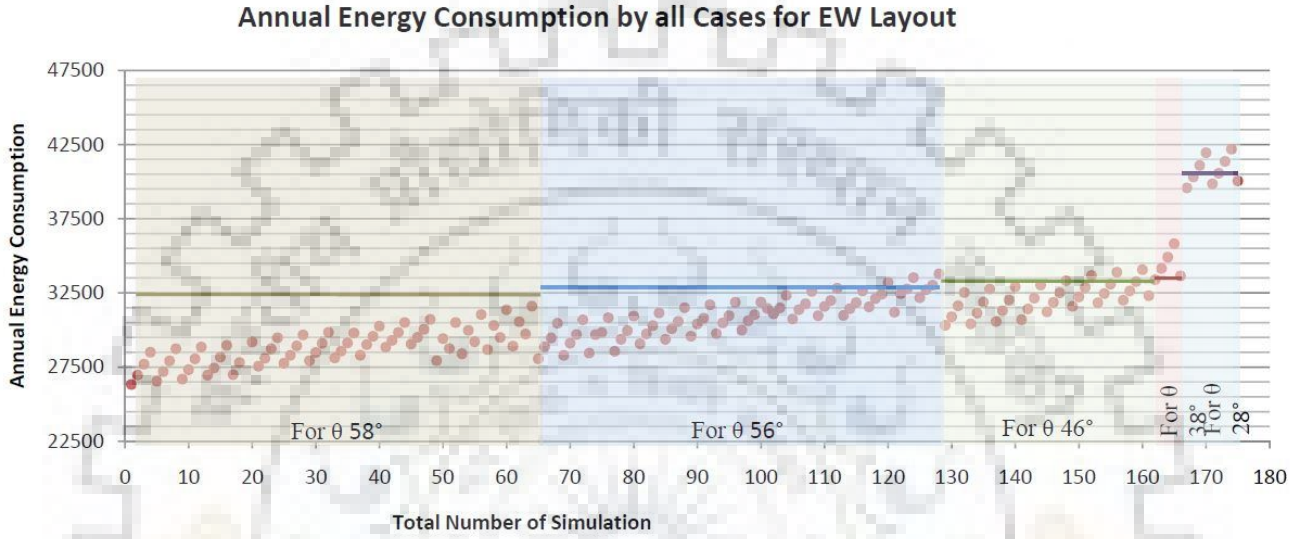


Fig. – 28 Annual energy consumption for each case simulated for EW layout.

Hence the impact of changing materials is halved in this layout. Therefore the favourable cases formed for EW layout are ones with the AEC values closest to the base case's energy consumption. The AEC value is not coinciding with the base case's energy consumption in the case studied for angle of obstruction 58°.

Recommendations For Building Shaded From EW Sides						
S. No.	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption	Base Case Energy Consumption
1	58°	50%	G_3	W_4	31357.15	32793.97
2		50%	G_4	W_4	31603.59	
3	56°	50%	G_2	W_4	33190.81	33177.63
4		50%	G_3	W_4	33526.76	
5		50%	G_4	W_3	33011.46	

6		20%	G_2	W_4	32760.05	
7		20%	G_3	W_4	32908.59	
8		20%	G_4	W_4	33024.11	
9		30%	G_1	W_4	33314.88	
10	46°	30%	G_2	W_3	32859.15	33265.85
11		30%	G_2	W_4	33674.06	
12		30%	G_3	W_3	33086.26	
13		30%	G_4	W_3	33255.99	
14		40%	G_1	W_1	32305.44	
15	38°	20%	G_1	W_1	33381.36	33272.27
16		20%	G_2	W_1	33641.02	
17		20%	G_1	W_3	41088.71	
18	28°	20%	G_2	W_3	41354.29	41164.78
19		20%	G_3	W_1	40938.85	

Table – 15 List of favourable cases for building shaded from EW sides.

6.2.4 Annual energy consumption variations for W layout

Out of the 4 layouts simulated, this is case that is least impacted by mutual shading with an AEC reduction of 5.8% as compared to the base case. But for the arrangement of a single adjacent building, W side layout gave the best results. For this layout, the impact of varying parameter values is very less, that is why the pointers are much cluttered in the graph plotted for this layout. That is because the variations are only applied to the west facade which is mutually shaded, while the other 3 sides remain the same.

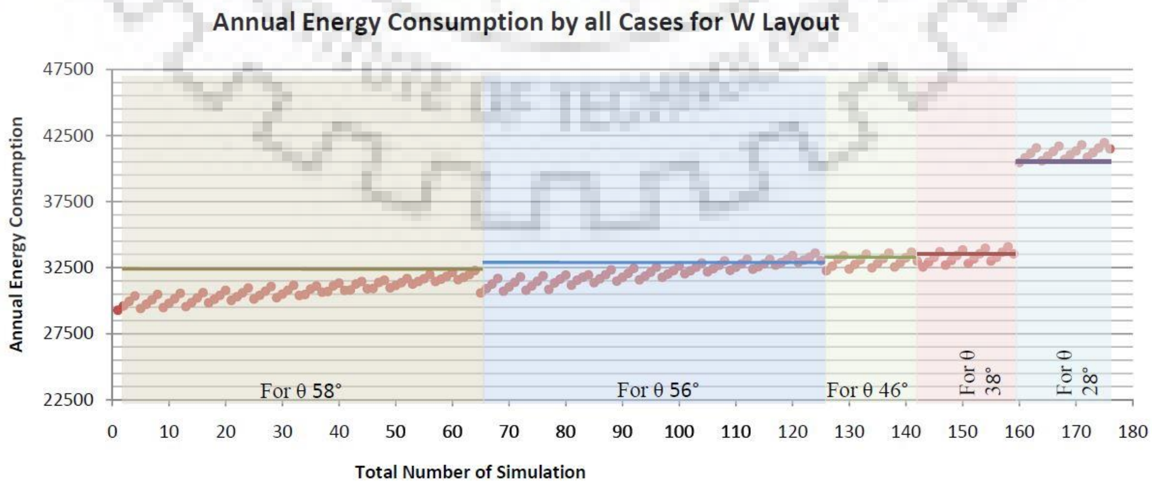


Fig. – 29 Annual energy consumption for each case simulated for W layout.

The impact of varying the parameter values in 1/4th in this layout as of the EWNS layout. Even for angle of obstruction 28°, AEC values for different case is not going much above the base case line. The favourable cases with the alternate recommendations for the W layout are shown in table below.

Recommendations For Building Shaded From W Side						
S. No.	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption	Base Case Energy Consumption
1	58°	50%	G_3	W_4	32136.76	32793.97
2		50%	G_4	W_4	32274.09	
3	56°	40%	G_2	W_4	32849.06	33177.63
4		40%	G_3	W_4	33006.73	
5		40%	G_4	W_4	33122.67	
6		50%	G_1	W_4	33110.73	
7		50%	G_2	W_3	33094.47	
8		50%	G_3	W_2	33067.83	
9		50%	G_3	W_3	33281.71	
10		50%	G_4	W_1	33022.95	
11	46°	20%	G_1	W_3	33148.34	33265.85
12		20%	G_1	W_4	33386.77	
13		20%	G_2	W_3	33097.95	
14		20%	G_3	W_3	33182.03	
15		20%	G_4	W_3	33248.89	
16	38°	20%	G_1	W_3	33281.22	33272.27
17		20%	G_2	W_3	33416.7	
18		20%	G_3	W_2	33168.52	
19		20%	G_4	W_2	33286.65	
20	28°	20%	G_1	W_3	41150.17	41164.78
21		20%	G_2	W_3	41286.18	
22		20%	G_3	W_2	41035.91	
23		20%	G_4	W_2	41197.01	

Table – 16 List of favourable cases for building shaded from W side.

In all the layouts studied, it was observed that the maximum numbers of alternate recommendations are for the angle of obstruction 56° and above. Above that angle the impact of mutual shading is maximum, as that area is shaded for the longer duration. As the energy consumption of the floors existing in that area is very low, we were able to test multiple variations. We went till testing WWR value of 50%. While for angle of construction we could only reach till WWR 30%. And for 38° and above where impact of mutual shading was less, we could only test WWR 20%. Increasing that was leading to more energy consumption then the base case, even when the wall and glazing types are applied as per the properties recommended by BEEP design guidelines.

6.3 Envelope Parameters Analysis

There are three main building envelope parameters discussed, namely, wall type (u-value), glazing type (u-value, SHGC and VLT) and Window Wall Ratio. Each parameter has its own impact on the building's energy consumption. In the graph shown below, the maximum and minimum energy consumption of each layout for each angle of obstruction is plotted. This shows how much the AEC of a subject building in a layout is varying by changing the envelope parameter values.

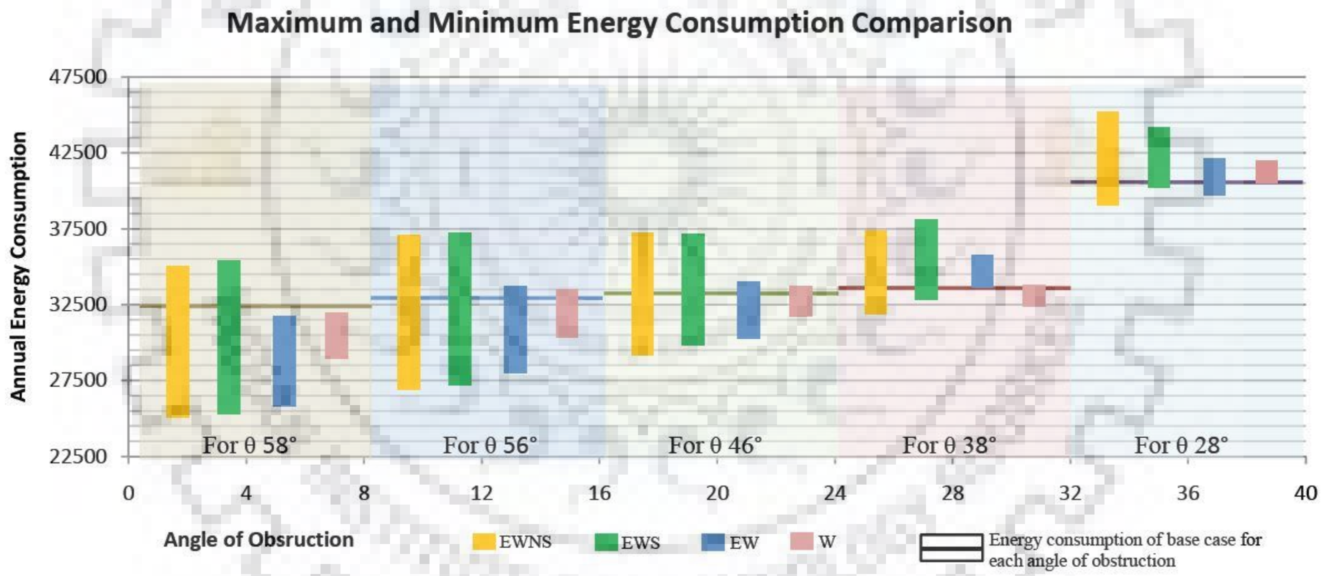


Fig. – 30 Difference in energy consumption values due to variations in the envelope parameter properties.

It is known that the number of cases simulated is less for angle of obstruction 46°, 38° and 28° (because of the AEC values for these angles exceeding the AEC value of the base case). But a clear trend is visible that shows the impact of the envelope parameter values on the energy consumption for each layout. The impact is maximum in the EWNS case because the area of application for this case is more. Here the variables are applied to the entire facade of that floor, hence resulting in huge change in the energy consumption. Due to the reduction in the area of applicability of the variation, the impact is reducing from the case of building shaded from 4 sides (EWNS) to the building shaded from only one side (W). However, there is not much difference in the 4 sides shaded layout and 3 sides shaded layout. This is because in the 3 sides shaded case, the non shaded side is the Northern side and as the sun is not observed at the north, the impact of mutual shading is negligible. It does not matter if the building is shaded from north or not, as it does not contribute much towards the overall energy consumption. That was the discussion on the overall impact of the envelope parameters. Individually, how these parameters impact the results is explained further.

6.3.1 Impact of varying WWR

The impact of WWR is studied for an angle of obstruction 58° for each layout. The energy consumption for the 2 cases with same glazing type and same wall type but with the minimum and maximum values of the WWR is noted. For EWNS, the difference in energy consumption observed is 7252.11 kWh, for EWS is 4929 kWh, for EW is 1599.8 kWh and for W is 1691.78 kWh.

Orientation	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption
EWNS	58°	20%	G_1	W_1	25311.89
	58°	50%	G_1	W_1	32564.77
EWS	58°	20%	G_1	W_1	25429.86
	58°	50%	G_1	W_1	30358.33
EW	58°	20%	G_1	W_1	26320.22
	58°	50%	G_1	W_1	27920.02
W	58°	20%	G_1	W_1	29275
	58°	50%	G_1	W_1	30966.79

Table – 17 Impact of varying WWR on annual energy consumption.

6.3.2 Impact of varying Glazing Type

The impact of glazing type is studied with similar methodology as the WWR. The energy consumption of two cases with G-1 and G-4 values of glazing type is noted for all the layout for an angle of obstruction 58°. The difference in energy consumption EWNS, EWS, EW and W is 2158.27 kWh, 1974.53 kWh, 985 kWh and 613.45 kWh respectively.

Orientation	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption
EWNS	58°	50%	G_1	W_1	32564.77
	58°	50%	G_4	W_1	34723.04
EWS	58°	50%	G_1	W_1	30358.33
	58°	50%	G_4	W_1	32332.86
EW	58°	50%	G_1	W_1	27920.02
	58°	50%	G_4	W_1	28905.96
W	58°	50%	G_1	W_1	30966.79
	58°	50%	G_4	W_1	31580.24

Table – 18 Impact of varying Glazing type on annual energy consumption.

6.3.3 Impact of varying Wall Type

When the wall types is varied from W-1 to W-4, by keeping glazing type and WWR same, for all layouts for angle of obstruction 58°, the difference in the energy consumption came as 2761.74 kWh for EWNS, 2728.31 kWh for EWS, 2575.28 kWh for EW and 701.48 kWh for W.

Orientation	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption
EWNS	58°	50%	G_1	W_1	32564.77
	58°	50%	G_1	W_4	35326.51
EWS	58°	50%	G_1	W_1	30358.33
	58°	50%	G_1	W_4	33086.64
EW	58°	50%	G_1	W_1	27920.02
	58°	50%	G_1	W_4	30495.3
W	58°	50%	G_1	W_1	30966.79
	58°	50%	G_1	W_4	31668.27

Table – 19 Impact of varying Wall type on annual energy consumption

From the values came out from the studies above, it is clear that the WWR has the maximum impact out of the three building envelope parameters studied. One second is the Wall type and Glazing type has the least impact. To make the comparison between wall type and glazing type more appropriate, 50% WWR ratio is considered, which means both window and wall have equal properties on the facade.

CHAPTER 7

RESEARCH FINDINGS

7.1 Result and Discussion

7.2 Conclusion

7.3 Further Research

7.1 Result and Discussion

The study conducted has provided us with a lot better understanding of the term mutual shading and its impact on a building's energy consumption. Mutual shading has been a topic of discussion around the globe. But not much work has been done in detail on it for the Indian context. The purpose of the study was to add an extension to the energy efficient design guidelines practices in India. the guidelines practiced in the present does not consider the impact of mutual shading or any other type of inter building effect. We can be a little easy on the design recommendations to save building's energy for buildings shaded by adjacent buildings. To provide the guidelines based on the buildings adjacent to our building, we need to have a control of the entire building network. The guidelines are applicable to the projects where multiple buildings are to be designed on a single site. Usually, these types of development projects are observed for the residential sectors. Huge townships with multiple multi-storey residential towers are being developed around the nation. In addition, various reports and research journals has mentioned the potential of saving building energy in residential buildings. This is the next step in building's energy efficient design.

The first step for analysing the impact of mutual shading was to identify the parameters that impact mutual shading. A vast literature study was conducted by reading various research papers and journals. In total 6 parameters were identified: 1. Form of the adjacent building, 2. Setbacks around building, 3. The canyon ratio, 4. Height of the adjacent building, 5. Orientation of the adjacent building and 6. Solar reflectance from adjacent buildings. For the study, the most relevant parameters were the adjacent building's orientation and height. Also the height of the adjacent building was measured in terms of the angle of obstruction, which covered two variables, the distance between the two buildings and of course the height of the adjacent building. This was the first major finding of the study.

After that, basic building layouts were prepared considering the real scenarios in which buildings exist. In total 15 layouts were prepared. These 15 layouts were prepared were then modelled and simulated in all the 5 climate zones of India, to check in which climate the impact of mutual shading is maximum. It was found that mutual shading is beneficial in saving a building's energy consumption for all the climates accept the cold climate. There the impact of mutual shading was negative. This study concluded that in Hot-Dry climate the savings due to mutual shading is maximum. Therefore for further study best energy efficient cases from each set of arrangements (adjacent building on 1 side, 2 sides, 3 sides and 4 sides) is taken up for the hot-dry climate.

The final step of the study was to recommend prescriptions for the building's envelope parameters, considering mutual shading for all the above mentioned 4 cases. A set of different materials and conditions for the major building envelope parameters, (WWR, Walls and Glazing) was prepared, and then their various combinations were made. After doing complete permutations and combinations, around 695 cases were prepared and simulated. The results showed in total 91 cases, for the prescriptions of envelope parameters of a mutual shaded building, out of which 24 are for EWNS layout, 25 are for EWS layout, 19 are for EW layout and 23 are for the W layout. All these 91 recommendations have lenient values then the generally recommended guidelines. This can help us in creating compliant energy efficient buildings at comparatively less cost as we will be able to save a lot on the expenditure done for energy efficient building materials.

7.2 Conclusion

After completing the study it can be clearly said that mutual shading is a very important factor while accessing a building's energy consumption. The energy consumption values of building are very different for a standalone building and a building present in a network pf other buildings. A difference of as much as 62,948.97 kWh is observed in the annual energy consumption between a standalone building and building surrounded 4 other buildings in a Hot-Dry climate. In the case like residential township projects, in which multiple building towers are placed on a single site, we can take advantage of the mutual shading to design a compliant energy efficient building with a lenient set of prescriptive guidelines for the building envelope parameter. The results proved that for a large part of the shaded facade of the building, we don't even have to go for any specific energy efficient building material. The generic materials used in the common practice can give us the similar results to that of the special results to that of the special recommended building materials in the case of non shaded building. To utilise the mutual shading, we need to have a control of the adjacent building as well, therefore we cannot use any building present on another property as it may get demolished as per requirements of the owner of that property, due to which our building will lose the mutual shading and our guidelines will fail.

7.3 Further Research

Impact of mutual shading on a building's energy consumption is an emerging area of research. A lot of work can be done in many directions on the same. The direction picked for the study, that is, to analyse the impact of mutual shading on energy consumption in a mid-rise residential building and provide alternate set of compliant energy efficient design recommendations that are more lenient than the general design guidelines, has a lot more additional work to be done. In this study only 4 cases from the

Hot-Dry climate are studied in detail to come up with the design recommendations. To complete the study of only Hot-Dry climate, further 11 more cases out of the identified 15 layouts are needed to be simulated with all the combinations of the materials identified for the parameters. That gives us 3,520 more cases to be simulated only to complete the study for Hot-Dry climate. There are other 3 climates (composite, warm-humid, temperate), that are benefited from mutual shading as well. For a preparing a complete comprehensive study in this direction of work, there are further 14,400 more cases to be simulated and then analysed to present final set of recommendations for each climatic zone of India.

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1Annexure A

VARIABLE CASES						
S. No.	Orientation	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption
1	EWNS	58°	20%	G_1	W_1	25311.89
2		58°	20%	G_1	W_2	26686.27
3		58°	20%	G_1	W_3	28101.01
4		58°	20%	G_1	W_4	29806.12
5		58°	20%	G_2	W_1	25870.45
6		58°	20%	G_2	W_2	27228.32
7		58°	20%	G_2	W_3	28632.03
8		58°	20%	G_2	W_4	30353.36
9		58°	20%	G_3	W_1	26264.07
10		58°	20%	G_3	W_2	27498.35
11		58°	20%	G_3	W_3	28882.32
12		58°	20%	G_3	W_4	30595.4
13		58°	20%	G_4	W_1	26427.89
14		58°	20%	G_4	W_2	27738.91
15		58°	20%	G_4	W_3	29100.85
16		58°	20%	G_4	W_4	30799.59
17		58°	30%	G_1	W_1	27544.83
18		58°	30%	G_1	W_2	28657.93
19		58°	30%	G_1	W_3	29847.37
20		58°	30%	G_1	W_4	31429.74
21		58°	30%	G_2	W_1	28344.98
22		58°	30%	G_2	W_2	29436.33
23		58°	30%	G_2	W_3	30613.08
24		58°	30%	G_2	W_4	32219.14
25		58°	30%	G_3	W_1	28751.01
26		58°	30%	G_3	W_2	29813.64
27		58°	30%	G_3	W_3	30976.1
28		58°	30%	G_3	W_4	32564.89
29		58°	30%	G_4	W_1	29094.14
30		58°	30%	G_4	W_2	30132.66
31		58°	30%	G_4	W_3	31261.47
32		58°	30%	G_4	W_4	32840.92
33		58°	40%	G_1	W_1	29777.7
34		58°	40%	G_1	W_2	30591.15
35		58°	40%	G_1	W_3	31572.24
36		58°	40%	G_1	W_4	33021.3

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

37		58°	40%	G_2	W_1	30727.32
38		58°	40%	G_2	W_2	31567.05
39		58°	40%	G_2	W_3	32540.41
40		58°	40%	G_2	W_4	34019.43
41		58°	40%	G_3	W_1	31220.19
42		58°	40%	G_3	W_2	32039.68
43		58°	40%	G_3	W_3	32980.78
44		58°	40%	G_3	W_4	34450.41
45		58°	40%	G_4	W_1	31611.59
46		58°	40%	G_4	W_2	32408.41
47		58°	40%	G_4	W_3	33328.28
48		58°	40%	G_4	W_4	34777.29
49		58°	50%	G_1	W_1	32564.77
50		56°	20%	G_1	W_1	27150.19
51		56°	20%	G_1	W_2	28535.48
52		56°	20%	G_1	W_3	29947.33
53		56°	20%	G_1	W_4	31655.48
54		56°	20%	G_2	W_1	27721.35
55		56°	20%	G_2	W_2	29089.1
56		56°	20%	G_2	W_3	30489.59
57		56°	20%	G_2	W_4	32211.59
58		56°	20%	G_3	W_1	28026.42
59		56°	20%	G_3	W_2	29370.4
60		56°	20%	G_3	W_3	30750.18
61		56°	20%	G_3	W_4	32462.46
62		56°	20%	G_4	W_1	28287.74
63		56°	20%	G_4	W_2	29607.57
64		56°	20%	G_4	W_3	30967.97
65		56°	20%	G_4	W_4	32670.18
66		56°	30%	G_1	W_1	29533.56
67		56°	30%	G_1	W_2	30749.07
68		56°	30%	G_1	W_3	31833.66
69		56°	30%	G_1	W_4	33422.85
70		56°	30%	G_2	W_1	30640.6
71		56°	30%	G_2	W_2	31441.41
72		56°	30%	G_2	W_3	32871.98
73		56°	30%	G_2	W_4	34225.46
74		56°	30%	G_3	W_1	30768.82
75		56°	30%	G_3	W_2	31832.91
76		56°	30%	G_3	W_3	32979.26
77		56°	30%	G_3	W_4	34585.13
78		56°	30%	G_4	W_1	31104.09

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

79		56°	30%	G_4	W_2	32148.81
80		56°	30%	G_4	W_3	33269.25
81		56°	30%	G_4	W_4	34856.79
82		56°	40%	G_1	W_1	31851.54
83		56°	40%	G_1	W_2	32721.63
84		56°	40%	G_1	W_3	33693.28
85		56°	40%	G_1	W_4	35156.08
86		56°	40%	G_2	W_1	32879.45
87		56°	40%	G_2	W_2	33722.08
88		56°	40%	G_2	W_3	34672.17
89		56°	40%	G_2	W_4	36167.74
90		56°	40%	G_3	W_1	33386.86
91		56°	40%	G_3	W_2	34102.44
92		56°	40%	G_3	W_3	35131.22
93		56°	40%	G_3	W_4	36616.26
94		56°	40%	G_4	W_1	33766.65
95		56°	40%	G_4	W_2	34597.72
96		56°	40%	G_4	W_3	35512.19
97		56°	40%	G_4	W_4	36937.17
98		56°	50%	G_1	W_1	34073.75
99		46°	20%	G_1	W_1	29308.77
100		46°	20%	G_1	W_2	30703.35
101		46°	20%	G_1	W_3	32121.34
102		46°	20%	G_1	W_4	34029.49
103		46°	20%	G_2	W_1	29890.87
104		46°	20%	G_2	W_2	31270.84
105		46°	20%	G_2	W_3	32675.78
106		46°	20%	G_2	W_4	34415.68
107		46°	20%	G_3	W_1	30207.91
108		46°	20%	G_3	W_2	31564.21
109		46°	20%	G_3	W_3	32948.87
110		46°	20%	G_3	W_4	34713.4
111		46°	20%	G_4	W_1	30462.91
112		46°	20%	G_4	W_2	31798.2
113		46°	20%	G_4	W_3	33190.86
114		46°	20%	G_4	W_4	34887.16
115		46°	30%	G_1	W_1	31886.91
116		46°	30%	G_1	W_2	33005.05
117		46°	30%	G_1	W_3	34188.22
118		46°	30%	G_1	W_4	35803.48
119		46°	30%	G_2	W_1	32722.67
120		46°	30%	G_2	W_2	33818.04

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

121		46°	30%	G_2	W_3	34981.8
122		46°	30%	G_2	W_4	36796.4
123		46°	30%	G_3	W_1	33158.96
124		46°	30%	G_3	W_2	34225.06
125		46°	30%	G_3	W_3	35366.71
126		46°	30%	G_3	W_4	36995
127		46°	30%	G_4	W_1	33482.41
128		46°	30%	G_4	W_2	34527.75
129		46°	30%	G_4	W_3	35715.71
130		46°	30%	G_4	W_4	37265.52
131		46°	40%	G_1	W_1	34392.22
132		38°	20%	G_1	W_1	31788.08
133		38°	20%	G_1	W_2	33194.99
134		38°	20%	G_1	W_3	34191.16
135		38°	20%	G_1	W_4	36353.26
136		38°	20%	G_2	W_1	32292.41
137		38°	20%	G_2	W_2	32773.37
138		38°	20%	G_2	W_3	35203.21
139		38°	20%	G_2	W_4	36929
140		38°	20%	G_3	W_1	32727.06
141		38°	20%	G_3	W_2	34086.03
142		38°	20%	G_3	W_3	35496.99
143		38°	20%	G_3	W_4	37213.27
144		38°	20%	G_4	W_1	32967.81
145		38°	20%	G_4	W_2	34338.13
146		38°	20%	G_4	W_3	35739.55
147		38°	20%	G_4	W_4	37440.37
148		38°	30%	G_1	W_1	34683.1
149		28°	20%	G_1	W_1	39333.4
150		28°	20%	G_1	W_2	40719.87
151		28°	20%	G_1	W_3	41999.12
152		28°	20%	G_1	W_4	43698.72
153		28°	20%	G_2	W_1	39954.69
154		28°	20%	G_2	W_2	41313.43
155		28°	20%	G_2	W_3	42578.41
156		28°	20%	G_2	W_4	44275.44
157		28°	20%	G_3	W_1	40306.89
158		28°	20%	G_3	W_2	41642.31
159		28°	20%	G_3	W_3	42876.15
160		28°	20%	G_3	W_4	44577.57
161		28°	20%	G_4	W_1	40510.92
162		28°	20%	G_4	W_2	41825.94

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

S. No.	Orientation	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption
163		28°	20%	G_4	W_3	43053.9
164		28°	20%	G_4	W_4	44745.09
165		28°	30%	G_1	W_1	42703.04
166	EWS	58°	20%	G_1	W_1	25429.86
167		58°	20%	G_1	W_2	26761.95
168		58°	20%	G_1	W_3	28251.45
169		58°	20%	G_1	W_4	20807.69
170		58°	20%	G_2	W_1	25902.47
171		58°	20%	G_2	W_2	27218.66
172		58°	20%	G_2	W_3	28695.78
173		58°	20%	G_2	W_4	30258.11
174		58°	20%	G_3	W_1	26182.76
175		58°	20%	G_3	W_2	27480.28
176		58°	20%	G_3	W_3	28946.23
177		58°	20%	G_3	W_4	30497.5
178		58°	20%	G_4	W_1	26422.24
179		58°	20%	G_4	W_2	27702.13
180		58°	20%	G_4	W_3	29154.52
181		58°	20%	G_4	W_4	30693.59
182		58°	30%	G_1	W_1	27100.4
183		58°	30%	G_1	W_2	28194.33
184		58°	30%	G_1	W_3	29482.79
185		58°	30%	G_1	W_4	30902.62
186		58°	30%	G_2	W_1	27778.36
187		58°	30%	G_2	W_2	28849.95
188		58°	30%	G_2	W_3	30118.01
189		58°	30%	G_2	W_4	31559.49
190		58°	30%	G_3	W_1	28172.57
191		58°	30%	G_3	W_2	29221.28
192		58°	30%	G_3	W_3	30475.42
193		58°	30%	G_3	W_4	31900.41
194		58°	30%	G_4	W_1	28489.68
195		58°	30%	G_4	W_2	29517.48
196		58°	30%	G_4	W_3	30758.5
197		58°	30%	G_4	W_4	32167.65
198		58°	40%	G_1	W_1	28747.95
199		58°	40%	G_1	W_2	29619.25
200		58°	40%	G_1	W_3	30706.67
201		58°	40%	G_1	W_4	31999.98
202		58°	40%	G_2	W_1	29609.79

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

203		58°	40%	G_2	W_2	30457.6
204		58°	40%	G_2	W_3	31526.54
205		58°	40%	G_2	W_4	32830.77
206		58°	40%	G_3	W_1	30096.38
207		58°	40%	G_3	W_2	30920
208		58°	40%	G_3	W_3	31975.91
209		58°	40%	G_3	W_4	33266.75
210		58°	40%	G_4	W_1	30574.71
211		58°	40%	G_4	W_2	31267.59
212		58°	40%	G_4	W_3	32313.58
213		58°	40%	G_4	W_4	32866.25
214		58°	50%	G_1	W_1	30358.33
215		58°	50%	G_1	W_2	31023.74
216		58°	50%	G_1	W_3	31922.48
217		58°	50%	G_1	W_4	33086.64
218		58°	50%	G_2	W_1	31372.69
219		58°	50%	G_2	W_2	32013.06
220		58°	50%	G_2	W_3	32892.51
221		58°	50%	G_2	W_4	34071.08
222		58°	50%	G_3	W_1	31936.37
223		58°	50%	G_3	W_2	32555.36
224		58°	50%	G_3	W_3	33426.46
225		58°	50%	G_3	W_4	34588.44
226		58°	50%	G_4	W_1	32332.86
227		58°	50%	G_4	W_2	32937.16
228		58°	50%	G_4	W_3	33799.33
229		58°	50%	G_4	W_4	34944.68
230		56°	20%	G_1	W_1	27407.23
231		56°	20%	G_1	W_2	28757.53
232		56°	20%	G_1	W_3	30325.69
233		56°	20%	G_1	W_4	31826.25
234		56°	20%	G_2	W_1	27893.8
235		56°	20%	G_2	W_2	29225.87
236		56°	20%	G_2	W_3	30715.43
237		56°	20%	G_2	W_4	32304.07
238		56°	20%	G_3	W_1	28188.25
239		56°	20%	G_3	W_2	29501.18
240		56°	20%	G_3	W_3	30977.12
241		56°	20%	G_3	W_4	32538.82
242		56°	20%	G_4	W_1	28426.93
243		56°	20%	G_4	W_2	29721.84
244		56°	20%	G_4	W_3	31498.21

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

245		56°	20%	G_4	W_4	32737.18
246		56°	30%	G_1	W_1	29936.05
247		56°	30%	G_1	W_2	30313.04
248		56°	30%	G_1	W_3	31311.18
249		56°	30%	G_1	W_4	33044.92
250		56°	30%	G_2	W_1	30632.69
251		56°	30%	G_2	W_2	30988.44
252		56°	30%	G_2	W_3	32965.04
253		56°	30%	G_2	W_4	33707.46
254		56°	30%	G_3	W_1	31040.63
255		56°	30%	G_3	W_2	31376.88
256		56°	30%	G_3	W_3	33335.16
257		56°	30%	G_3	W_4	34071.65
258		56°	30%	G_4	W_1	31346.55
259		56°	30%	G_4	W_2	31670.02
260		56°	30%	G_4	W_3	33612.21
261		56°	30%	G_4	W_4	34338.11
262		56°	40%	G_1	W_1	31703.26
263		56°	40%	G_1	W_2	31865.07
264		56°	40%	G_1	W_3	33650.02
265		56°	40%	G_1	W_4	34263.94
266		56°	40%	G_2	W_1	32583.71
267		56°	40%	G_2	W_2	32724.11
268		56°	40%	G_2	W_3	34484.3
269		56°	40%	G_2	W_4	35109.45
270		56°	40%	G_3	W_1	33086.85
271		56°	40%	G_3	W_2	33208.03
272		56°	40%	G_3	W_3	34950.69
273		56°	40%	G_3	W_4	35570.14
274		56°	40%	G_4	W_1	33436.38
275		56°	40%	G_4	W_2	33588.19
276		56°	40%	G_4	W_3	35317.51
277		56°	40%	G_4	W_4	35884.02
278		56°	50%	G_1	W_1	32727.87
279		56°	50%	G_1	W_2	33393.84
280		56°	50%	G_1	W_3	34289.6
281		56°	50%	G_1	W_4	35472.23
282		56°	50%	G_2	W_1	33765.87
283		56°	50%	G_2	W_2	34405.86
284		56°	50%	G_2	W_3	35280.16
285		56°	50%	G_2	W_4	36474.46
286		56°	50%	G_3	W_1	34356.95

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

287		56°	50%	G_3	W_2	34972.99
288		56°	50%	G_3	W_3	35838.55
289		56°	50%	G_3	W_4	37017.51
290		56°	50%	G_4	W_1	34777.43
291		56°	50%	G_4	W_2	35386.72
292		56°	50%	G_4	W_3	36248.64
293		56°	50%	G_4	W_4	37411.69
294		46°	20%	G_1	W_1	30035.78
295		46°	20%	G_1	W_2	31408.96
296		46°	20%	G_1	W_3	32936.4
297		46°	20%	G_1	W_4	34528.4
298		46°	20%	G_2	W_1	30538.61
299		46°	20%	G_2	W_2	31894.01
300		46°	20%	G_2	W_3	33407.72
301		46°	20%	G_2	W_4	35000.28
302		46°	20%	G_3	W_1	30847.76
303		46°	20%	G_3	W_2	32183.61
304		46°	20%	G_3	W_3	33685.14
305		46°	20%	G_3	W_4	35269.2
306		46°	20%	G_4	W_1	31083.72
307		46°	20%	G_4	W_2	32401.71
308		46°	20%	G_4	W_3	33892.9
309		46°	20%	G_4	W_4	35465.5
310		46°	30%	G_1	W_1	32014.79
311		46°	30%	G_1	W_2	33129.57
312		46°	30%	G_1	W_3	34438.72
313		46°	30%	G_1	W_4	35904.61
314		46°	30%	G_2	W_1	32736.57
315		46°	30%	G_2	W_2	33827.34
316		46°	30%	G_2	W_3	35115.59
317		46°	30%	G_2	W_4	36585.39
318		46°	30%	G_3	W_1	33170.16
319		46°	30%	G_3	W_2	34237.43
320		46°	30%	G_3	W_3	35512.63
321		46°	30%	G_3	W_4	36972.05
322		46°	30%	G_4	W_1	33472.73
323		46°	30%	G_4	W_2	34521.06
324		46°	30%	G_4	W_3	35825.21
325		46°	30%	G_4	W_4	37232.61
326		46°	40%	G_1	W_1	33964.24
327		46°	40%	G_1	W_2	34844.67
328		38°	20%	G_1	W_1	33041.05

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

329		38°	20%	G_1	W_2	34431.09
330		38°	20%	G_1	W_3	35974.1
331		38°	20%	G_1	W_4	37573.88
332		38°	20%	G_2	W_1	33562.79
333		38°	20%	G_2	W_2	34928.88
334		38°	20%	G_2	W_3	36456.06
335		38°	20%	G_2	W_4	38055.59
336		28°	20%	G_1	W_1	41319.83
337		28°	20%	G_1	W_2	40704.1
338		28°	20%	G_1	W_3	42163.94
339		28°	20%	G_1	W_4	43709.82
340		28°	20%	G_2	W_1	39875.59
341		28°	20%	G_2	W_2	41217.87
342		28°	20%	G_2	W_3	42656.94
343		28°	20%	G_2	W_4	44200.82
344		28°	20%	G_3	W_1	40218.61

S. No.	Orientation	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption
345	EW	58°	20%	G_1	W_1	26320.22
346		58°	20%	G_1	W_2	26955.41
347		58°	20%	G_1	W_3	27687.6
348		58°	20%	G_1	W_4	28498.7
349		58°	20%	G_2	W_1	26550.27
350		58°	20%	G_2	W_2	27182.86
351		58°	20%	G_2	W_3	27914.34
352		58°	20%	G_2	W_4	28721.21
353		58°	20%	G_3	W_1	26687.17
354		58°	20%	G_3	W_2	27317.26
355		58°	20%	G_3	W_3	28046.62
356		58°	20%	G_3	W_4	28848.9
357		58°	20%	G_4	W_1	26949.15
358		58°	20%	G_4	W_2	27432.48
359		58°	20%	G_4	W_3	28159.2
360		58°	20%	G_4	W_4	28958.51
361		58°	30%	G_1	W_1	26983.69
362		58°	30%	G_1	W_2	27800.52
363		58°	30%	G_1	W_3	2812.63
364		58°	30%	G_1	W_4	29188.26
365		58°	30%	G_2	W_1	27548.13
366		58°	30%	G_2	W_2	28091.28
367		58°	30%	G_2	W_3	28730.7
368		58°	30%	G_2	W_4	29476.43

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

369		58°	30%	G_3	W_1	27752.22
370		58°	30%	G_3	W_2	28289.94
371		58°	30%	G_3	W_3	28928.55
372		58°	30%	G_3	W_4	29664.05
373		58°	30%	G_4	W_1	27920.38
374		58°	30%	G_4	W_2	28477.71
375		58°	30%	G_4	W_3	29092.68
376		58°	30%	G_4	W_4	29845.1
377		58°	40%	G_1	W_1	28113.32
378		58°	40%	G_1	W_2	28562.72
379		58°	40%	G_1	W_3	29120.45
380		58°	40%	G_1	W_4	29794.82
381		58°	40%	G_2	W_1	28292.63
382		58°	40%	G_2	W_2	29000.67
383		58°	40%	G_2	W_3	29571.58
384		58°	40%	G_2	W_4	30246.62
385		58°	40%	G_3	W_1	28832.87
386		58°	40%	G_3	W_2	29288.2
387		58°	40%	G_3	W_3	29832.78
388		58°	40%	G_3	W_4	30501.75
389		58°	40%	G_4	W_1	29048
390		58°	40%	G_4	W_2	29497.45
391		58°	40%	G_4	W_3	30041.88
392		58°	40%	G_4	W_4	30705.9
393		58°	50%	G_1	W_1	27920.02
394		58°	50%	G_1	W_2	29415.05
395		58°	50%	G_1	W_3	28746.74
396		58°	50%	G_1	W_4	30495.3
397		58°	50%	G_2	W_1	28392.3
398		58°	50%	G_2	W_2	29968.3
399		58°	50%	G_2	W_3	29214.25
400		58°	50%	G_2	W_4	31039.2
401		58°	50%	G_3	W_1	28674.42
402		58°	50%	G_3	W_2	30295.03
403		58°	50%	G_3	W_3	29490.04
404		58°	50%	G_3	W_4	31357.15
405		58°	50%	G_4	W_1	28905.96
406		58°	50%	G_4	W_2	30549.61
407		58°	50%	G_4	W_3	29717.1
408		58°	50%	G_4	W_4	31603.59
409		56°	20%	G_1	W_1	28046.97
410		56°	20%	G_1	W_2	28864.84

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

411		56°	20%	G_1	W_3	29457.02
412		56°	20%	G_1	W_4	30443.91
413		56°	20%	G_2	W_1	28286.64
414		56°	20%	G_2	W_2	29102.22
415		56°	20%	G_2	W_3	29691.61
416		56°	20%	G_2	W_4	30675.04
417		56°	20%	G_3	W_1	28433.6
418		56°	20%	G_3	W_2	29685.49
419		56°	20%	G_3	W_3	29833.2
420		56°	20%	G_3	W_4	30812.51
421		56°	20%	G_4	W_1	28553.84
422		56°	20%	G_4	W_2	29363.22
423		56°	20%	G_4	W_3	29949.78
424		56°	20%	G_4	W_4	30925.03
425		56°	30%	G_1	W_1	29061.25
426		56°	30%	G_1	W_2	29730.34
427		56°	30%	G_1	W_3	30285.22
428		56°	30%	G_1	W_4	31145.52
429		56°	30%	G_2	W_1	29363.6
430		56°	30%	G_2	W_2	30083.28
431		56°	30%	G_2	W_3	30578.37
432		56°	30%	G_2	W_4	31490.49
433		56°	30%	G_3	W_1	29575.26
434		56°	30%	G_3	W_2	30396.48
435		56°	30%	G_3	W_3	30787.94
436		56°	30%	G_3	W_4	31695.82
437		56°	30%	G_4	W_1	29748.45
438		56°	30%	G_4	W_2	30464.78
439		56°	30%	G_4	W_3	30956.09
440		56°	30%	G_4	W_4	31858.39
441		56°	40%	G_1	W_1	29979.38
442		56°	40%	G_1	W_2	30621
443		56°	40%	G_1	W_3	31024.17
444		56°	40%	G_1	W_4	31873.35
445		56°	40%	G_2	W_1	31449.92
446		56°	40%	G_2	W_2	31084.56
447		56°	40%	G_2	W_3	31485
448		56°	40%	G_2	W_4	32328.93
449		56°	40%	G_3	W_1	30734.81
450		56°	40%	G_3	W_2	31364.49
451		56°	40%	G_3	W_3	31762.67
452		56°	40%	G_3	W_4	32600.66

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

453		56°	40%	G_4	W_1	30955.26
454		56°	40%	G_4	W_2	31580.13
455		56°	40%	G_4	W_3	31977.6
456		56°	40%	G_4	W_4	32808.22
457		56°	50%	G_1	W_1	30979.28
458		56°	50%	G_1	W_2	31431.49
459		56°	50%	G_1	W_3	31841.82
460		56°	50%	G_1	W_4	32625.02
461		56°	50%	G_2	W_1	31556.91
462		56°	50%	G_2	W_2	32105.2
463		56°	50%	G_2	W_3	32412.57
464		56°	50%	G_2	W_4	33190.81
465		56°	50%	G_3	W_1	31190.3
466		56°	50%	G_3	W_2	32450.36
467		56°	50%	G_3	W_3	32755.63
468		56°	50%	G_3	W_4	33526.76
469		56°	50%	G_4	W_1	32169.68
470		56°	50%	G_4	W_2	32706.09
471		56°	50%	G_4	W_3	33011.46
472		56°	50%	G_4	W_4	33775.14
473		46°	20%	G_1	W_1	30309.29
474		46°	20%	G_1	W_2	30888.35
475		46°	20%	G_1	W_3	31624.39
476		46°	20%	G_1	W_4	32519.24
477		46°	20%	G_2	W_1	30408.28
478		46°	20%	G_2	W_2	31134.96
479		46°	20%	G_2	W_3	31869.85
480		46°	20%	G_2	W_4	32760.05
481		46°	20%	G_3	W_1	30566.75
482		46°	20%	G_3	W_2	31289.91
483		46°	20%	G_3	W_3	32022.51
484		46°	20%	G_3	W_4	32908.59
485		46°	20%	G_4	W_1	30690.14
486		46°	20%	G_4	W_2	31409.7
487		46°	20%	G_4	W_3	32140.6
488		46°	20%	G_4	W_4	33024.11
489		46°	30%	G_1	W_1	31221.79
490		46°	30%	G_1	W_2	31853.1
491		46°	30%	G_1	W_3	32494.16
492		46°	30%	G_1	W_4	33314.88
493		46°	30%	G_2	W_1	31592.9
494		46°	30%	G_2	W_2	32221.91

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

495		46°	30%	G_2	W_3	32859.15
496		46°	30%	G_2	W_4	33674.06
497		46°	30%	G_3	W_1	31826.04
498		46°	30%	G_3	W_2	32450.75
499		46°	30%	G_3	W_3	33086.26
500		46°	30%	G_3	W_4	33895.31
501		46°	30%	G_4	W_1	32001.77
502		46°	30%	G_4	W_2	32622.4
503		46°	30%	G_4	W_3	33255.99
504		46°	30%	G_4	W_4	34060.8
505		46°	40%	G_1	W_1	32305.44
506		38°	20%	G_1	W_1	33381.36
507		38°	20%	G_1	W_2	34137.42
508		38°	20%	G_1	W_3	34909.41
509		38°	20%	G_1	W_4	35814.35
510		38°	20%	G_2	W_1	33641.02
511		28°	20%	G_1	W_1	39577.08
512		28°	20%	G_1	W_2	40306.1
513		28°	20%	G_1	W_3	41088.71
514		28°	20%	G_1	W_4	41938.22
515		28°	20%	G_2	W_1	39843.6
516		28°	20%	G_2	W_2	40561.04
517		28°	20%	G_2	W_3	41354.29
518		28°	20%	G_2	W_4	42183.64
519		28°	20%	G_3	W_1	40038.85

S. No.	Orientation	Angle of Obstruction θ	WWR	Glazing Type	Wall Type	Annual Energy Consumption
520	W	58°	20%	G_1	W_1	29275
521		58°	20%	G_1	W_2	29593.2
522		58°	20%	G_1	W_3	29939.22
523		58°	20%	G_1	W_4	30348.01
524		58°	20%	G_2	W_1	29399.76
525		58°	20%	G_2	W_2	29717.04
526		58°	20%	G_2	W_3	30062.42
527		58°	20%	G_2	W_4	30468.96
528		58°	20%	G_3	W_1	29474.08
529		58°	20%	G_3	W_2	29789.53
530		58°	20%	G_3	W_3	30133.73
531		58°	20%	G_3	W_4	30548.18
532		58°	20%	G_4	W_1	29537.43
533		58°	20%	G_4	W_2	29852.76
534		58°	20%	G_4	W_3	30195.09

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

535		58°	20%	G_4	W_4	30598.19
536		58°	30%	G_1	W_1	29826.8
537		58°	30%	G_1	W_2	30102.35
538		58°	30%	G_1	W_3	30393.81
539		58°	30%	G_1	W_4	30778.68
540		58°	30%	G_2	W_1	30014.36
541		58°	30%	G_2	W_2	30287.58
542		58°	30%	G_2	W_3	30585.07
543		58°	30%	G_2	W_4	30958.91
544		58°	30%	G_3	W_1	30123.93
545		58°	30%	G_3	W_2	30396.61
546		58°	30%	G_3	W_3	30702.15
547		58°	30%	G_3	W_4	31063.35
548		58°	30%	G_4	W_1	30217.26
549		58°	30%	G_4	W_2	30488.07
550		58°	30%	G_4	W_3	30781.62
551		58°	30%	G_4	W_4	31150.96
552		58°	40%	G_1	W_1	30386.21
553		58°	40%	G_1	W_2	30457.72
554		58°	40%	G_1	W_3	30874.14
555		58°	40%	G_1	W_4	31104.73
556		58°	40%	G_2	W_1	30632.62
557		58°	40%	G_2	W_2	30682.53
558		58°	40%	G_2	W_3	31114.72
559		58°	40%	G_2	W_4	31324.71
560		58°	40%	G_3	W_1	30778.08
561		58°	40%	G_3	W_2	30809.13
562		58°	40%	G_3	W_3	31257.08
563		58°	40%	G_3	W_4	31446.26
564		58°	40%	G_4	W_1	30895.67
565		58°	40%	G_4	W_2	30914.59
566		58°	40%	G_4	W_3	31373.17
567		58°	40%	G_4	W_4	31546.92
568		58°	50%	G_1	W_1	30966.79
569		58°	50%	G_1	W_2	31143.47
570		58°	50%	G_1	W_3	31356.71
571		58°	50%	G_1	W_4	31668.27
572		58°	50%	G_2	W_1	31257.49
573		58°	50%	G_2	W_2	31444.79
574		58°	50%	G_2	W_3	31654.92
575		58°	50%	G_2	W_4	31963.5
576		58°	50%	G_3	W_1	31437.81

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

577		58°	50%	G_3	W_2	31624.17
578		58°	50%	G_3	W_3	31831.05
579		58°	50%	G_3	W_4	32136.76
580		58°	50%	G_4	W_1	31580.24
581		58°	50%	G_4	W_2	31764.99
582		58°	50%	G_4	W_3	31970.73
583		58°	50%	G_4	W_4	32274.09
584		56°	20%	G_1	W_1	30572.88
585		56°	20%	G_1	W_2	30902.55
586		56°	20%	G_1	W_3	31256.99
587		56°	20%	G_1	W_4	31670.45
588		56°	20%	G_2	W_1	30702.01
589		56°	20%	G_2	W_2	31029.89
590		56°	20%	G_2	W_3	31384.12
591		56°	20%	G_2	W_4	31795.16
592		56°	20%	G_3	W_1	30780.97
593		56°	20%	G_3	W_2	31107.89
594		56°	20%	G_3	W_3	31460.06
595		56°	20%	G_3	W_4	31869.84
596		56°	20%	G_4	W_1	30847.42
597		56°	20%	G_4	W_2	31330.28
598		56°	20%	G_4	W_3	31623.33
599		56°	20%	G_4	W_4	31931.99
600		56°	30%	G_1	W_1	31165.91
601		56°	30%	G_1	W_2	31539.03
602		56°	30%	G_1	W_3	31757.04
603		56°	30%	G_1	W_4	31943.65
604		56°	30%	G_2	W_1	31357.59
605		56°	30%	G_2	W_2	31640.45
606		56°	30%	G_2	W_3	31946.41
607		56°	30%	G_2	W_4	32323.27
608		56°	30%	G_3	W_1	31474.85
609		56°	30%	G_3	W_2	31756
610		56°	30%	G_3	W_3	32060.87
611		56°	30%	G_3	W_4	32434.95
612		56°	30%	G_4	W_1	31569.62
613		56°	30%	G_4	W_2	31849.11
614		56°	30%	G_4	W_3	32152.92
615		56°	30%	G_4	W_4	32525.63
616		56°	40%	G_1	W_1	31764.7
617		56°	40%	G_1	W_2	32003.97
618		56°	40%	G_1	W_3	32267.02

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

619		56°	40%	G_1	W_4	32612.44
620		56°	40%	G_2	W_1	32026.33
621		56°	40%	G_2	W_2	32254.89
622		56°	40%	G_2	W_3	32525.79
623		56°	40%	G_2	W_4	32849.06
624		56°	40%	G_3	W_1	32177.51
625		56°	40%	G_3	W_2	32407.8
626		56°	40%	G_3	W_3	32666.32
627		56°	40%	G_3	W_4	33006.73
628		56°	40%	G_4	W_1	32293.53
629		56°	40%	G_4	W_2	32528.31
630		56°	40%	G_4	W_3	32785.03
631		56°	40%	G_4	W_4	33122.67
632		56°	50%	G_1	W_1	32374.99
633		56°	50%	G_1	W_2	32569.16
634		56°	50%	G_1	W_3	32788
635		56°	50%	G_1	W_4	33110.73
636		56°	50%	G_2	W_1	32685.97
637		56°	50%	G_2	W_2	32877.85
638		56°	50%	G_2	W_3	33094.47
639		56°	50%	G_2	W_4	33405.21
640		56°	50%	G_3	W_1	32882.35
641		56°	50%	G_3	W_2	33067.83
642		56°	50%	G_3	W_3	33281.71
643		56°	50%	G_3	W_4	33589.37
644		56°	50%	G_4	W_1	33022.95
645		46°	20%	G_1	W_1	32258.32
646		46°	20%	G_1	W_2	32610.13
647		46°	20%	G_1	W_3	33148.34
648		46°	20%	G_1	W_4	33386.77
649		46°	20%	G_2	W_1	32392.02
650		46°	20%	G_2	W_2	32734.14
651		46°	20%	G_2	W_3	33097.95
652		46°	20%	G_2	W_4	33515.41
653		46°	20%	G_3	W_1	32478.17
654		46°	20%	G_3	W_2	32818.5
655		46°	20%	G_3	W_3	33182.03
656		46°	20%	G_3	W_4	33596.89
657		46°	20%	G_4	W_1	32547.59
658		46°	20%	G_4	W_2	32887.2
659		46°	20%	G_4	W_3	33248.89
660		46°	20%	G_4	W_4	33661.62

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562

661		46°	30%	G_1	W_1	32991.47
662		38°	20%	G_1	W_1	32548.93
663		38°	20%	G_1	W_2	32903.04
664		38°	20%	G_1	W_3	33281.22
665		38°	20%	G_1	W_4	33702.3
666		38°	20%	G_2	W_1	32687.88
667		38°	20%	G_2	W_2	33039.77
668		38°	20%	G_2	W_3	33416.7
669		38°	20%	G_2	W_4	33834.93
670		38°	20%	G_3	W_1	32818.08
671		38°	20%	G_3	W_2	33168.52
672		38°	20%	G_3	W_3	33543.22
673		38°	20%	G_3	W_4	33957.94
674		38°	20%	G_4	W_1	32993.09
675		38°	20%	G_4	W_2	33286.65
676		38°	20%	G_4	W_3	33659.65
677		38°	20%	G_4	W_4	34072.54
678		38°	30%	G_1	W_1	33531.11
679		28°	20%	G_1	W_1	40439.22
680		28°	20%	G_1	W_2	40793.28
681		28°	20%	G_1	W_3	41150.17
682		28°	20%	G_1	W_4	41552.2
683		28°	20%	G_2	W_1	40580.31
684		28°	20%	G_2	W_2	40931.67
685		28°	20%	G_2	W_3	41286.18
686		28°	20%	G_2	W_4	41686.84
687		28°	20%	G_3	W_1	40685.93
688		28°	20%	G_3	W_2	41035.91
689		28°	20%	G_3	W_3	41325.09
690		28°	20%	G_3	W_4	41784.82
691		28°	20%	G_4	W_1	40848.72
692		28°	20%	G_4	W_2	41197.01
693		28°	20%	G_4	W_3	41547.11
694		28°	20%	G_4	W_4	41942.79
695		28°	30%	G_1	W_1	41488.67

Material	U-Factor	Material	U-Factor	Material	U-Factor	Material	U-Factor
G_1	2.708	G_2	4.233	G_3	4.945	G_4	5.447
W_1	0.403	W_2	0.825	W_3	0.95	W_4	1.562