DESIGN OF A SUSTAINABLE HIGHRISE BUILDING INCORPORATING BUILDING AUGMENTED WIND TURBINES

Final Year Project UG 2017

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This is to certify that

Final Year Project titled

“Design of a Sustainable Highrise Building Incorporating Building Augmented Wind Turbines”

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has been accepted towards the requirements

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in

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In the name of Allah, the most Beneficent and the most Merciful as well as due salutations upon Prophet Muhammad (P.B.U.H).

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Dedication

To

Our Supervisor Dr. Muhammad Usman

& Our Families

ABSTRACT

In recent years we have seen the alarming conditions of depleting resources. The conventional means of energy production used all around the world have had adverse effects on the environment and continue to do so. Seeing the decline in the environmental conditions United Nations formulated a set of goals called the UN Sustainable Development Goals (SDGs). The achievement of these goals ensures sustainability in every sector of life. In this project we have focused on the attainment of sustainability in construction sector by targeting SDG 7, 9 and 11 which deal with Affordable and Clean Energy, Industry Innovation and Infrastructure and Sustainable Cities and Communities. With our project we have addressed the negative impacts of conventional means of energy production and provided a way to rectify them. We have analyzed three different models of buildings against wind using Computational Fluid Dynamics (CFD) to check the feasibility or Wind Energy Potential at specific points on the building where turbines can be placed. Numerous research papers have addressed the green energy production using wind turbines and what types of turbines have the highest potential. Our project uses Vertical Axis Building Augmented Wind Turbines (VA-BAWT) of the Gorlov Helical design incorporated in a highrise building placed on the positions of highest wind potential identified by CFD Analysis. The original model of the building is based on an existing highrise building in Karachi. The results of our project were very promising however we made two revisions of our original model to optimize the energy generating potential. For the ambient wind velocity of 7 m/s in Karachi, the highest potential out of the three models was found to be 3.71 kW. We also observed that energy generating potential can be significantly increased by incorporating more than one wind turbines in the building.

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LIST OF ACRONYMS

BMWT	Building Mounted Wind Turbine
BIWT	Building Integrated Wind Turbine
BAWT	Building Augmented Wind Turbine
VAWT	Vertical Axis Wind Turbine
CFD	Computational Fluid Dynamics
c	Scale parameter
k_s	Shape Parameter
V	Wind Speed.
RANS	Reynold’s Averaged Navier Stokes
u	Flow Velocity.
ρ	Density of Fluid (air).
P	Pressure.
ν	Kinematic Viscosity of the fluid.
Φ_e	Wall Effect
C_{pw}	Windward Co-efficient
C_{pl}	Leeward Coefficient
Kz_t	Topographical Factor
K_d	Directionality Factor
C_t	Numerical Coefficient
R	Overstrength Factor
C_a	Seismic Coefficient
C_v	Seismic Coefficient
I	Importance factor
A_{rot}	Swept Area of Rotor

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CHAPTER 1

INTRODUCTION

1.1 General

With rapidly increasing population the need for construction is burgeoning. A rise in construction of commercial and residential high-rise buildings can be seen throughout the world. A high-rise commercial building on average takes up 22.5 kWh per square feet of energy. The supply and demand situation of energy is facing alarming conditions. The demand for energy is increasing exponentially whilst the resources used for conventional energy production are decreasing at an alarming rate. Another problem is the pollution caused by the conventional methods. Hence, it is imminent to find a solution to rectify these issues. The best way to tackle these problems is sustainability through clean and green energy.

1.2 Wind Energy

Wind Energy is produced by using wind power to drive mechanical turbines which rotate to generate electric power through electrical generators. Wind power is a sustainable form of energy production and is very effective in coastal areas. It is being adopted all around the world to mitigate the adverse effects caused by the traditional means of energy production. Wind energy has a high potential on offshore areas as the offshore winds are usually stronger and steadier as compared to inland winds. Although wind energy cannot be produced on demand so it can be termed as intermittent source of energy, but it is still feasible to use in order to break the dependance on conventional energy sources which are detrimental towards the environment of the planet and in turn to the health of its inhabitants.

1.2.1 Wind Turbines in Buildings

There are three broad categories of wind turbines used in buildings: -

Building Mounted Wind Turbines (BMWT) = Building mounted wind turbines are just mounted onto the surface of the building. They are mounted on the roof typically. They are linked physically to the façade of the building and the loads, vibration and noise must be catered for by the structure.

Building Integrated Wind Turbines (BIWT) = Building integrated wind turbines are integrated into the structure design. This can be done as architectural, structural, or even electrical integration.

Building Augmented Wind Turbines (BAWT) = Building Augmented Wind Turbines are where the turbine is a part of the building structure or façade such that the flow is being deliberately altered and augmented into the turbine by the building itself.

1.2.2 Building Augmented Wind Turbines

The point of interest is Augmentation which means that the building must be specifically designed to optimize the wind flow towards the turbine such that the maximum output can be generated. Examples of building augmented wind turbines include the World Trade Center in Bahrain, Greenway Self Park in Chicago, Pearl River Tower in China, and Kinetica in London. There are two categories of BAWT which are Vertical Axis BAWT being where the rotor of the turbine rotates around a vertical axis and Horizontal Axis BAWT being where the rotor of the turbine rotates around a horizontal axis. There are also different designs of wind turbines.

1.2.2.1 Gorlov Design Vertical Axis Wind Turbine

This design of a vertical axis wind turbine is very optimal for low to medium wind speeds. However, for higher speeds, specifically more than 20 m/s it requires modifications to function. Gorlov designed the turbine as a helical structure such that the blades are efficient and optimized for speed and entail a better energy generating potential. Keeping this in mind Gorlov VAWT was used as BAWT in our project.

1.3 Impact on Environment

Usage of coal and other conventional methods to produce energy has proven detrimental towards the environment in several ways. In the recent years however, much research has alarmed the leaders of the world about the worsening situation, and they have started taking due measures to mitigate and rectify these issues.

Large amount of nonrenewable energy is consumed by highrise buildings or buildings in general. The conventional means of energy production entail hazards toward the environment. In Pakistan, around 97% of the total energy production is by conventional means including Hydro Power and only 3% is Renewable form of energy. Water scarcity and depletion is a major issue for Pakistan so the focus must be shifted towards renewable energy.

Use of renewable energy is becoming a necessity to take on the issues of Pollution, Global Warming, and related health issues. The energy sector produces about two thirds of global greenhouse gas emissions and one fourth of the total carbon dioxide emissions in the word. Pakistan ranks 2nd on the World's Most Polluted Countries according to the World Air Quality Report and Lahore ranks 3rd on the most polluted major cities according to the world AQI ranking.

1.4 Problem Statement

The major issue Pakistan faces now and has faced for decades is the energy crisis. Shortfall of energy has been deteriorating Pakistan's economical condition for years and years. A renewable form of energy production is direly needed to make up the shortfall.

Resources that are conventionally used to produce energy are Coal, Fossil fuel, Natural Gas and Nuclear Energy. Apart from Nuclear energy all these resources are depleting and the need for alternatives is rising rapidly. Nuclear energy also cannot be relied on solely because using atomic fission to create energy is not easily scalable and only a few plants are producing energy throughout the world. Nuclear

Energy production also carries with itself many risks which can be very fatal. To cater for this issue of depleting resources, renewable energy is the way to go.

With our project we have aimed to address all the forementioned problems by incorporating building augmented wind turbines in a high-rise building to produce clean and green energy and make the building sustainable.

1.5 Objectives

1. To model a high-rise building incorporating wind turbines to meet UN Sustainable Development Goals.
2. To analyze the effect of wind speed and pressure variation on the surface of building.
3. To select optimum type of turbines that can be used in our building.
4. To compare energy generating potential of different highrise buildings of different architectural shape.

1.6 Thesis Structure

Introduction is given in the Chapter 1 followed by a thorough literature review in Chapter 2 regarding Building Augmented Wind Turbines, their usage in construction sector, energy generating potential and CFD analysis of buildings.

The experimental methodology used in our project is explained in depth in Chapter 3.

Chapter 4 entails the results of the analyses done and their explanation and finally the energy generation. This is diligently presented with figures and graphs.

Chapter 5 of this thesis includes the conclusions that we have drawn from our project and the recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 WIND ENERGY AND CONSTRUCTION

2.1.1 Energy crisis and potential solutions

Analysis of electricity mix of Pakistan indicates that the potential of renewable and green energy has been totally ignored by the policy makers and planners driving our energy sector. There are plans to reduce the share of oil in energy sector by 2030, however no such progress has been made. The wind energy is potential source to minimize the environmental effects of non-renewable energy sources[1].

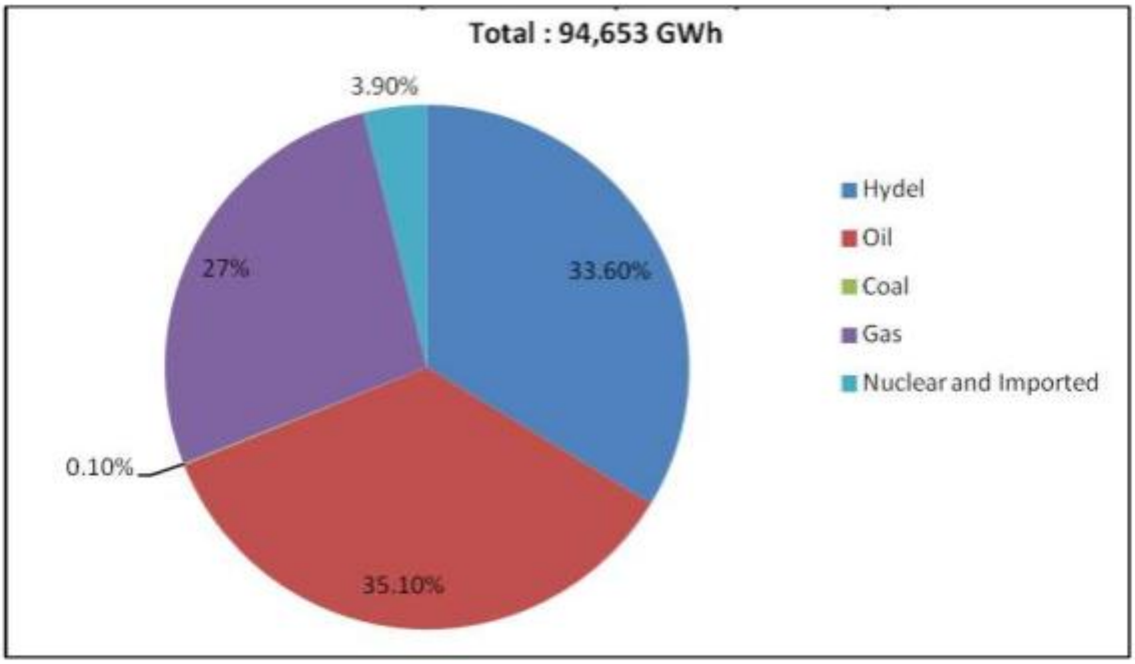

Figure 1 *Energy Production Distribution in Pakistan*

Pakistan has flat coastal terrain stretching 1046 km and has very favorable wind conditions. Surveys carried out in this belt reveal that wind corridor stretches about 60km along the coastline of Sindh province between the towns of Gharo to Keti-

Bandar and more than 170 km deep inland towards Hyderabad shown in Figure 1.3 [2].

Figure 2 *Wind Energy Potential in Pakistan*

Wind energy potential from the same corridor is being harnessed in neighboring India’s Gujrat region, where more than 700 MW wind energy has been installed.

2.1.2 Wind Risk Mechanism

There are various technical and financial risks associated with the uncertainty and intermittency of wind. Wind risk mechanism is used to account for these variations, where statistical methods are used to predict the probability distribution of yields[3].

2.1.3 Utilization of Wind Energy in high rise buildings in urban area

As the disturbed flows around buildings can locally increase wind speeds and the energy yields may be increased compared to open sites. Disturbed flows around buildings can increment wind speeds locally and can increase energy yields compared to flat area e.g wind farms[4, 5].

One of the examples is of Bahrain world trade center, where three wind turbines, each 29 m in diameter are installed between the twin towers on walkways, and together they can meet 11-15% of the building's power requirements **.**

Figure 3 *Wind Turbines used in Bahrain World Trade Center*

In general, Weibull distribution is used to describe the wind speed probability density function (PDF) as follows:

$$f(v) = \frac{k_s}{c}\left(\frac{v}{c}\right)^{k_s-1} \exp\left(-\left(\frac{v}{c}\right)^{k_s}\right), \qquad (k_s > 0, v > 0, c > 1)$$

(1)

Once the mean and variance of the wind speed are known, the following approximation can be used to calculate the Weibull parameters c and ks:

$$k_s = \left(\frac{\sigma}{\overline{v}}\right) \qquad (2)$$

$$c = \frac{\overline{v}}{\Gamma(1+1/k_s)} \qquad (3)$$

$$\overline{v} = \frac{1}{n}\sum_{i=1}^{n} v_i$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(v_i - \overline{v})^2 \qquad (4)$$

Lu [5] observed the wind changes between obstacle free and reverse environments using above mentioned Weibull distribution. The results revealed lower wind speeds and shape factor for an urban setting. This was due to disturbances generated due to surrounding buildings [6-8].

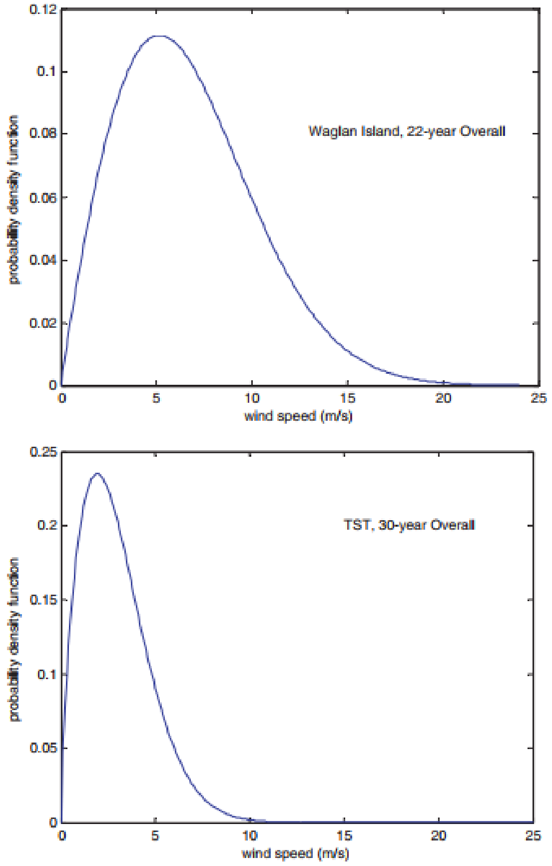

Figure 4 *Weibull Distribution for Wind against Obstacle Free and Reverse Environment*

2.2 COMPUTATIONAL FLUID DYNAMICS

2.2.1 CFD Analysis

CFD (Computational Fluid Dynamics) is numerical process to demonstrate fluid flows using computational techniques. It can be used to analyze complex problems involving fluid-fluid, fluid-solid or fluid-gas interaction. Aerodynamics and hydrodynamics are the areas where CFD is widely used [9-11].

2.2.2 Significance

CFD is fast and cheaper as compared to conventional testing methods. It is becoming easier with increase in computational power. It has various applications in automobiles, avionics, and structural dynamics.

2.2.3 Mathematical Models

As mentioned previously, CFD is based on numerical models, from which, two of them are most used:

Navier-Stokes Equation

It is a partial differentiation equation that is used to model the flow of incompressible fluids. It also accounts for viscosity of the fluid [12].

$$\frac{\partial u}{\partial t} + \mathbf{u}.\nabla\, \mathbf{u} = -\frac{1}{\rho} \nabla\, p + v\, \nabla^2\, \mathbf{u} \qquad (5)$$

K-€ Model

It is one of the most used Turbulence model, which is based upon two equations and caters for the so-called wall effect (ϕ_ε)[9, 13, 14].

$$\frac{\partial \rho K}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho v_j K\right) = \frac{\partial}{\partial x_j}\left[\left(\mu_L + \frac{\mu_T}{\sigma_K}\right)\frac{\partial K}{\partial x_j}\right] + \tau_{ij}^F S_{ij} - \rho\varepsilon \qquad (6)$$

$$\frac{\partial \rho \varepsilon^*}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho v_j \varepsilon^*\right) = \frac{\partial}{\partial x_j}\left[\left(\mu_L + \frac{\mu_T}{\sigma_{\varepsilon^*}}\right)\frac{\partial \varepsilon^*}{\partial x_j}\right] + C_{\varepsilon 1} f_{\varepsilon 1} \frac{\varepsilon^*}{K} \tau_{ij}^F S_{ij} \qquad (7)$$

$$- C_{\epsilon 2} f_{\varepsilon 2}\, \rho \,\frac{(\varepsilon^{*})^{2}}{K} + \phi_{\varepsilon}$$

2.2.4 Modelling of Domain

Domain is the part of space where the CFD simulation is run and calculations are made. This domain is discretized into a mesh which is used to solve the equations of fluid flows [15, 16].

Dimensions of the model's domain significantly effects the result of CFD. The best possible combination is to be considered while modelling the domain. One combination is shown below [17]:

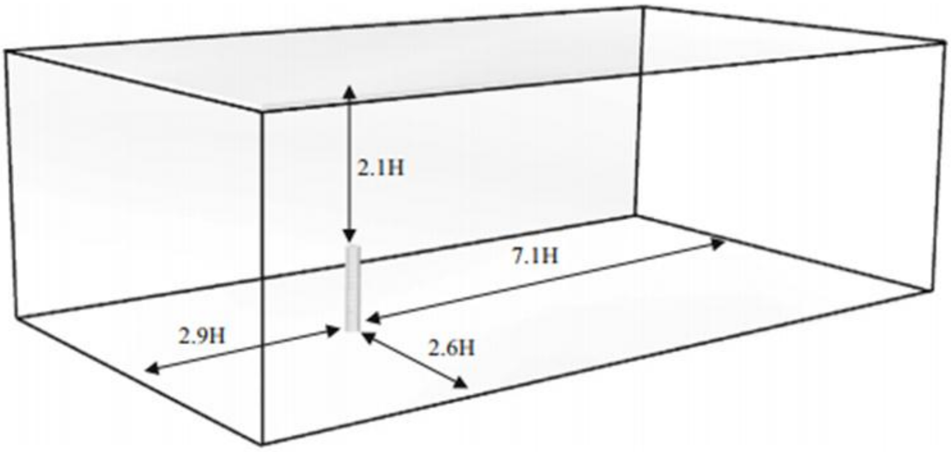

Figure 5 Minimum Domain Dimensions

2.3 WIND TURBINES

Wind turbines turn mechanical energy of wind to electrical energy using aerodynamic forces of wind to turn the rotor blades.

2.3.1 Horizontal Axis Wind Turbines

In HAWT's, the main rotor shaft rotates about horizontal axis, i.e. in the direction of wind. These turbines have a large swept area, which is perpendicular to the direction of wind, and hence hey can produce more energy for a given amount of wind. Due to the large swept area, they can be used efficiently in wind farms, but they can't be used in an urban environment due to space constraint [18].

2.3.2 Vertical Axis Wind Turbines

In this type of turbine, the main components of the turbines are placed at the base, while the rotors rotate about a vertical shaft. A VAWT has its axis perpendicular to the wind streamlines and vertical to the ground [19].

2.3.2.1 Gorlov Turbine

It is a helical VAWT which was designed by Alexander M. Gorlov. It operates under the lift-based concept**.** One of the major advantages is that it can spin equally in both directions [20].

Figure 6 *A Typical Gorlov Wind Turbine*

2.3.2.2 Significance

The VAWT has reduced size of blades as compared to HAWT, also less cost per unit rated power. In the future, the use of VAWT’s is going to increase due to increasing demand of renewable energy and space limitation. Economic aspect makes use of VAWT’s justifiable.

2.3.2.4 Solidity ratio

Solidity is the ratio of total rotor platform area to total swept area. Mathematically, it can be defined as:

$$\sigma = \frac{Nc}{2\pi R} \tag{8}$$

Turbines with higher solidity have more preference for wind generation since they have increased area of blades[21].

2.4 Building Augmented Wind Turbines

In building augmented wind turbines, the geometry of the building is used to augment the wind velocity, thus increasing the power generation potential of a wind turbine. It has several advantages over a conventional standalone wind turbine (Heo 2016).

Young gun et al [22] reported that the wind acceleration of wind leads to concentration effect in building thus affecting the output of stand-alone wind turbine is far less than BAWT.

The above-mentioned fact is evident from a case study by Young gun [22] in which he investigated the output of a 110kW building augmented wind turbine and compared it with a conventional mounted turbine [22-24].

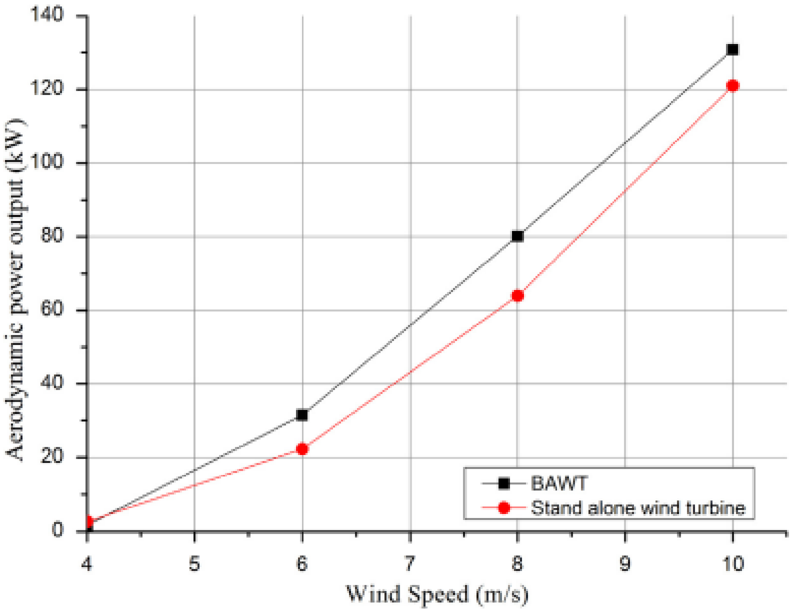

***Figure 7** Comparison of BAWT vs Stand Alone Wind Turbine*

CHAPTER 03

METHODOLOGY

3.1 INTRODUCTION

This chapters covers the methodology steps undertaken for the completion of the project, ranging from the acquisition of plans to modelling and analysis of plans on ETABs to analysis of building geometry on COMSOL. The tests were carried out on different geometrical facades to make a comparison between the models for better aerodynamics.

The procedure, and the codes and standard followed are also mentioned along in this Chapter.

3.2 METHODOLOGY SCHEME

With the plan acquisition, we went on to model our building in ETABs which was later to be analyzed after the addition of wind turbines. Once the analysis on the model was carried out after the addition of turbine loads the model was regenerated on SOLIDWORKS. After the regeneration of model, it was analyzed on COMSOL against the wind blowing and finally the potential power generation was computed based on analysis of different models. At the end, various conclusions and recommendations were made based on the obtained results showing the effectiveness of the project for future prospects. As shown in *fig. 3.1*.

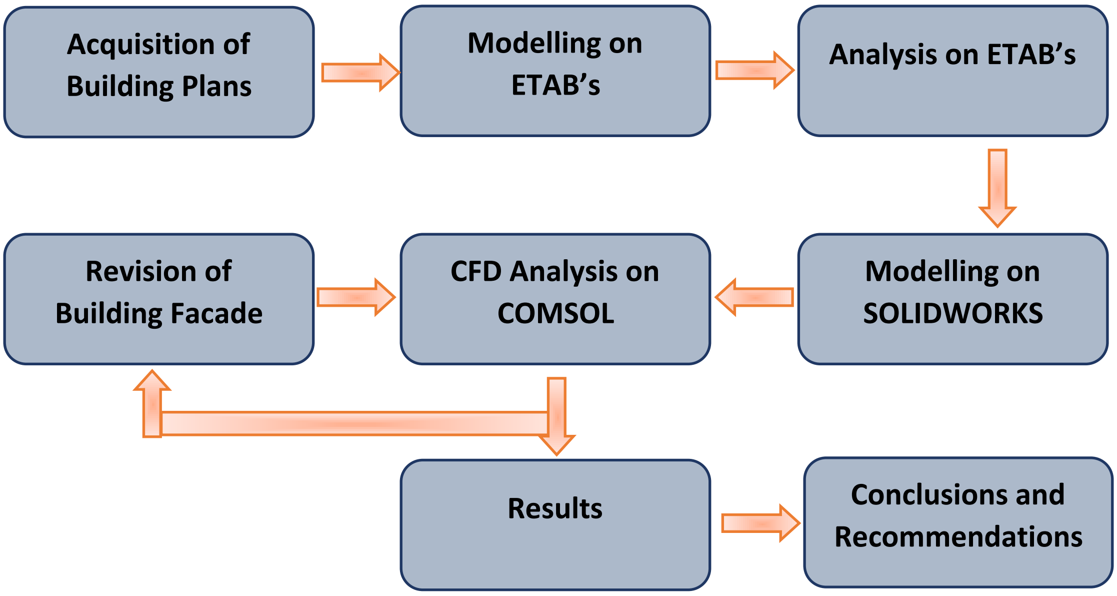

Figure 8 *Project Methodology*

3.3 PLAN ACQUISITION

The plans of **Lucky Mall One Apartments Tower A**, Block 21, Main Rashid Minhas Road, Karachi were acquired. It is a high-rise multi-story building composing of, thirty-four stories in total, with two levels of parking, a lower ground story, a ground floor story and the remaining stories would be used for commercial and residential purposes.

3.3.1 FAÇADE FEATURES

The building has lobbies within its center allowing for cross ventilation and other utility purposes. These openings provide an ideal location for the installation of turbines which requires an open environment from where wind can flow (as shown in fig. #). *See Annex A*

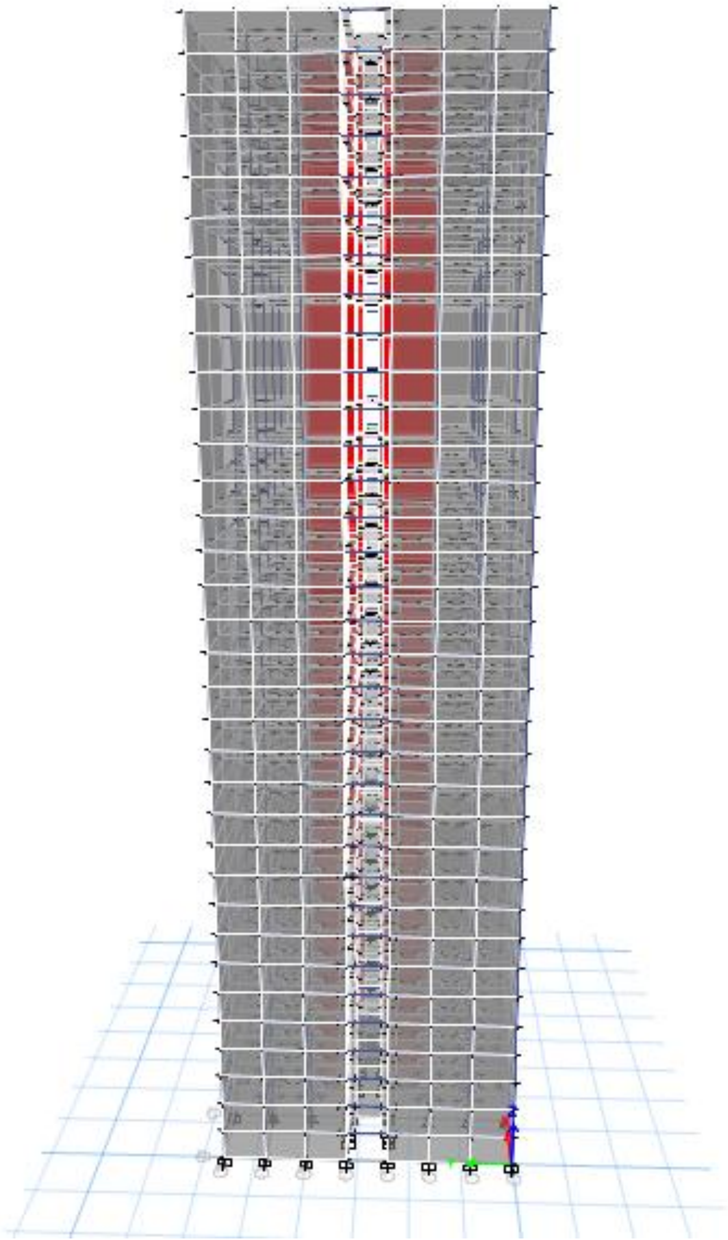

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Figure 9 *Façade Features showing floor openings on each floor*

3.3.2 CURRENT CONDITION

Lucky One Mall Apartment Tower A is currently in its final stages of construction with only interior finishes left, which compelled us to select this building as shown in fig.# 10 and a detailed layout attached in Appendix-1. Such that, based on our result findings recommendations may be proposed.

Figure 10 *Aerial view of Lucky Mall Apartments Tower A depicting current condition*

3.4 MODELLING AND ANALYSIS ON ETABS

Since our project mainly focused on to the geometrical facade of the building. the modeling and analysis part watch divided into two parts. Firstly, a relatively simplified model on ETABs was created, while maintaining the main and the original setting of the building. Once the modeling was done suitable loads that were to be acted upon each floor were applied and the analysis was carried out against the loads that the floor stories could take up on before failure. in the second part suitable and expected turbine loads were added and analysis was carried out along with any cross-sectional modifications by up to 2-3 %, were made.

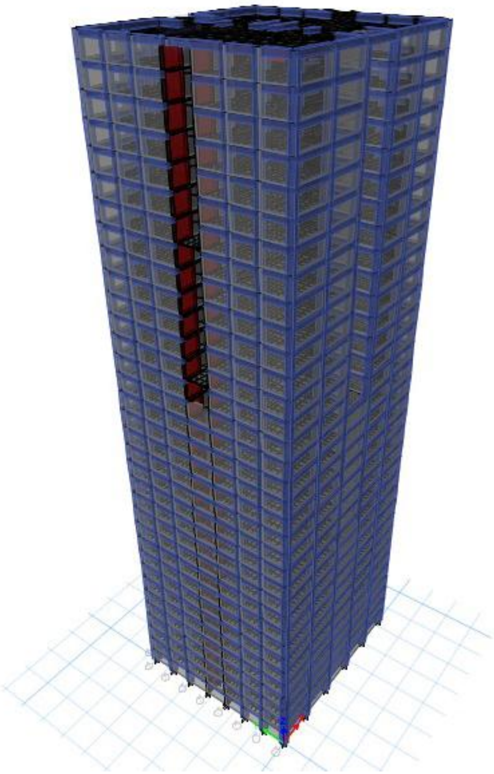


Figure 11 *3-D Elevation in ETABs*

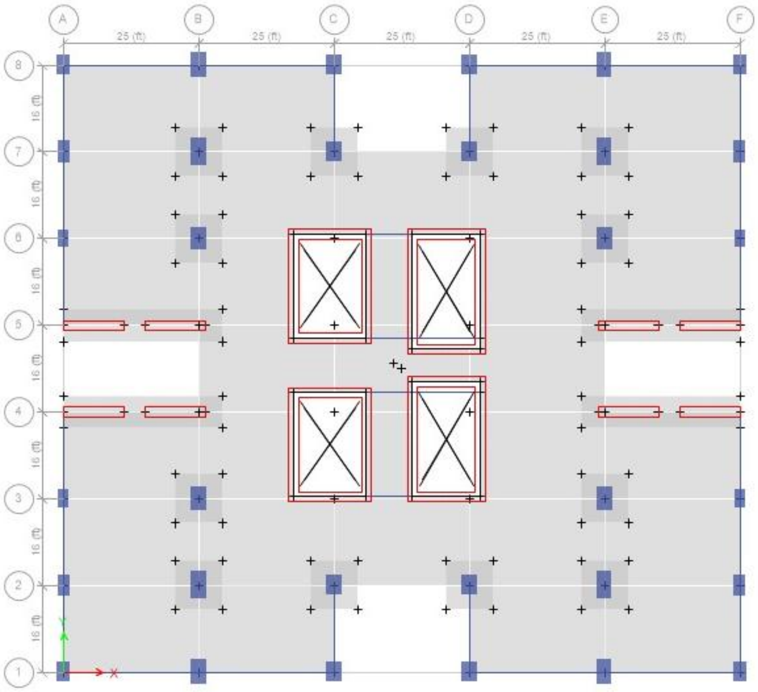


Figure 12 *Typical Plan View in ETABs*

3.4.1 CROSS SECTIONS USED

A list of the cross-sections that have been utilized are tabulated as follows:

For the columns as depicted in table 1:

Table 1 *Typical Column Dimensions (in)*

COLUMN NAME	P2 – 4F	5F – 16F	17F – 30F
C1	54 X 48	48 X 34	45 X 30
C2	54 X 42	54 X 33	54 X 33
C3	54 X 40	46 X 38	45 X 36
C4	54 X 42	48 X 33	48 X 27
C5	60 X 48	60 X 38	60 X 33
C6	54 X 42	46 X 39	45 X 36
C7	48 X 36	42 X 28	39 X 24
C8	60 X 42	54 X 38	51 X 36

A total of eight types of columns, differentiated based upon their cross-sectional dimensions, have been selected. Each column of specific geometry has been placed in a selection of stories for example the stories P2 – 4F indicate that floor stories ranging from the second parking floor up-till the 4th storey. Similarly, 5F – 16F means from the 5th floor up to 16th floor and 17F – 30F consequently means from 17th to 30th floor.

These cross sections of columns C7 have been increased by up to max. of 3%. Which were near the wind turbines, to cater for their loads.

For beams the cross-sections utilized for the structure is listed as follow in table 2:

Table 2 *Typical Beam Dimensions*

FLOOR RANGE	BEAM NAME	DIMENSIONS (in)
5F – 30F	B1	36 x 24
	B2	36 x 21
	B3	24 x 36
	B4	24 x 36
	B5	30 x 12
P2 – 4F	B10	21 x 24
	B2A	24 x 18
	B9	26 x 15
	B2	24 x 36
	B2A	24 x 18
	B3	24 x 36
	B5A	24 x 12
	B6	24 x 36
	B7	24 x 48

3.5 MODELLING ON SOLIDWORKS

For rapid analysis, the plans were remodeled in SOLIDWORKS, a solid modeler CAD utilizing a parametric feature-based approach for modelling of the objects. The geometry was unified into one complete model instead of components joined together, which would have made the analysis tedious and time taking. The apartment building once modelled (fig.#13) was ready for **CFD** analysis.

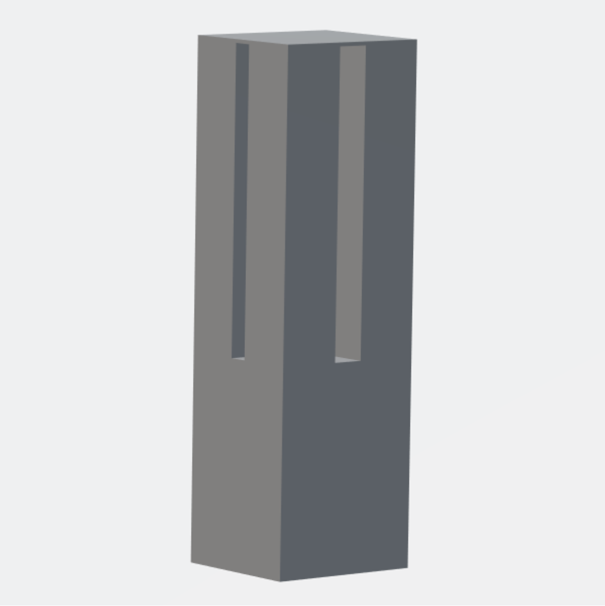


Figure 13 *3D Model Generated in SOLIDWORKS*

3.6 COMPUTATIONAL FLUID DYNAMIC (CFD) ANALYSIS

Once the model was prepared in SOLIDWORKS it was now time to carry out the CFD analysis on the building model. COMSOL, a product of COMSOL inc., was used for the simulation of coupled physics problem involving drag, lift, pressure, and velocity etc. once the model was imported analysis based on ambient weather conditions of Karachi was carried out. As shown in fig.# 3.7.

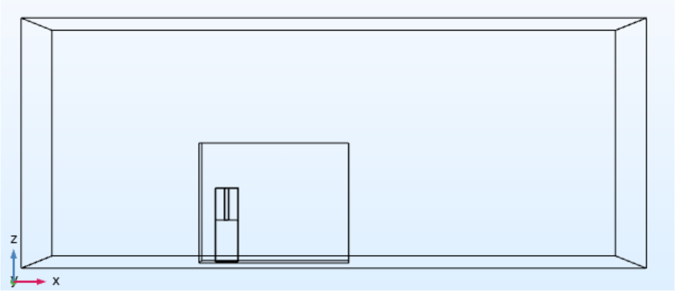


Figure 14 *3D Model Generated in COMSOL for Analysis*

3.7 MODIFICATIONS IN GEOMETRICAL FACADE

For a comparison, modifications in the façade were made. As a result, two new models fig.# 3.8 and 3.9 based on the original dimensions were modelled in SOILDWORKS and CFD analysis was carried out and finally the results were tabulated and finally, conclusions and recommendations were proposed based on the obtained results.

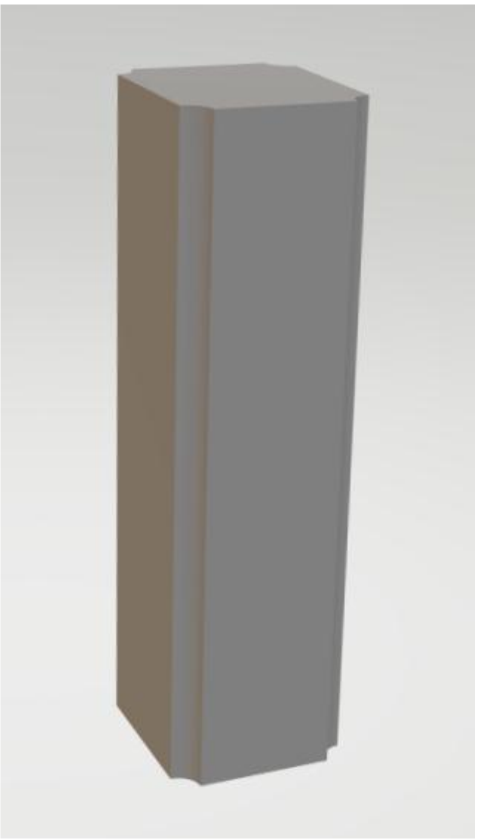


Figure 15 *Revised Model 1in SOLIDWORKS*

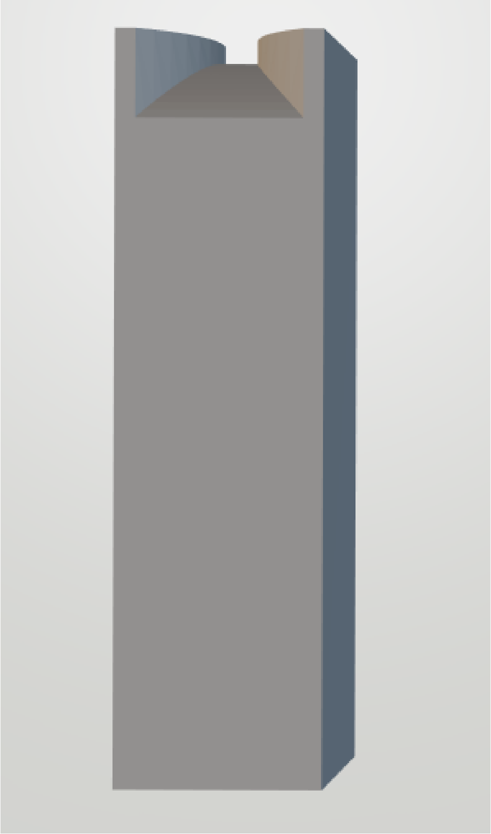


Figure 16 *Revised Model 2 in SOLIDWORKS*

CHAPTER 04

MODEL ANALYSIS AND RESULTS

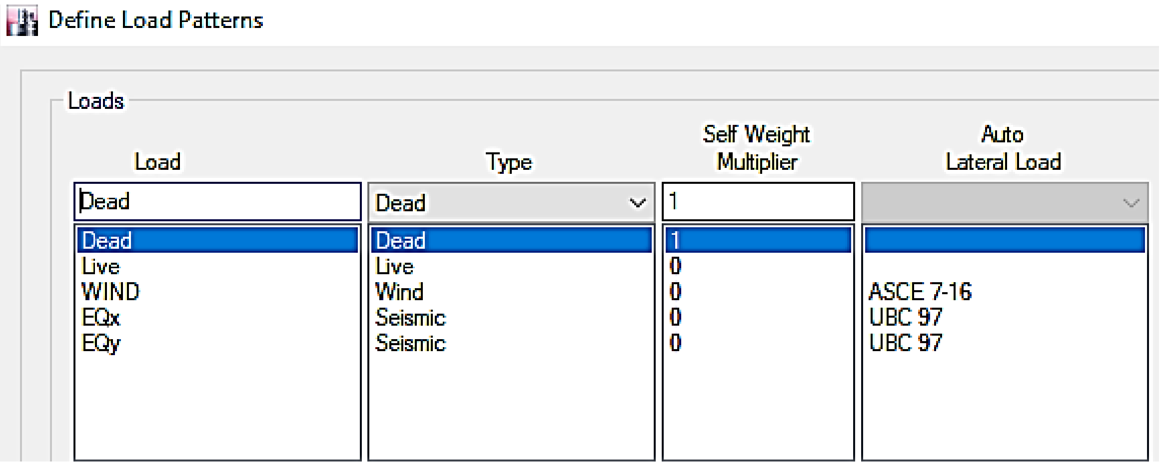
4.1 INTRODUCTION

After the modelling was carried out, the analysis on ETABs and COMSOL were ran to check the structural integrity of the building, the velocity, and the pressure contours. The analysis was carried out on all the proposed models and to have a trend of observed power generation for different models and the effect of geometrical setting of the building on the passage of wind.

4.2 STRUCTURAL ANALYSIS

The structural analysis was carried out on ETABS for our BAWT to ensure structural stability. The analysis was carried out for the following load patterns:

1. *Dead Load*
2. *Live Load*
3. *Wind Load (in x-direction)*
4. *Wind Load (In y-direction)*
5. *Earthquake Load (x-direction)*
6. *Earthquake Load (y-direction)*


Define Load Patterns

Loads

Load	Type	Self Weight Multiplier	Auto Lateral Load
Dead	Dead	1	
Dead	Dead	1	
Live	Live	0	
WIND	Wind	0	ASCE 7-16
EQx	Seismic	0	UBC 97
EQy	Seismic	0	UBC 97

Figure 17 *Load Patterns Defined in ETABs*

4.2.1 ANALYSIS CRITERIA

The load analysis was carried out based on the following criteria's as shown in *table #3.*

Table 3 *Used Design Codes:*

LOADS	**CODE FOLLOWED**
Gravitational	*ACI 318* - *14*
Wind	*ASCE 7 – 16*
Seismic	*UBC 97*

4.2.1.1 GRAVITATIONAL LOADS

The gravitational loads comprised of all kinds of self-loads plus the super imposed dead + live load. The loads are inclusive of all kinds of partitioning wall loads plus expected machinery loads. The values taken for the respective loads is shown in the following table #4 :

Table 4 *Applied Loads:*

Type of Load	**Load Value (psi)**
Dead	300
Live	500
Turbine Load	25
∑ **Dead + Live**	825

A typical cross-section on ETAB's having Gravitational Loads acted upon is shown:

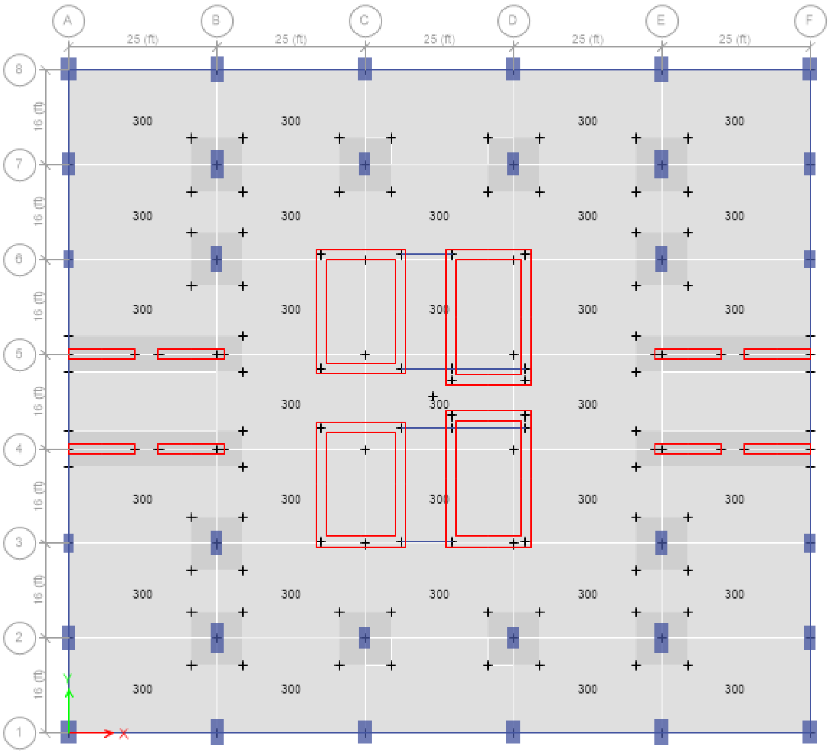


***Figure 18** Dead Load Applied*

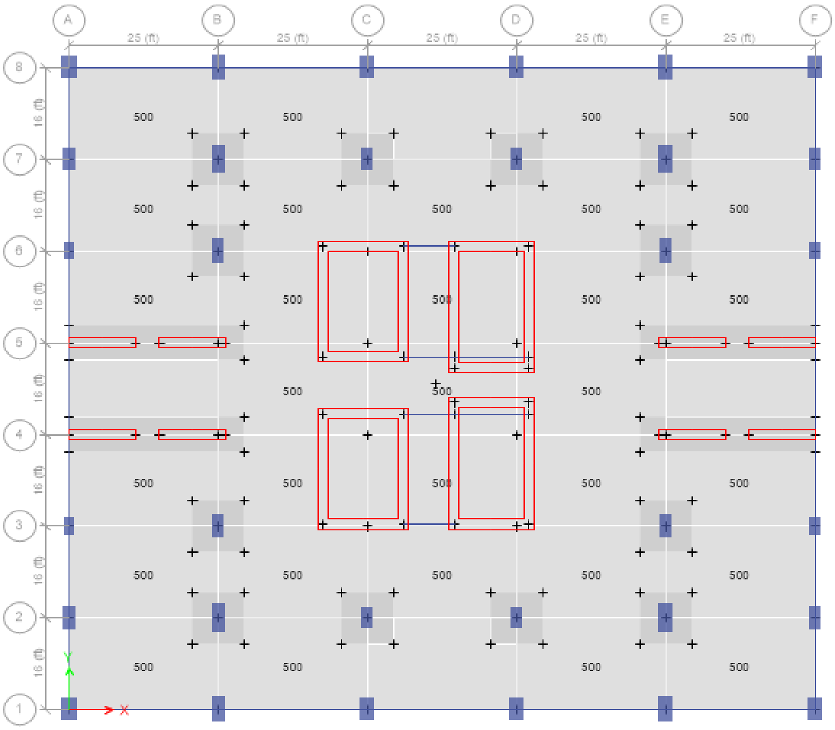


***Figure 19** Live Load Applied*

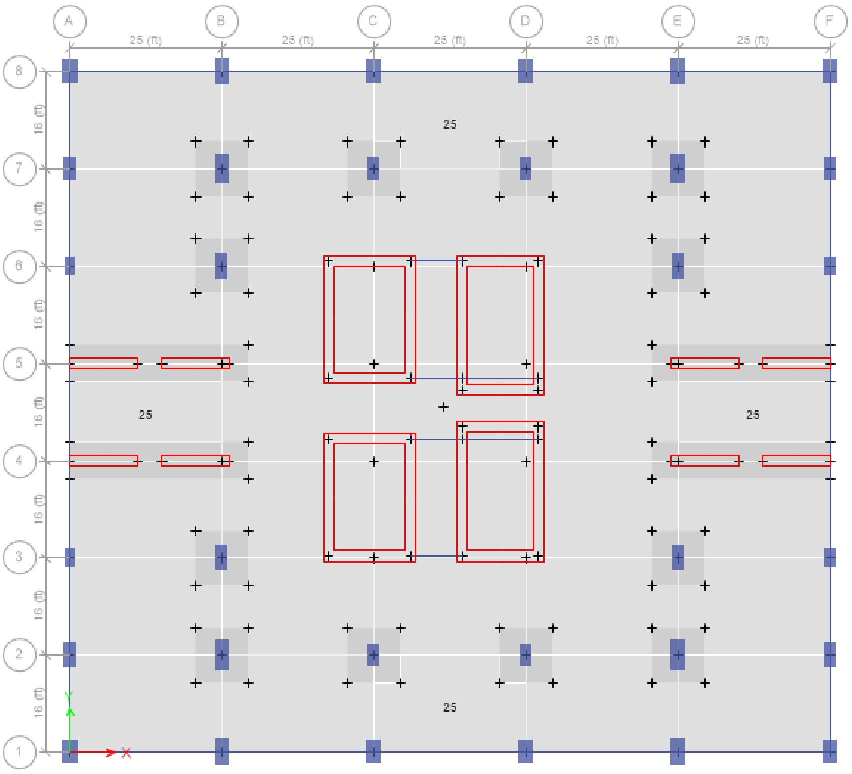


Figure 20 *Wind Turbine Load Applied*

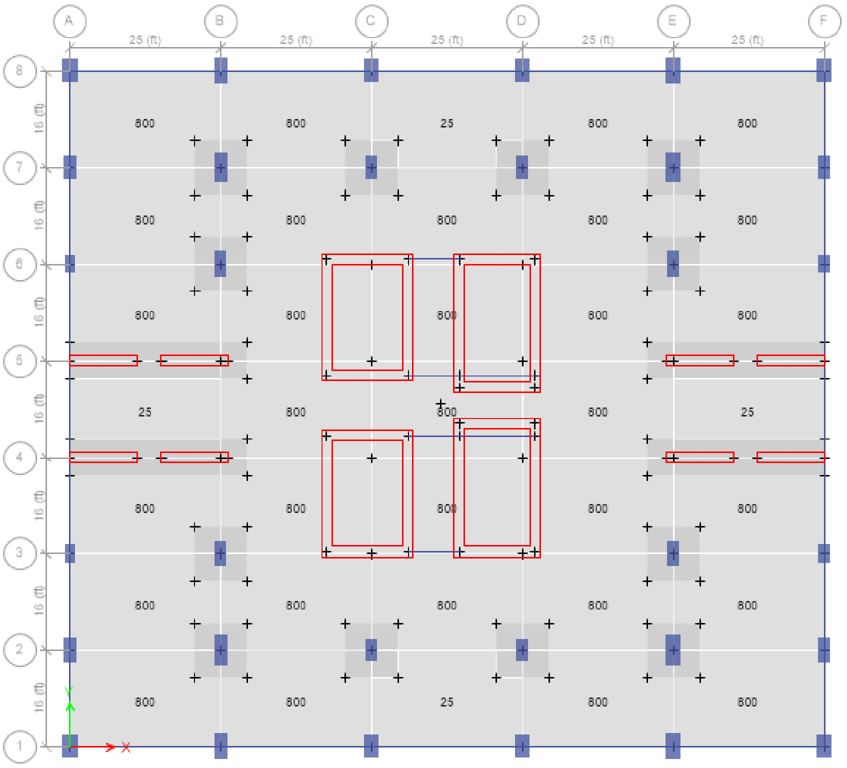


Figure 21 *All Loads Combined*

4.2.1.2 WIND LOADS

Wind loads were upon the ASCE 7-16 code. The parameters selected are tabulated as follow in *(table# 5)*

Table 5 *Wind Load Parameters:*

Parameters	Values
Cp_w	0.8
Cp_l	0.5
Exposure parameter	0.15
Exposure Type	B
Kz_t	1
Gust Factor	0.85
K_d	0.85
Wind Speed	25 (mph)

The figure indicates the wind loading applied on the structure:

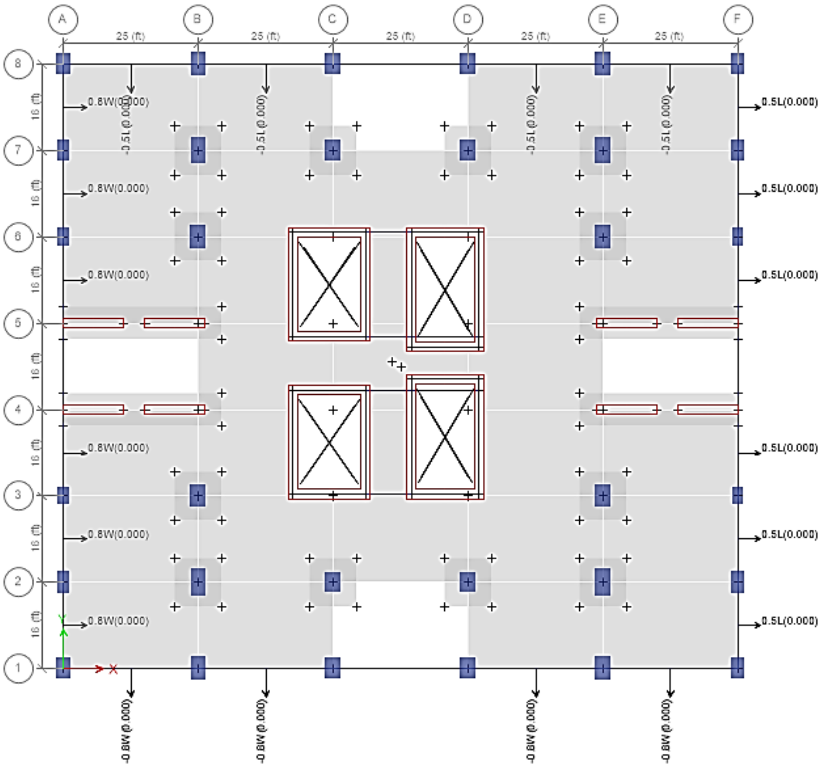


Figure 22 *Wind Loading Applied*

C_{pw} and **C_{pl}** also known as the external wind pressure coefficient and internal wind pressure coefficient respectively are the pressure exerted upon the building by wind before entering and leaving the building. The values of these coefficients depend upo the presence of window and other openings in the building. The topographical factor **Kz_t** depends upon where our structure is located. In our case it is located on mainland a bit far away from the ocean. **K_d** the directionality factor since our building has components of cladding attached to it as well as being the wind force resisting structure.

4.2.1.3 SEISMIC LOADS

The analysis against the seismic loadings were based upon **UBC – 97.** The selected parameters taken from the drawings are shown below in table #6:

Table 6 *Seismic Analysis Parameters*

Parameters	**Values**
Direction + Eccentricity	X + Y
Eccentricity Ratio	0.05
C_t	0.035
R	8.5
Soil Profile Type	SC
Seismic Zone Factor	0.2
Ca	0.24
Cv	0.32
I	1

In seismic designs the factor **C_t** is a numerical coefficient used for computing the time period of the structure. Its value ranges from 0.020 – 0.035 in FPS system. **R** which is a numerical value representing the inherent overstrength and the lateral ductility of the lateral force resisting system used. Whereas, the coefficients **C_a** and **C_v** are seismic coefficients dependent upon the source distance to the site and the soil conditions. The factor **I** also known as the importance factor, the value of which is dependent upon the occupancy category and is different for each type of building.

4.3 CFD ANALYSIS

The analysis was based on all the weather conditions that normally occurs in Karachi. The analysis was carried out for wind speeds ranging from 1 m/s – 8 m/s. the parameters selected to carry out the analysis are tabulated in table #7, followed by a description of the parameters used.

Table 7 *CFD Parameters Used*

PARAMETERS	
Turbulence Model Type	RANS Model
Turbulence Model	k-ϵ
Air Density	1.225 kg/m^3
Temperature	293.15 K
Inlet Distance	1183.2’
Depth of Domain	4080’
Boundary Conditions	No Slip Condition
Meshing Size	Fine

CFD analysis is based upon the numerical modelling approach of problems related to fluid flows or fluid dynamics. The analysis is based upon the RANS short of **R**eynolds **A**veraged **N**avier **S**tokes equation. The RANS model are time averaged equations of motion for modelling of turbulent fluid flows but can be used for laminar flows as well. They are based upon Reynold’s decomposition, a mathematical technique that separates the expected or the averaged value from its fluctuations. A solution is said to be completed or converged based upon the following 3 values:

1. **Residual:** this value provides us with the information of the errors present in the solution. A solution is said to be accurate if the fluctuations in the residual values are low.
2. **Imbalance in solution:** this value follows the principle of conservation of energy i.e the final solution must be conserved.
3. **Quantities of interest:** if all the quantities of interest are not fluctuating with each iteration of the RANS equations. A solution is said to be converged.

The turbulence model used for the analysis was the k-ϵ model. This model is robust in nature and quickly computes for the RANS equations. However, it is used only for fully turbulent flows with simple flow and not for complex flows.

The boundary condition which is selected to be as no slip condition. In this condition it is assumed in fluid dynamics that the fluid flowing near the walls of the surface i.e at the fluid-solid boundaries the fluid velocity will be that of the boundary that is at rest or zero. The effects of which are discussed in figure # 25.

Finally, for numerical modelling the meshing of the domain and the object of interest must be carried out. The finer the meshing is selected the more accurate and easily differentiable results are obtained. Consequently, the iterations for the solution to be converged increases. Which results on higher computational time.

4.4 STRUCTURAL ANALYSIS RESULTS

Before the application of turbine loads on to the structure the cross sections were safe against the designated applied loads. With the addition of turbine loads the cross-section sizes were increased by up to a maximum of 3%. After the increment in the x-sectional dimensions the cross-sections were large enough to carry the loads. The results of the analysis after the addition of wind turbine is shown below indicating that the cross-sections have passed. Figure 23 shows a plan view of the building passing the check. Whereas, the figure 24 shows a 3-D Elevation of the model indicating that all members have passed the checking criteria.

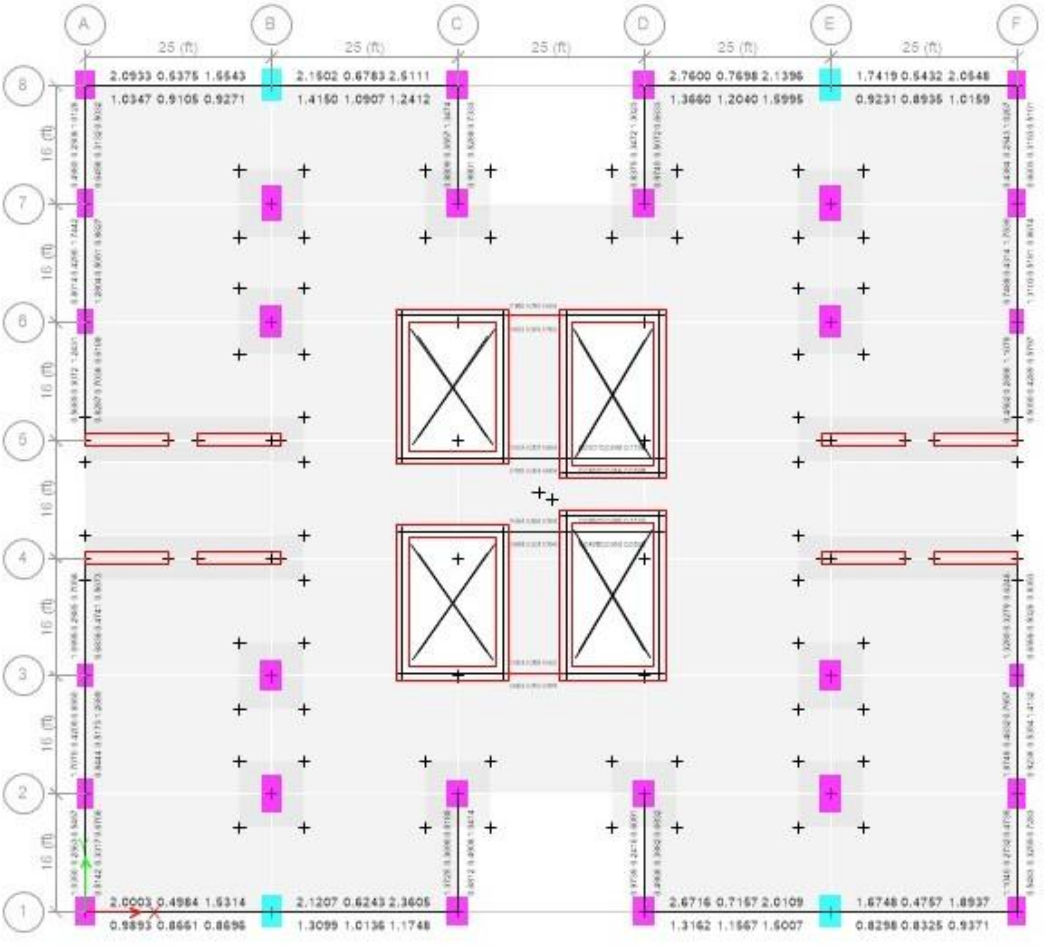


Figure 23 Plan View of X-section Check

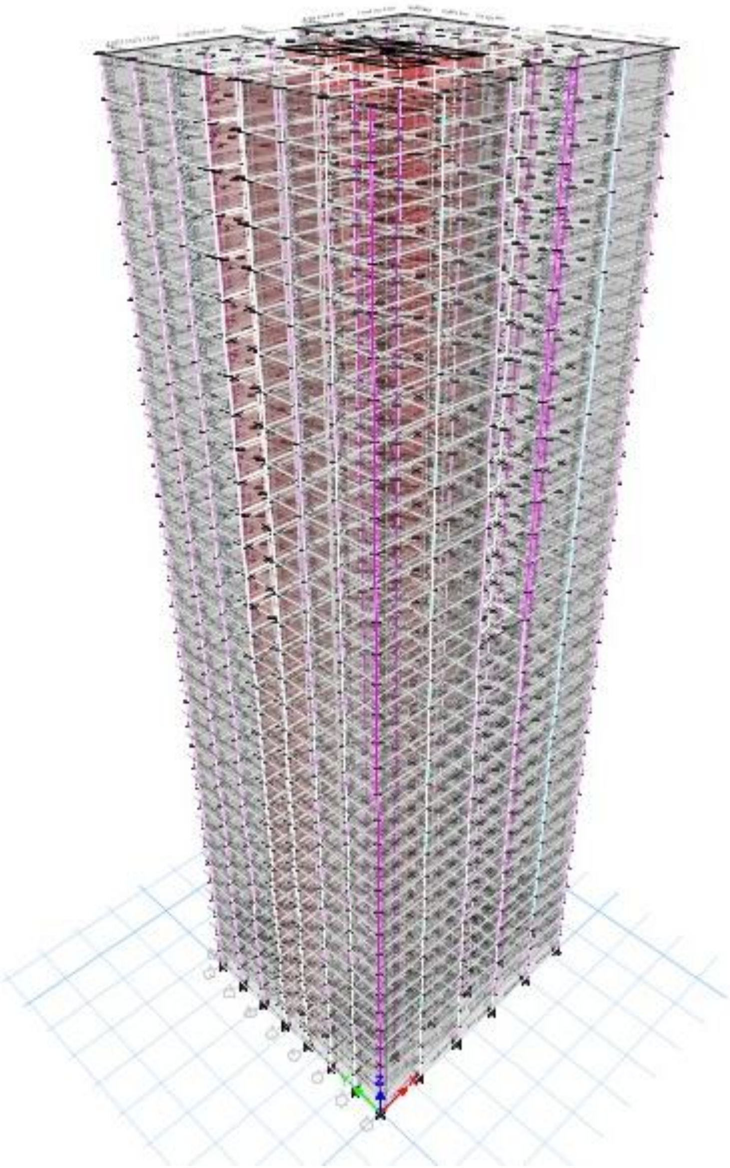


Figure 24 *3-D View of Cross-section Check*

4.5 CFD RESULTS

4.5.1 ORIGINAL MODEL

The analysis, as mentioned before was carried out all the speed conditions that normally prevail in Karachi with the parameters as mentioned in *section 4.3.*

The results obtained indicated that no noticeable velocities were observed inside the building however high velocities were observed at the rooftop. .

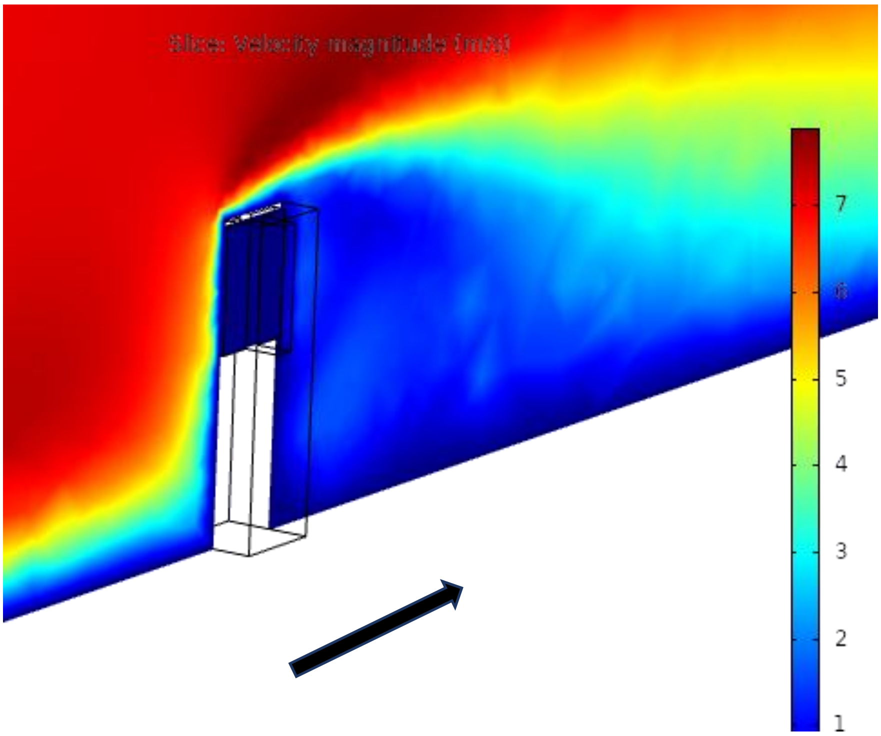


Figure 25 *Velocity Distribution at Ambient Conditions*

The different color shades in figure 25, indicate the wind velocities with the blue color showing minimum wind velocities which is expected. As, the wind velocities are nearing zero near the Earth's surface and goes on increasing with increasing height. As discussed in section 4.3 due to the wall effects the velocities nearing the surface are attaining a speed that of the surface of the earth and the building nearing zero. Due, to the flat surface of the building the wind gets diverted towards the side as indicated in fig. 26. With the side edges showing a reduced velocity then what was used at the ambient conditions (V = 7 m/s) using the legend the velocities within 1m radius indicate speeds ranging from 3 – 4 m/s.

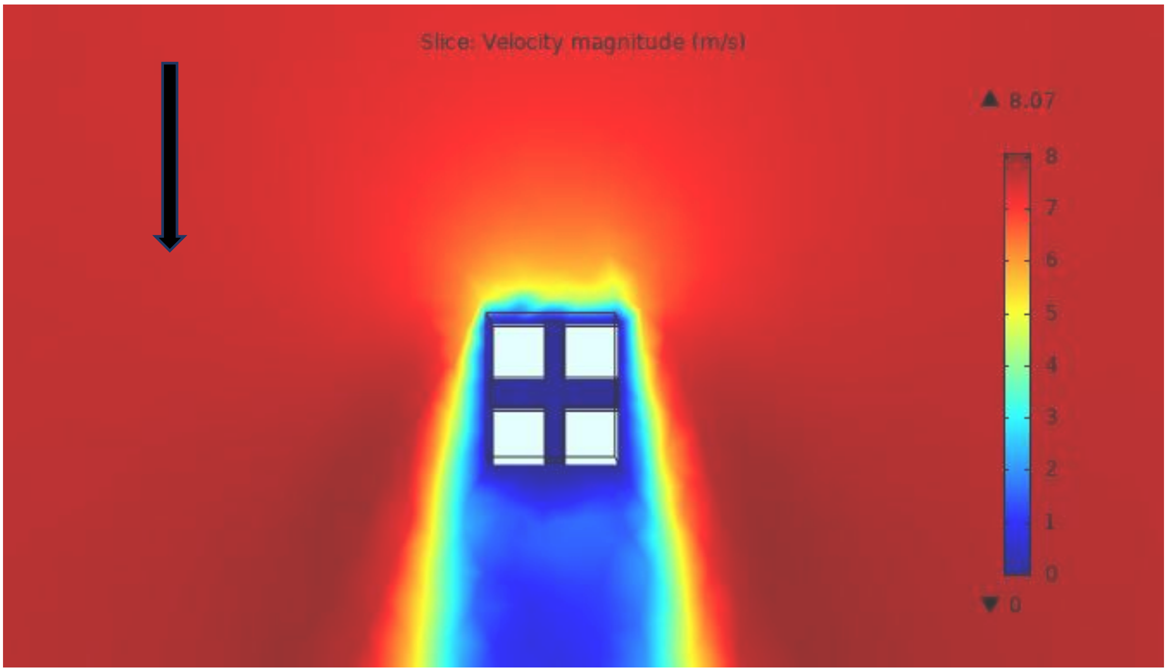


Figure 26 *Velocity Distribution on Sides at Ambient Conditions*

As indicated in the legends of the figure 24 and 26. The blue color shows the minimum velocity whereas red to orange red color shows the maximum velocity observed.

The analysis for the model with wind speeds varying from 1 – 8 m/s showed no significant development of wind velocity inside the building.

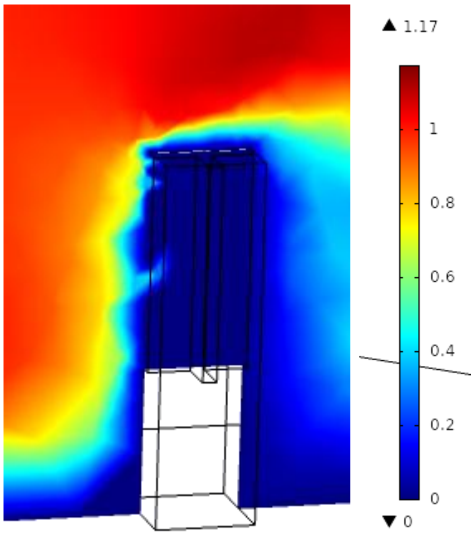


Figure 27 *Velocity at 1 m/s*

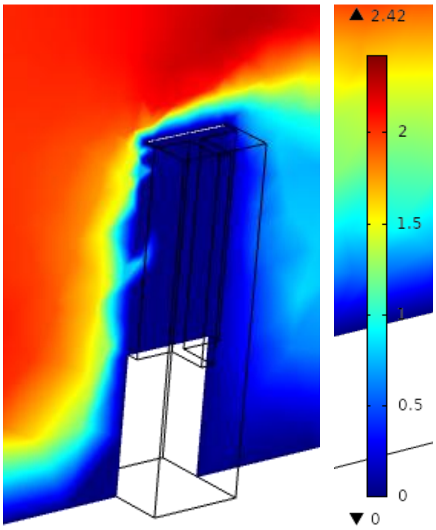


Figure 28 *Velocity at 2 m/s*

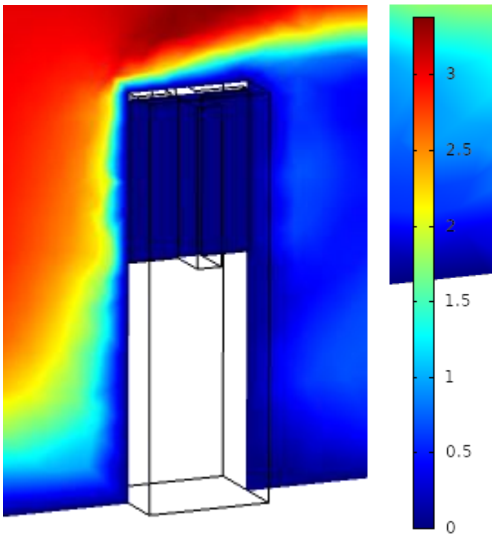


Figure 29 *Velocity at 3 m/s*

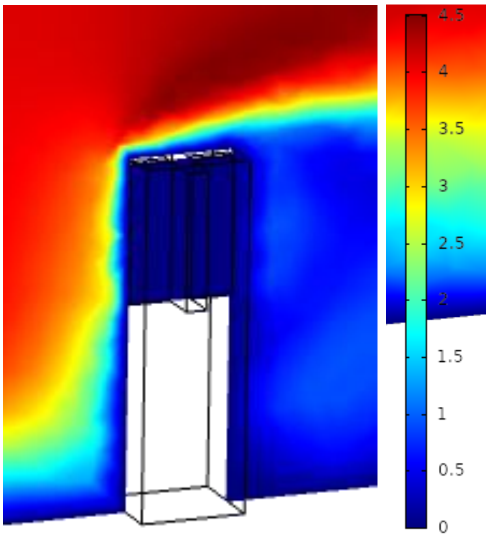


Figure 30 *Velocity at 4 m/s*

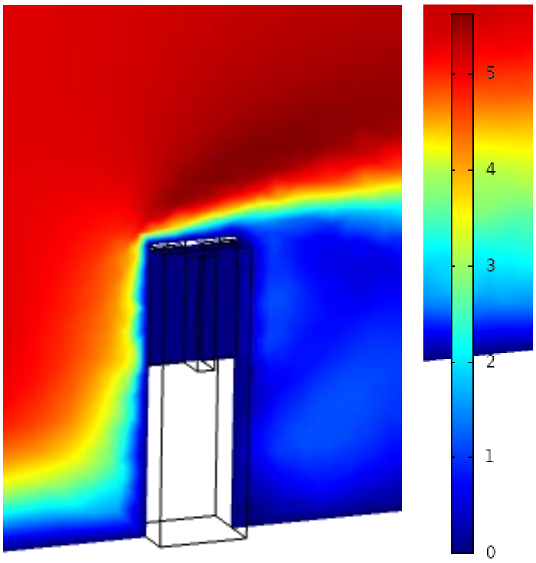


Figure 31 *Velocity at 5 m/s*

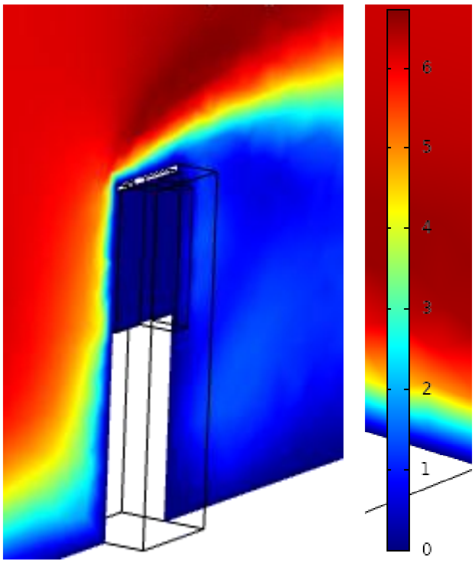


Figure 32 *Velocity at 6 m/s*

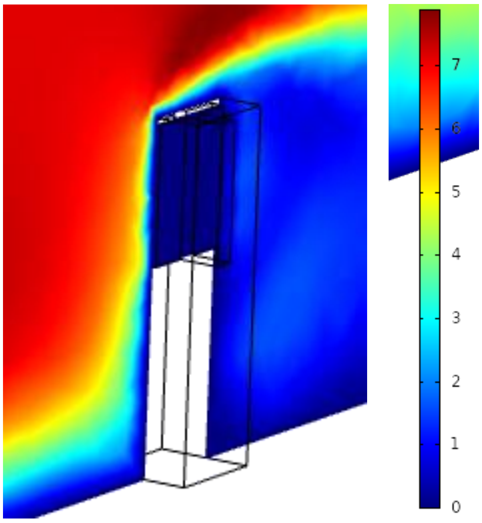


Figure 33 *Velocity at 7 m/s*

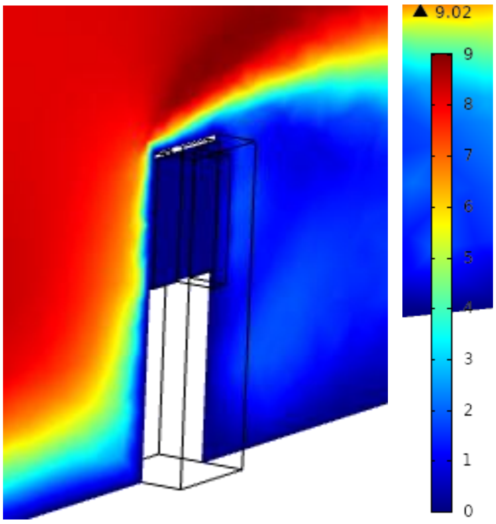


Figure 34 *Velocity at 8 m/s*

4.5.2 REVISED MODEL # 1

The first revised model had its edges tapered off. As mentioned in section 3.7 the models were so modified so as to avoid a completely flat surface of the building which would completely stop the wind velocities, to a more aerodynamic shape which would gradually increase the approaching wind velocities. The original model was first revised by tapering off its edges, as shown in fig.# 35 its elevation and plan view:

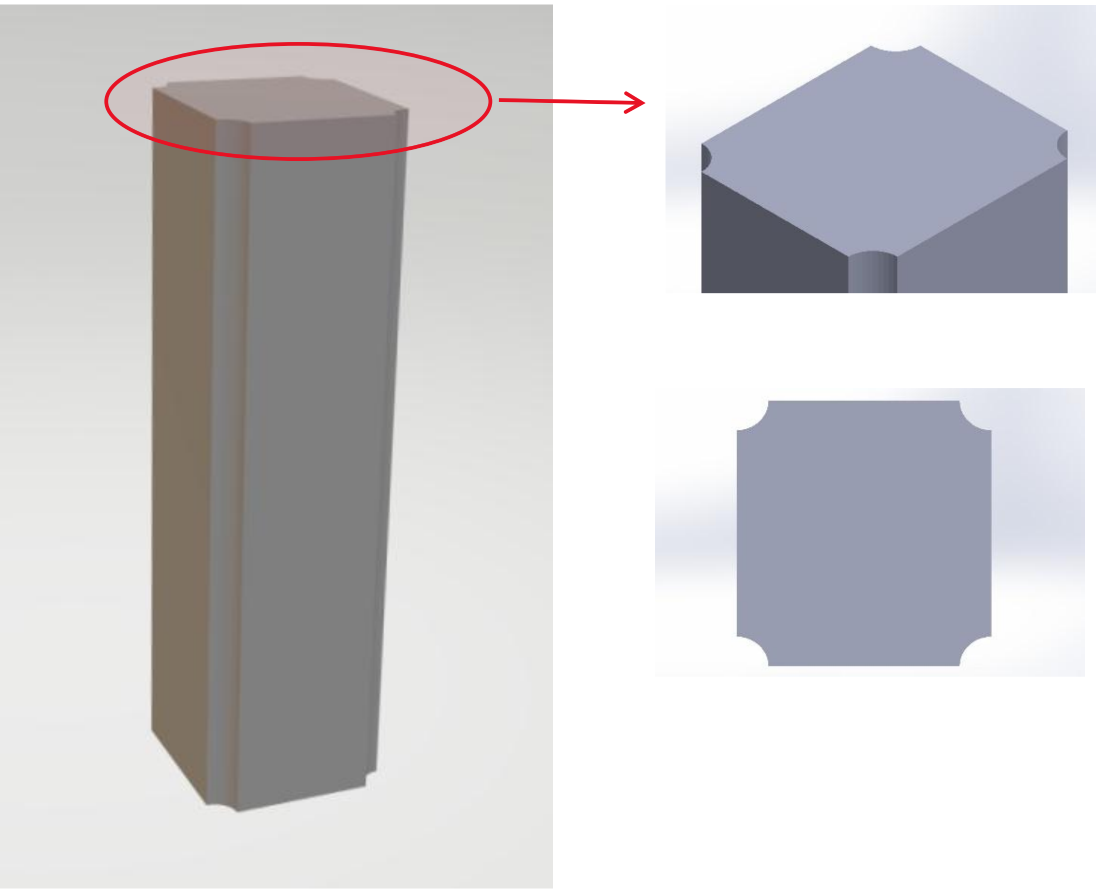


Figure 35 *Geometrical Arrangement #1 Modelled on SOIDWORKS*

The analysis showed that the curvilinear nature of building edges, allowing easy passage of wind, showing low pressure where velocities are high and vice versa.

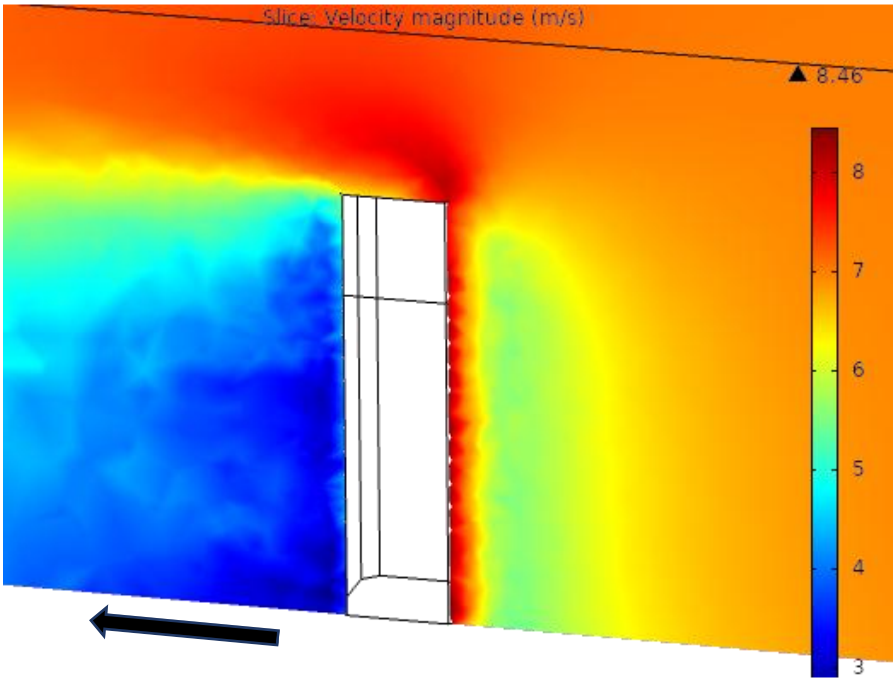


Figure 36 *Velocity Distribution at Ambient Conditions*

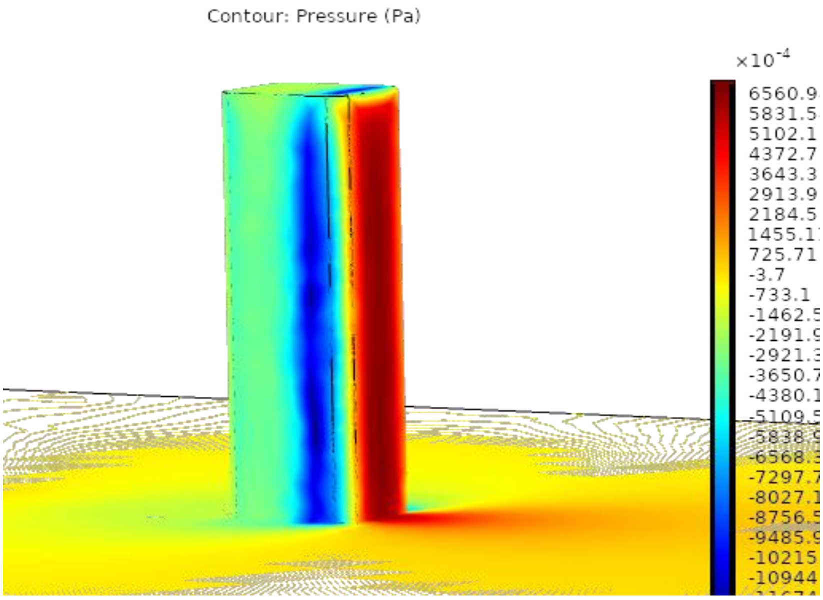


Figure 37 *Pressure Distribution at Ambient Conditions*

NOTE: The black arrow indicates the flow of direction of the wind.

The figure 37 indicates a pressure contour of the entire building where the red contours indicate positive pressure. The shades from yellow to dark blue represent negative pressures as shown in figure.

The results were consistent for all velocity ranges (1 – 8 m/s):

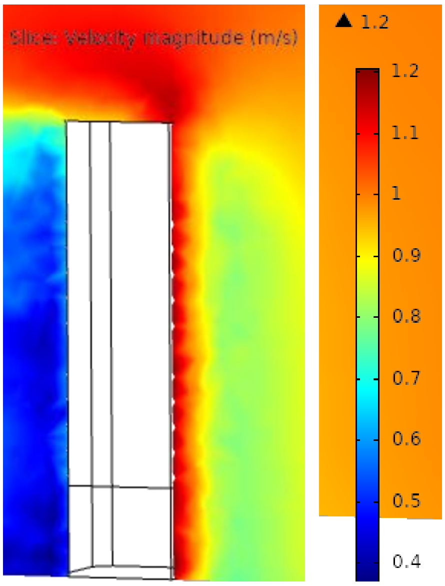


Figure 38 *Velocity at 1 m/s*

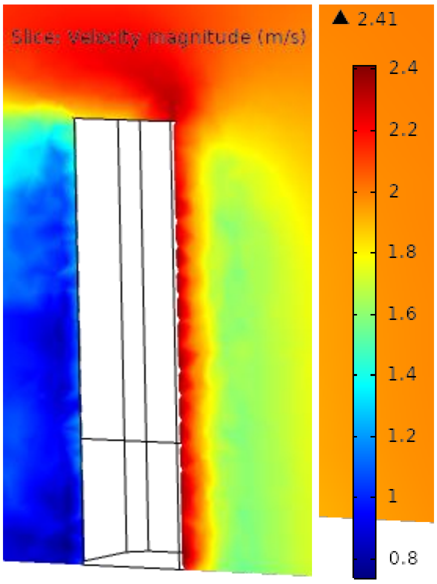


Figure 39 *Velocity at 2 m/s*

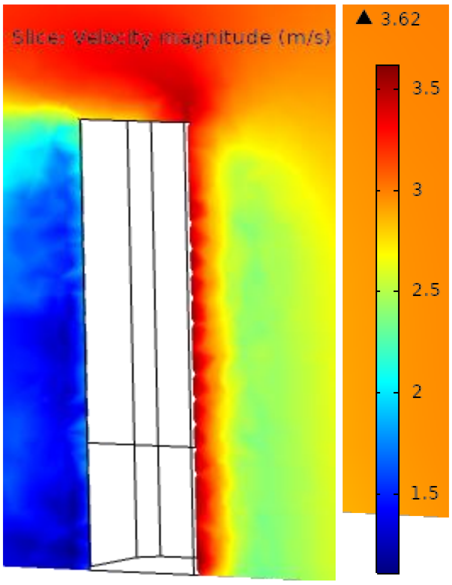


Figure 40 *Velocity at 3 m/s*

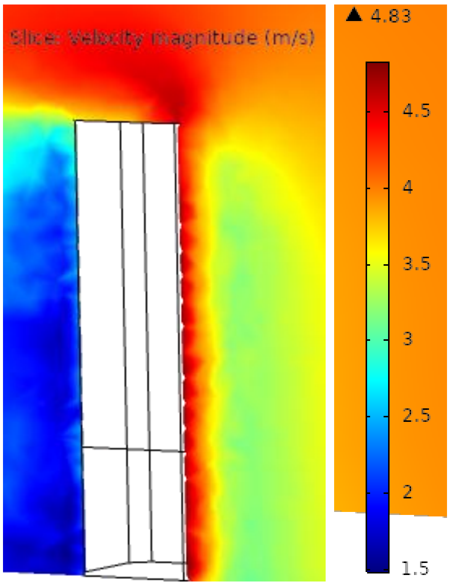


Figure 41 *Velocity at 4 m/s*

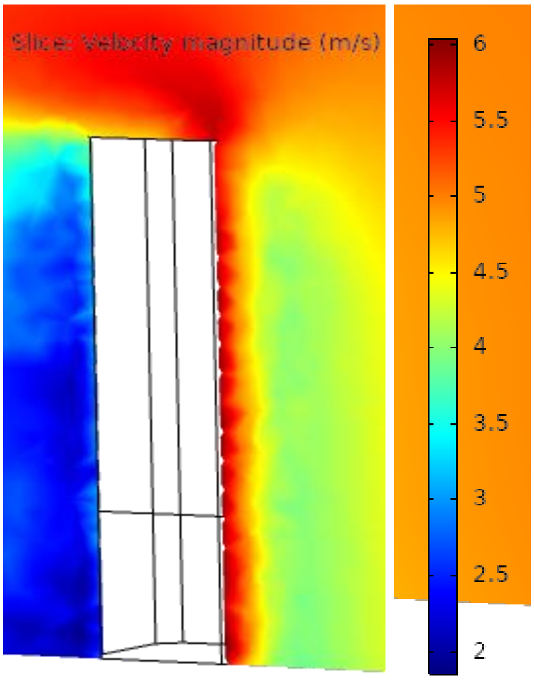


__Figure 42__ Velocity at 5 m/s

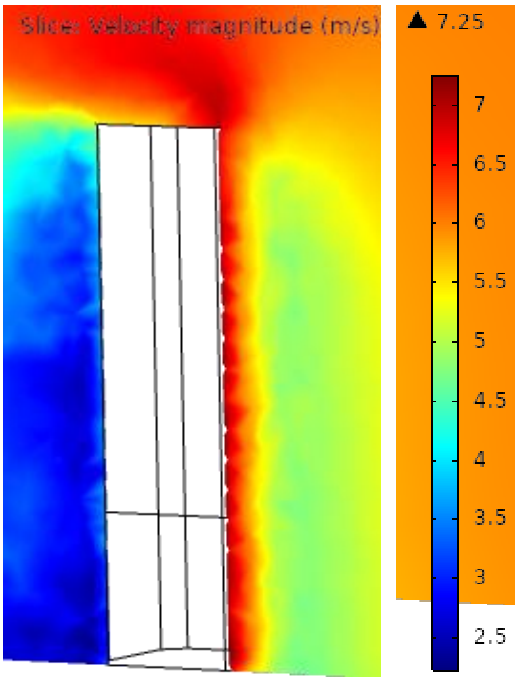


__Figure 43__ Velocity at 6 m/s

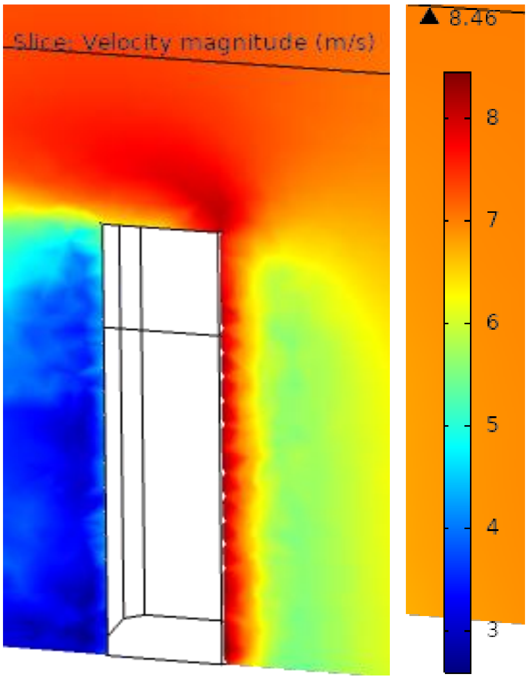


__Figure 44__ Velocity at 7 m/s

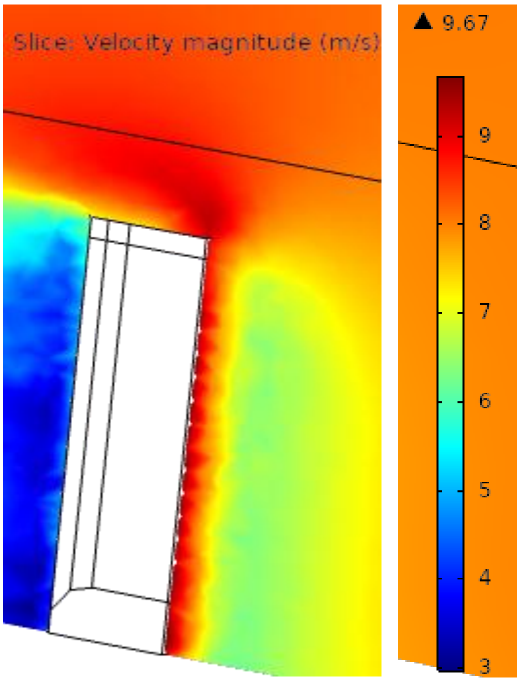


__Figure 45__ Velocity at 8 m/s

4.5.3 REVISE MODEL # 2

The second revision was made in the roof of the structure. The groove which can be used as a water storage tank or as a rooftop restaurant, was spaced **30 ft** apart with the roof pitched like a semi-circle, as shown in *fig. # 46.*

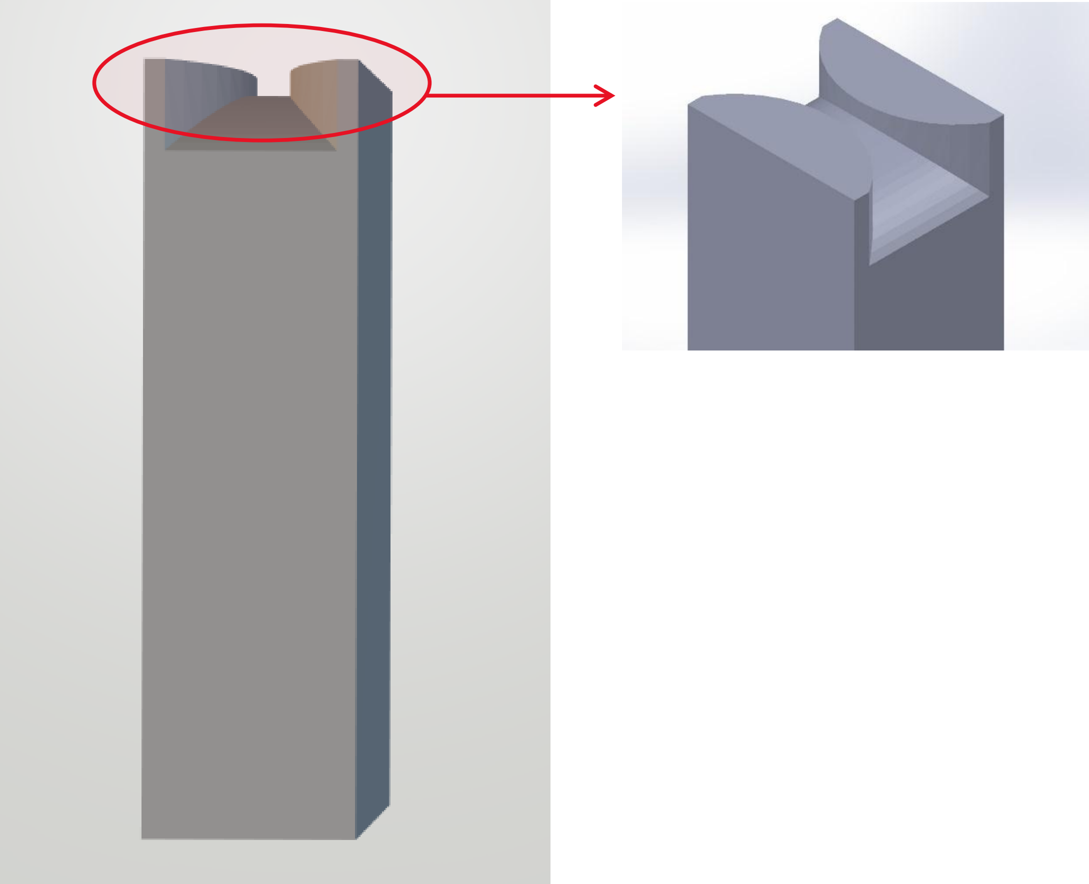


Figure 46 *Geometrical Arrangement #1 Modelled on SOIDWORKS*

High wind velocities with low pressure were observed at the rooftop for ambient conditions.

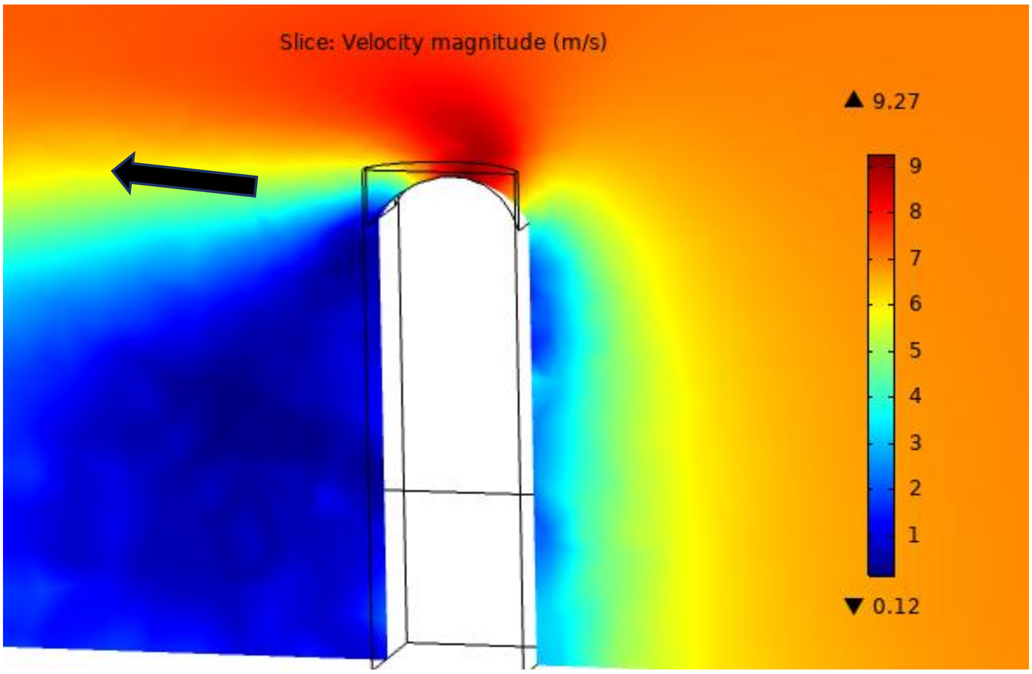


Figure 47 Velocity at ambient conditions

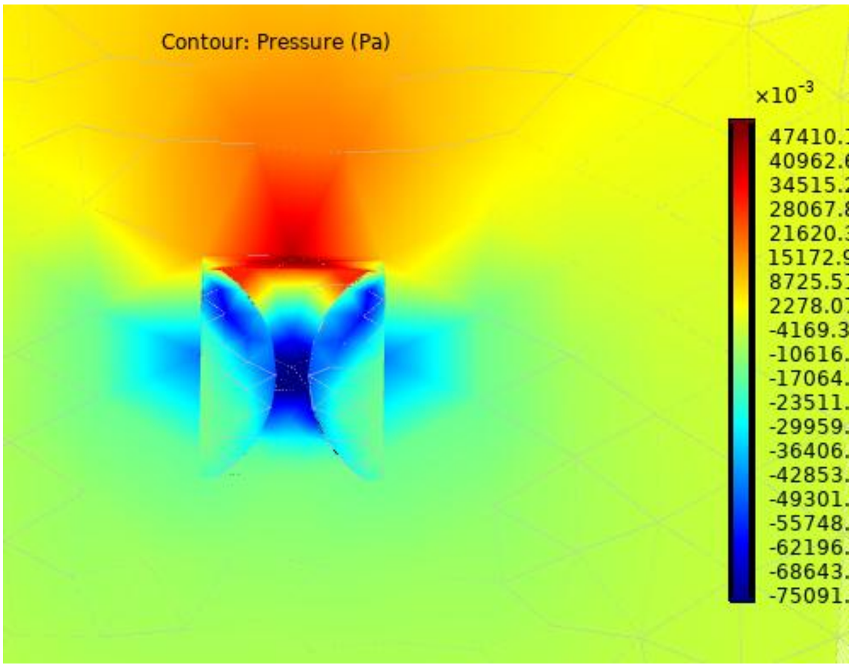


***Figure 48** Pressure Distribution at ambient conditions*

NOTE: The black arrow indicates the flow of direction of the wind.

Th results indicate that a high negative pressure develops with increasing wind velocities. The results were replicated for all wind speeds as shown in the following figs.

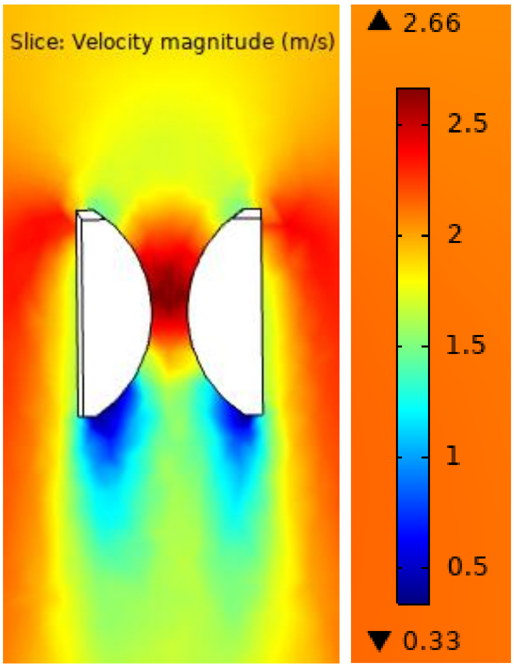


Figure 49 *Velocity at 2 m/s*

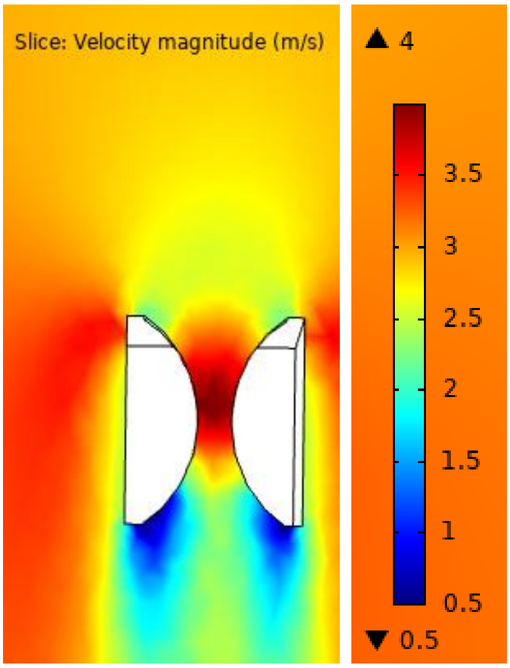


Figure 50 *Velocity at 3 m/s*

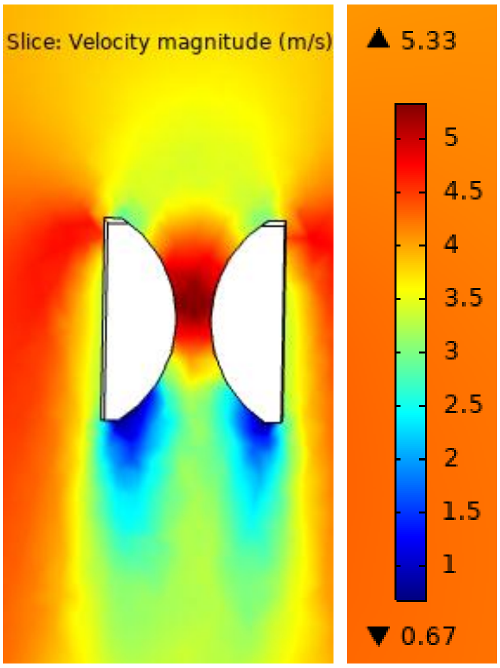


Figure 51 *Velocity at 4 m/s*

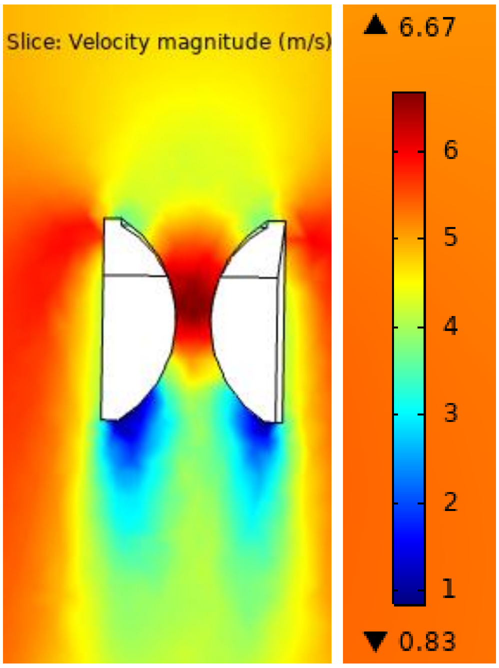


Figure 52 *Velocity at 5 m/s*

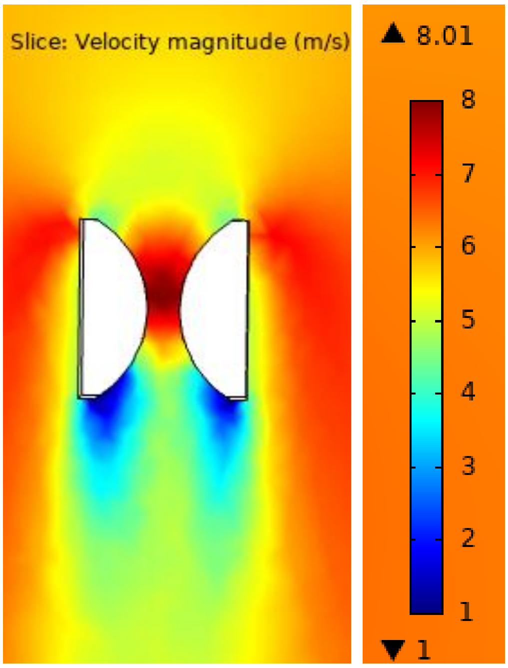


***Figure 53** Velocity at 6 m/s*

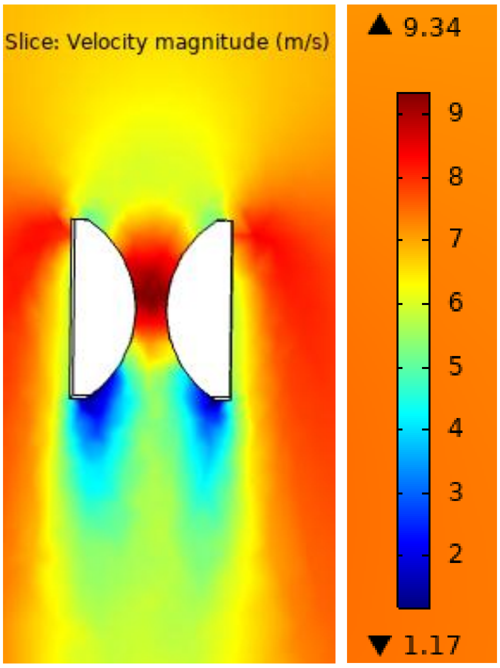


***Figure 54** Velocity at 7 m/s*

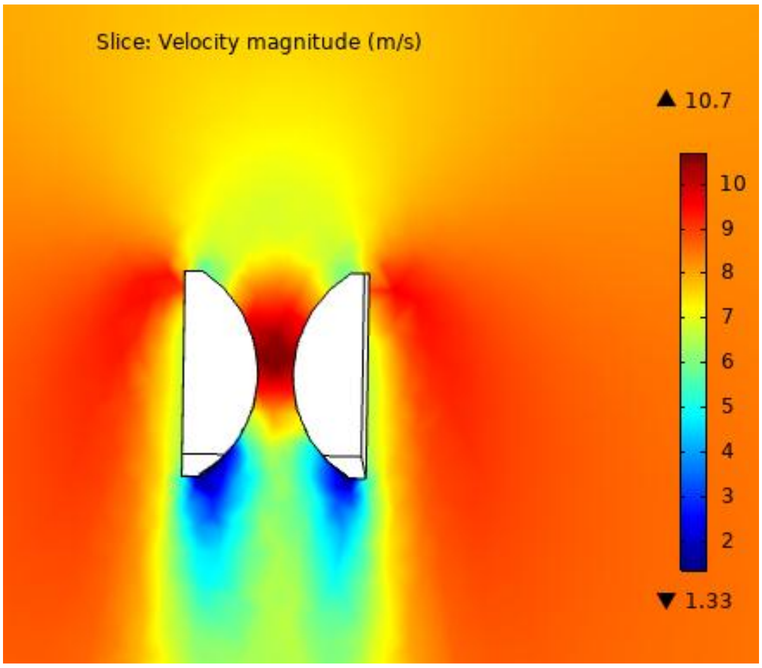


***Figure 55** Velocity at 8 m/s*

4.6 VELOCTIES AT VAWT

Based upon the analysis run as mentioned in previous section # 4.5.3 the velocites at the proposed VAWTs location are observed as follows

4.6.1 ORIGINAL MODEL

The velocity observed, based upon tha analysis carried out, at various locations on the building is shown in figure # 56

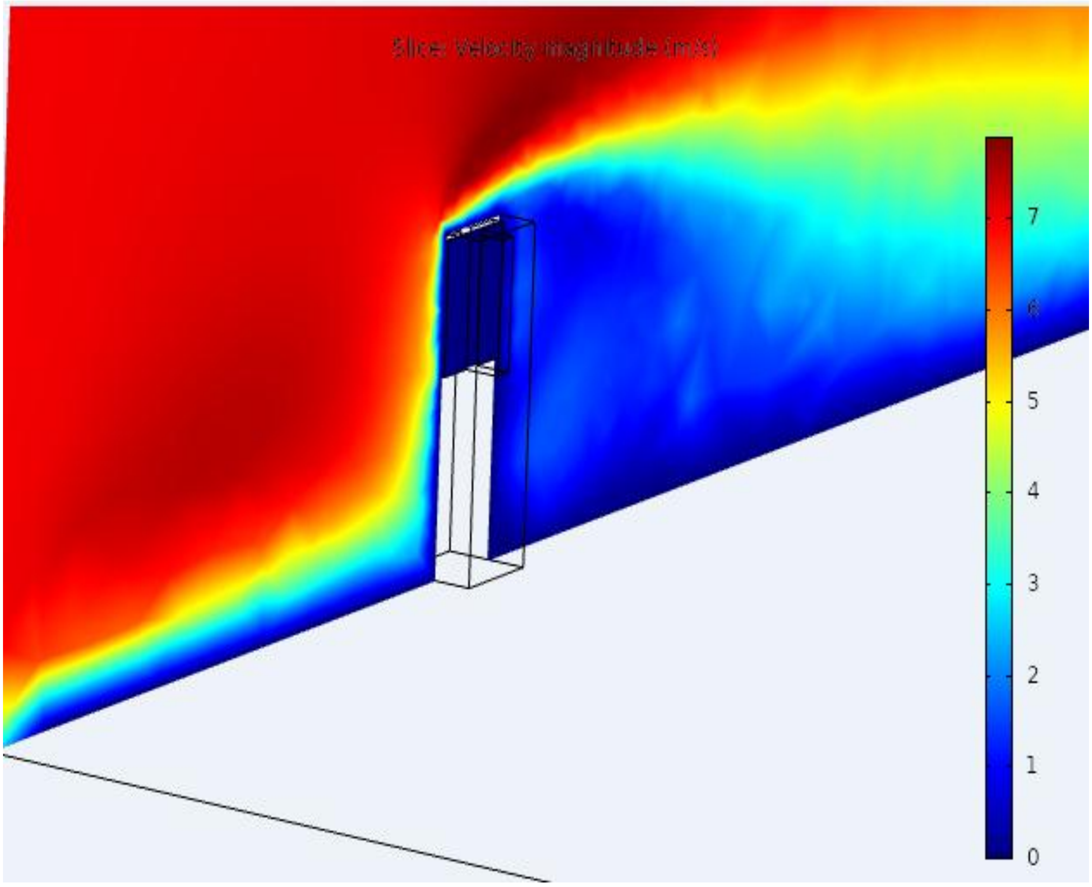


Figure 56 *Velocity Observed at VAWT's Possible Location for Original Model*

4.6.1.1 Face of the building

Based on the observed results the face of the building does not allow for the passage of wind instead at blocks and stops the wind blowing towards it as is shown in the *figures # 27 – 34* the wind velocities observed are nearing 0 m/s.

4.6.1.2 Roof of the building

Based on the observed results. The roof of the building does allow for the passage of wind and lets it pass through as shown in figure # 25. The velocities obtained at the roof as observed are suitable as opposed to the previous case, where the velocities came to be almost zero.

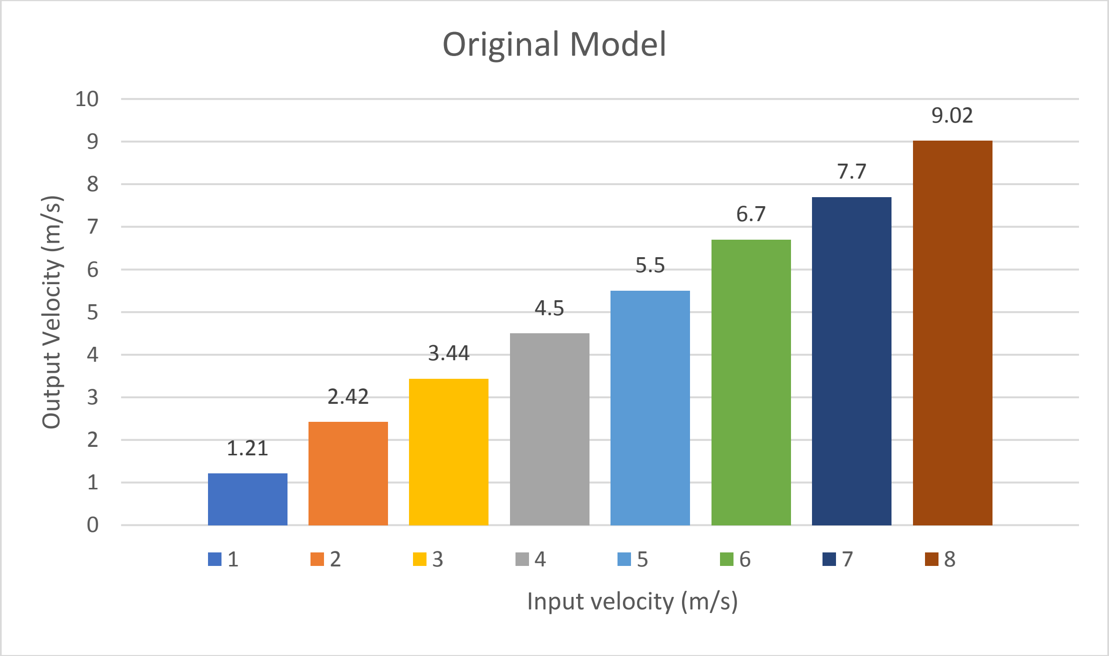


Figure 57 *Velocity observed at VAWT for Different Wind Speeds for Original Model*

The velocity output in its tabular form has been listed in table # 8 for analysis ran against various winds speeds.

Table 8 *Velocity observed at VAWT on Roof for Different Wind Speeds for Original Model*

Input Velocity	**Velocity at VAWT**
1	1.17
2	2.34
3	3.38
4	4.4
5	5.44
6	6.5
7	**7.66**
8	8.97

Discussion

Based upon the observed result the velocities at the face of our building are far lower than expected. Hence the face of building does not make for a suitable postion for VAWTs. However roof makes ideal location as observed from the table. Hence the roof should be selected for the positioning of VAWTs.

4.6.2 REVISED MODEL 1

4.6.2.1 Edge of the Building

Due to the curvilinear configuration of the building edges, It allows for the passage of air, an exit path and not blocking it hence allowing for suitable and ideal wind velocities that allows for the placement of VAWT's.

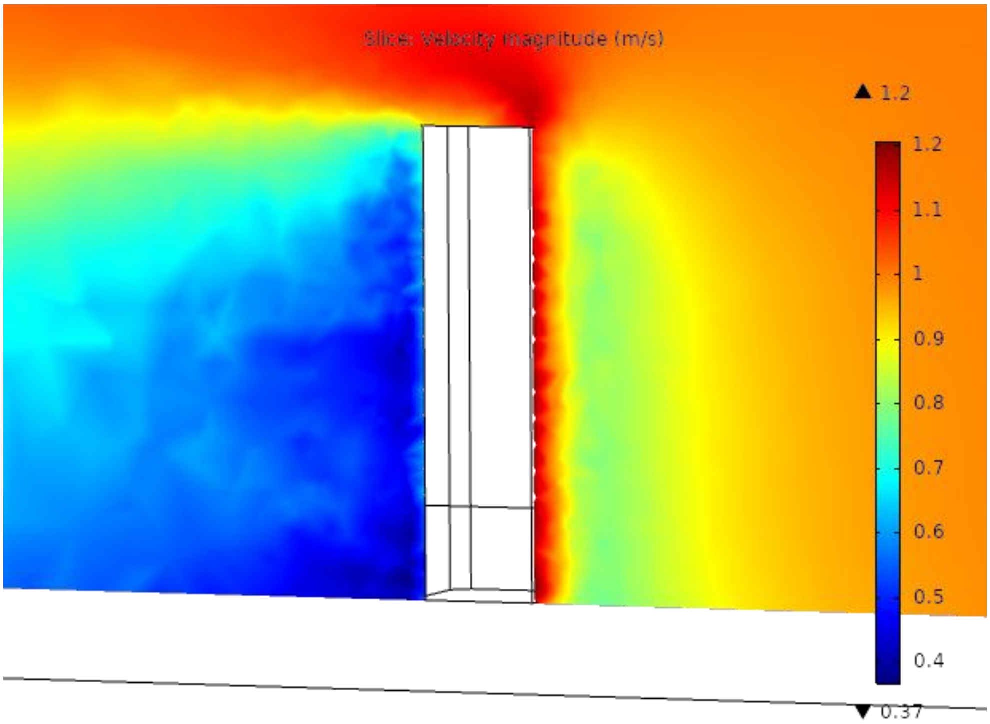


Figure 58 *Velocity Observed at VAWT's Possible Location for Model 1*

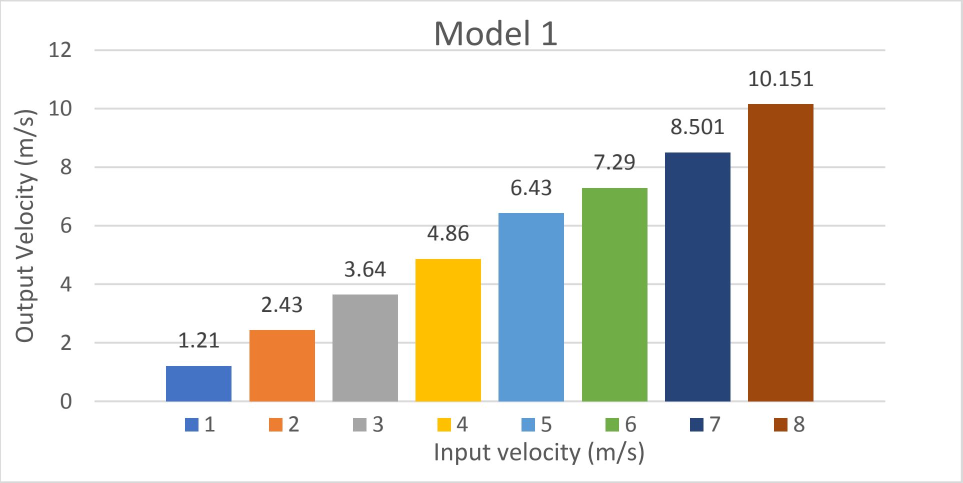


Figure 59 *Velocity observed at VAWT on Edge of the Building for Different Wind Speeds for Model 1*

The above fig. # 59 represents the graphical representation of the results. As mentioned before the edges allow for the easy flow of the air and a cluster of streamlines moving in the same direction increases the wind speed as is observed.

The velocity output for analysis ran against various winds speed has been tabulated.

Table 9 *Velocity observed at VAWT on Edge for Different Wind Speeds for Model 1*

Input Velocity	**Velocity at VAWT**
1	1.21
2	2.43
3	3.64
4	4.86
5	6.43
6	7.29
7	**8.501**
8	10.151

4.6.2.2 ROOF OF THE BUILDING

The analysis as showns in fig. # 58, clearly tells us that the roof allows for the easy passage of the wind thus making it also a viable position for the placement of wind turbines. This result is consistent with our initial finding in the original model.

Graphical representation for observed velocities are shown in figure#:

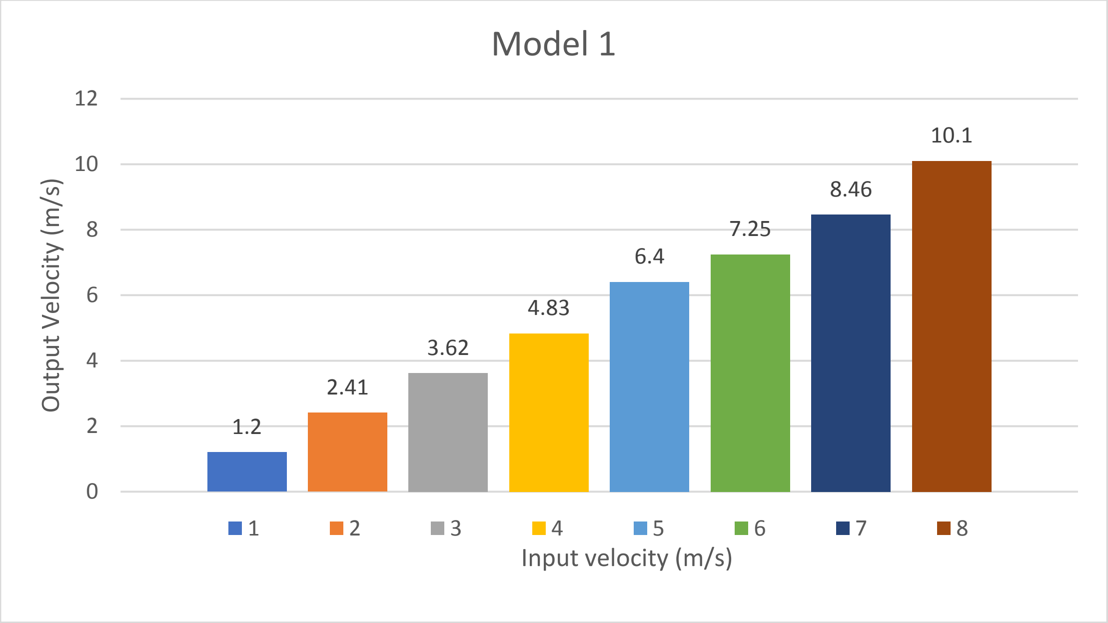


Figure 60 *Velocity observed at VAWT on Roof for Different Wind Speeds for Model 1*

It is interesting to note that that after the speed of 4 m/s. from speeds of 5 m/s and above the increase in velocities of input to the velocity observed is increasing at a rate of 18 – 20% i.e almost an increase of 1.5 – 2 m/s are observed for each increasing input velocities.

A tabular description of the velocities has been plotted as shown in table#10

Table 10 *Velocity observed at VAWT on Roof for Different Wind Speeds for Model 1*

Input Velocity	**Velocity at VAWT**
1	1.20
2	2.42
3	3.62
4	4.83
5	6.40
6	7.25
7	**8.46**
8	10.10

Based upon the similar the velocities observed at roof and edges of the building. The obtained velocity allow us to place turbines on the edges and roof of the structure.

4.6.3 REVISED MODEL 2

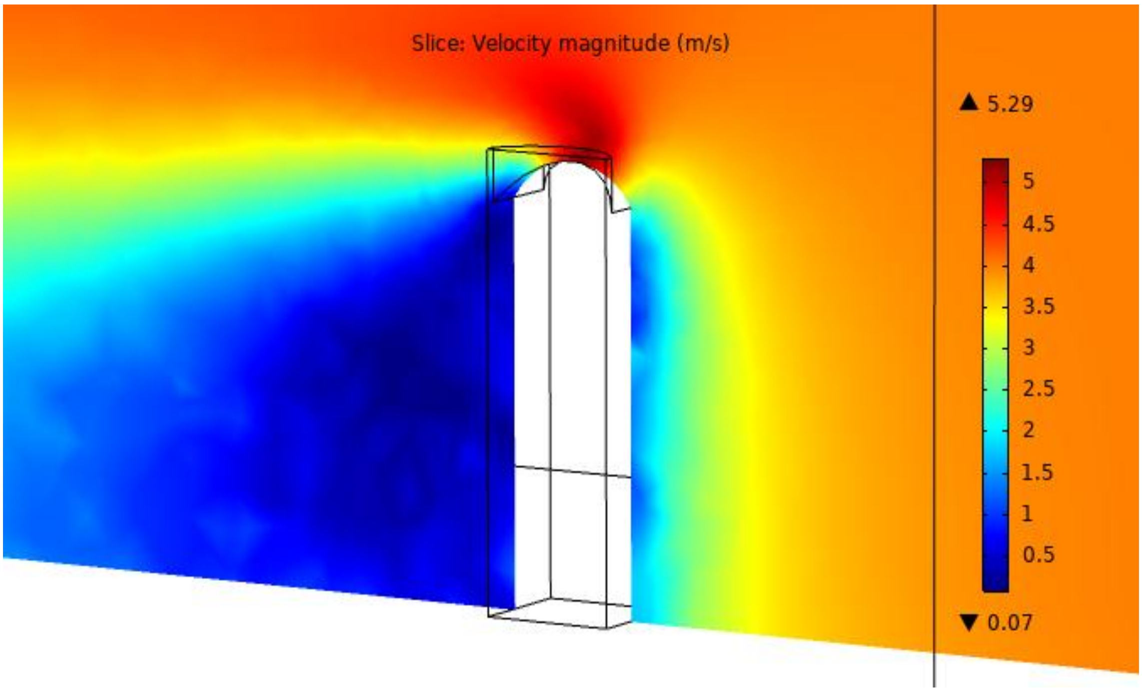


Figure 61 *Velocity Observed at VAWT's Possible Location on Roof for Model 2*

4.6.3.1 ROOF OF THE BUILDING

The analysis shows clearly that the curvature of the roof alows for the easy passage of the wind and also apmplifiying wind on its way. Thus, clearly making it the most viable position for the placement of wind turbines. The analysis also indicated that the side edges of the building are not generating wnough velocities near the building to select an appropriate location for the turbine placement.

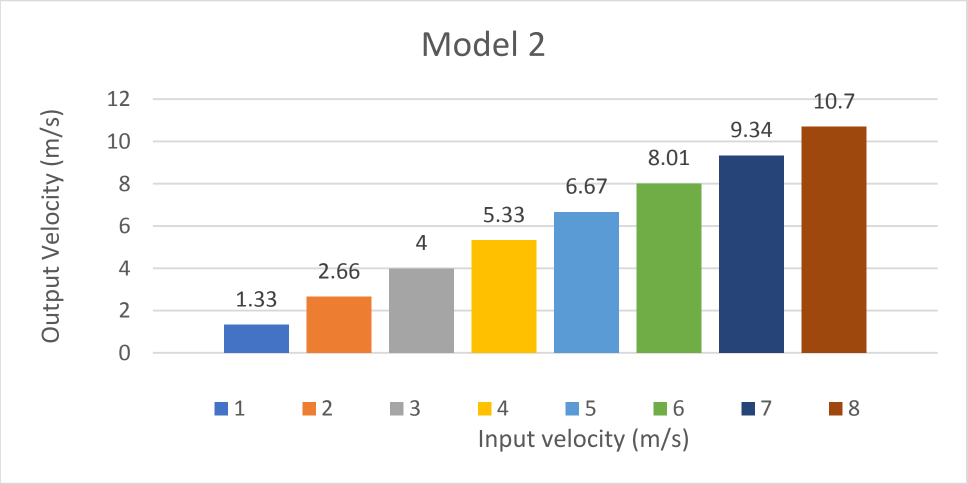


Figure 62 *Velocity observed at VAWT on Roof for Different Wind Speeds for Model 2*

The velocity output for analysis ran against various winds speed has been tabulated in table # 11

Table 11 *Velocity observed at VAWT on Roof for Different Wind Speeds for Model 2*

Input Velocity	**Velocity at VAWT**
1	1.33
2	2.66
3	4.00
4	5.33
5	6.67
6	8.01
7	**9.34**
8	10.7

Based upon the observed result the edges do not make for a suitable location. However, velocities are significantly amplified as observed in the table # 4.10 due to the clustering of the streamlines. Hence this makes the most suitable location with current geometrical façade for placement of VAWTs.

4.6.4 COMPARISON OF MODELS

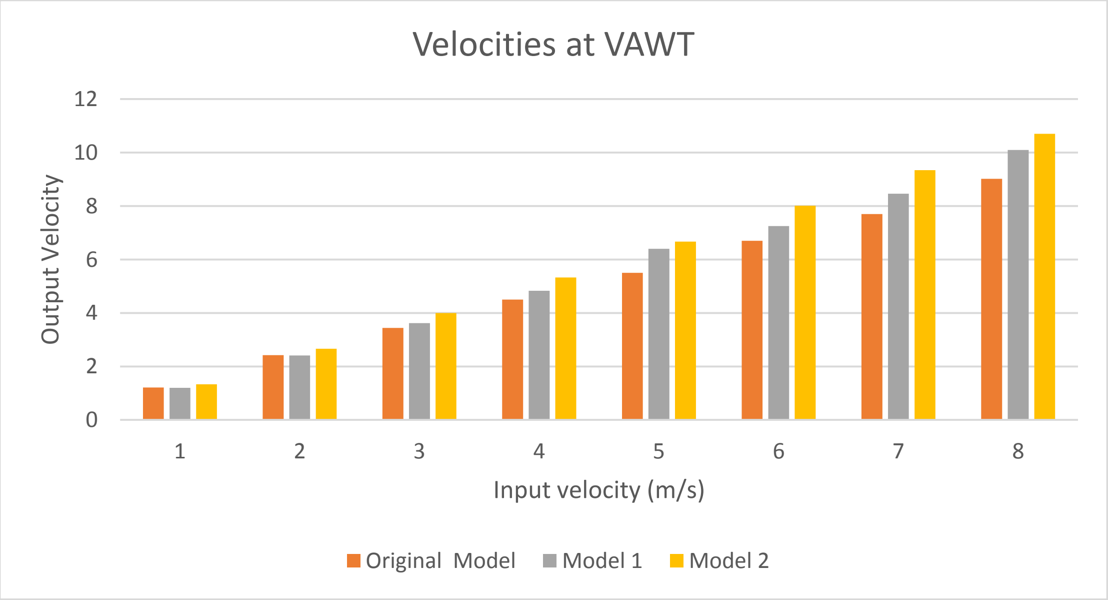


Figure 63 *Comparison of Velocities for All Models*

In the graph above(figure 63) comparing all models with each other for input velocity and velocity obtained model 2 has yielded maximum output velocity for each input velocity. Which indicate a façade arrangement of sorts is likely to yield high velocities.

4.7 PLACEMENT OF VAWT

Based on the experiments conducted by **Veena (2017)** the methodology was adopted for the selection of the most optimum position of VAWT, and the results observed in *section # 4.6.4* to generate maximum possible energy from a VAWT. The main objective is to place VAWTs at a position where there were highest wind velocities in order to harness maximum wind power.

4.7.1 Original Model

As in our model there were cavites in the faceof the struture. So an initial attempt was made to place turbines on the face of the building. However, based on the observed velocities the face was not an ideal location for the placement of Wind Turbines, due to very small opening in the face. Instead the roof of the building was found to be the most ideal location for installation of the wind turbines which require free flow passage of air. The optimum position that was then selected was the roof of the structure.

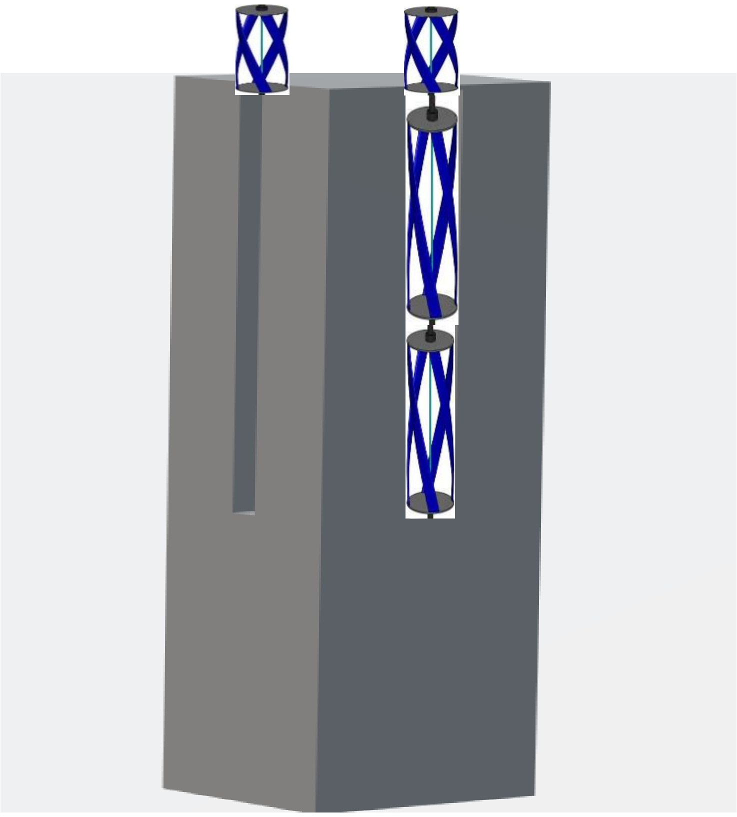


Figure 64 *Positioning of Gorlov Wind Turbine for Original Model*

As per the requirement for the passage of air the second most suitable position was the placemnt of the turbine on roof top of the structure

4.7.2 Model 1

Due to reconfiguration of geometrical façade the cornored edges were tapered off to cater for the free flow passage of air. As a result we observed as indicated in (table 9 & 10) two most suitable locations for the placement of VAWT are the edges of the building as well as the rooftop.

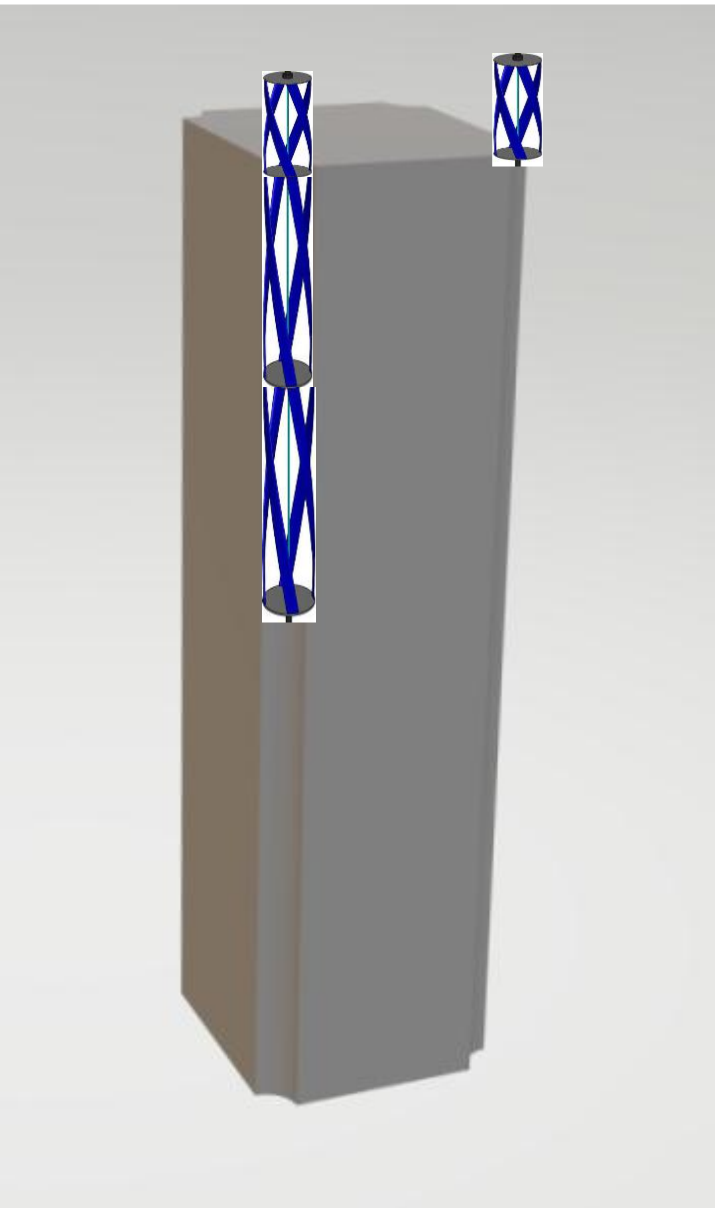


Figure 65 *Positioning of Gorlov Wind Turbine for Model 1*

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4.7.3 Model 2

The final configuration created for geometrical changes in the rooftop that allowed for the clustering of stream lines thus resulting in high observed velocities as shown in (table #11). The most suitable location supported by the analysis carried out is the rooftop of the structure.

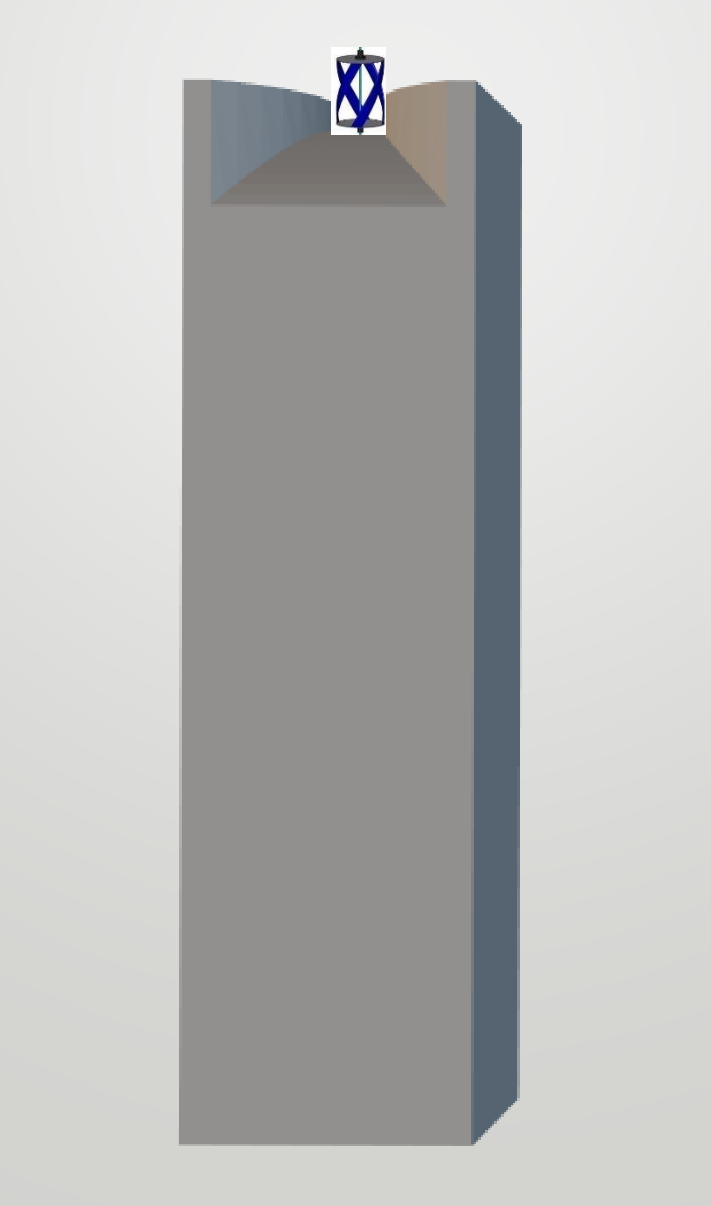

Figure 66 *Positioning of Gorlov Wind Turbine for Model 2*

4.8 POWER GENERATION

The following formula proposed by **Sagnik** gives power generated by a turbine.

$$\text{Power} = k\ .\ C_p\ .\ ½\ .\ \rho\ .\ A_{rot}\ .\ V^3$$

Based on observed velocities at all optimum turbine locations, power generated estimation was carried out:

4.8.1 Generated power at VAWT

Based on obtained velocities and the selection of places that best suits the placement of turbine. The power generated for various wind velocities in Karachi has been shown below for each model.

4.8.2 Original Model

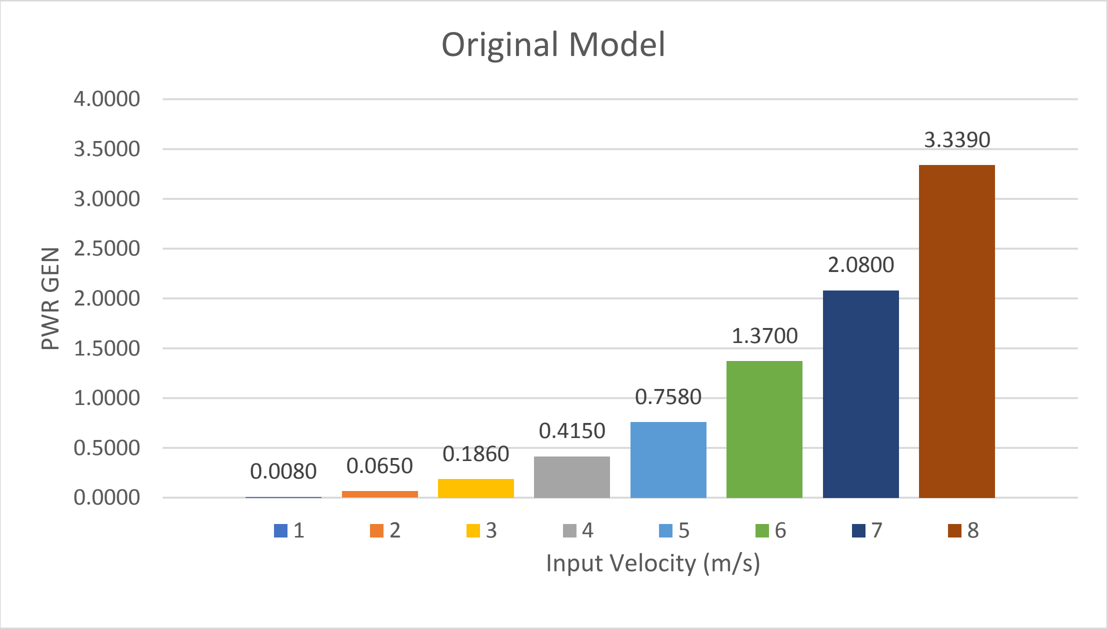

Figure 67 *Power Generated for Original Model Against Various Wind Speeds*

A tabulated form of the results is shown as follows:

Table 12 *Power Generated for Original Model Against Various Wind Speeds*

Input Velocity	**Power Generated**
1	0.0080
2	0.0650
3	0.1860
4	0.4150
5	0.7580
6	1.3700
7	**2.08**
8	3.3390

For the original model the roof was selected as the most ideal spot for the wind turbine placement. Based upon the computations carried out in the fore-mentioned table # 12 it was found out that for ambient conditions the energy generated was 2.08 **kW**

4.8.3 Revised Model 1

A Graphical representation is shown below for the estimated power output for the first revised model. Due to the similarity of observed wind velocities at the rooftop and the side edges the power estimation based on the proposed equation, were found to be equal. Therfore the estimation has been carried out for rooftop only to give us an idea of power generation.

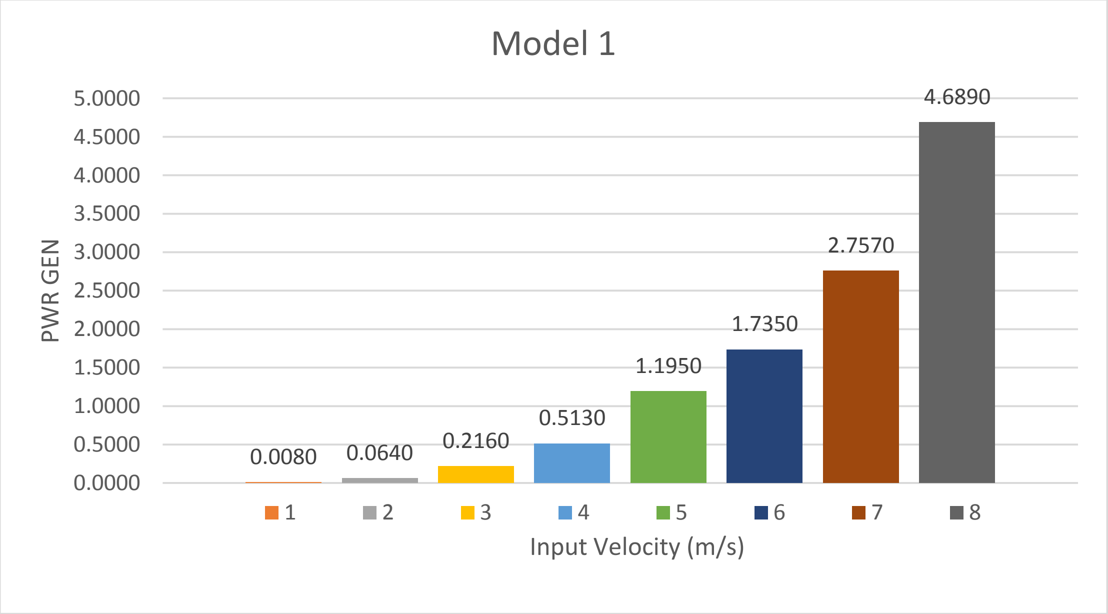

Figure 68 *Power Generated for Model 1 Against Various Wind Speeds*

The data is shown in tabulated form

Table 13 *Power Generated for Model 1 Against Various Wind Speeds*

Input Velocity	**Power Generated**
1	0.0080
2	0.0640
3	0.2160
4	0.5130
5	1.1950
6	1.7350
7	**2.7570**
8	4.6890

For the revised model 1 it was found out that both the edges and the roof of the structure were the ideal spot for the turbine placement. From the analysis it was observed that similar wind velocities were identical, and by placing of turbines on both the rooftop and t=on the edges of the building, both locations generated the same amount of power. The energy generated for our revised model 1 for ambient conditions was 2.76 **kW.**

4.8.4 Revised Model 2

Based on observed velocities and the placement of turbine for revised model 2 the power generated for various wind velocities was carried out a graphical representation of the results indicate very high power generated with this configuration of the building.

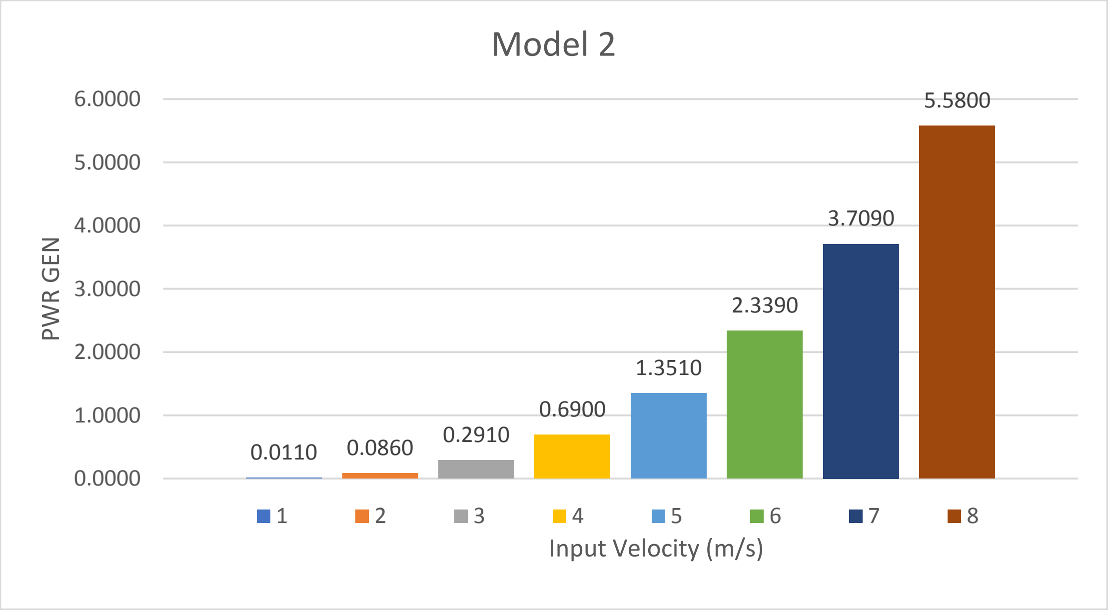

Figure 69 *Power Generated for Model 2 Against Various Wind Speeds*

For the final revised model 2 it was observed that the edges of the building behaved in the same manner as did in the case of our original model has no sufficient power development was observed

The data is shown in tabulated form

Table 14 *Power Generated for Model 1 Against Various Wind Speeds*

Input Velocity	**Power Generated**
1	0.0110
2	0.0860
3	0.2910
4	0.6900
5	1.3510
6	2.3390
7	**3.7090**
8	5.5800

So, the final selection for the placement of wind turbines was selected at the rooftop of the structure. The location was selected such that at velocities at ambient conditions and above an exponential increase in the power yielded was observed.

The observed velocities for the ambient conditions indicate a power generated of 3.7 **kW.**

4.8.5 Comparison of Power Generated by Each Model:

A comparison of all the models indicate that revised model 2 possesses the highest of the potentials to generate the maximum energy compared to all models at al speeds.

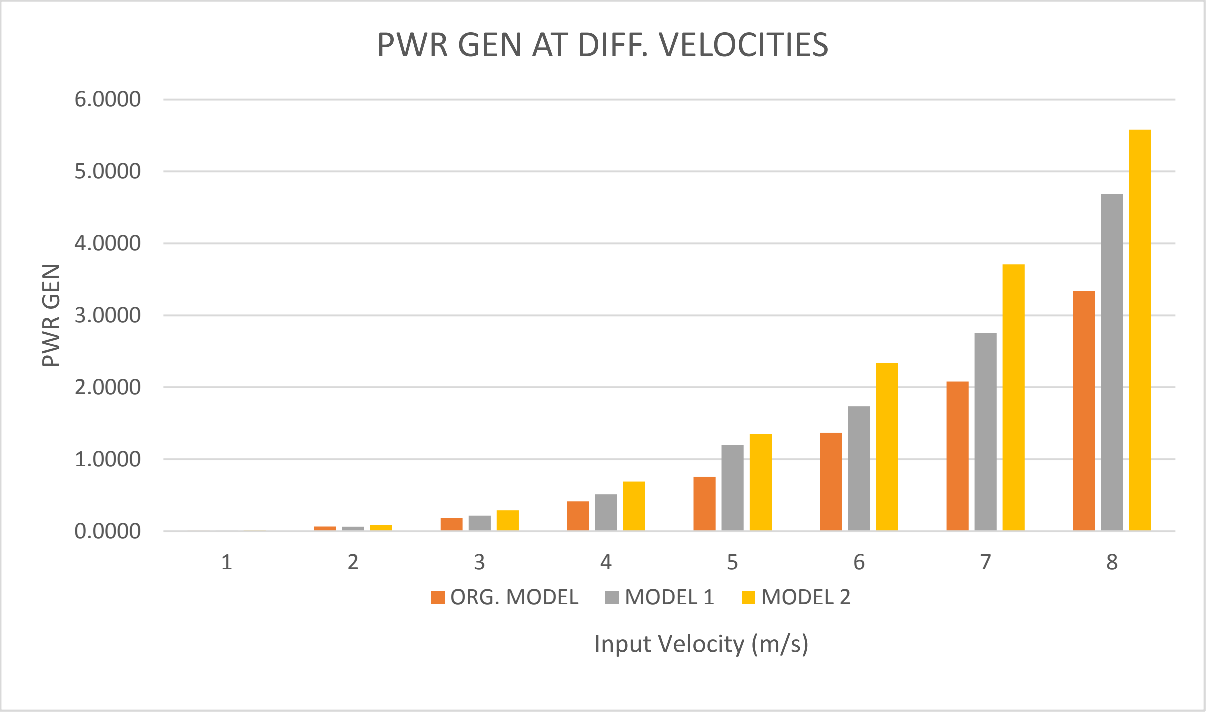

Figure 70 *Comparison of Power Generated by Each Model Against Various Wind Speeds*

The comparison charts indicate and as mentioned that for a small increase in the wind velocities the power generated increases exponentially *(section 4.8)*. This is quite evident for velocities of the range of 6 m/s – 8 m/s the power generated by revised model 2 is significantly greater than other models.

4.9 COST ANALYSIS

One of the most important factors in building construction is how to power the building and maintain it. The ever-increasing cost of electricity and the burgeoning construction of commercial buildings, especially high-rise buildings Is surely bound to affect Pakistan negatively. Pakistan already faces a power and energy shortfall and in coming years the demand will be too much to fulfill.

In order to check the cost effectiveness of the power generated by the wind turbines in our building a comparison was made against the production capacity of a wind turbine against the annual energy need of a regular Pakistani household. Graphical Representation of energy saving is shown in fig. #71. according to which if small scale wind turbines are augmented into a building **48.3 %** of energy of the residential apartments **c**an be saved which is equivalent to **4,861,800** RS/- annually.

The detailed calculations are attached as **Appendix - 2**

COST COMPARISON

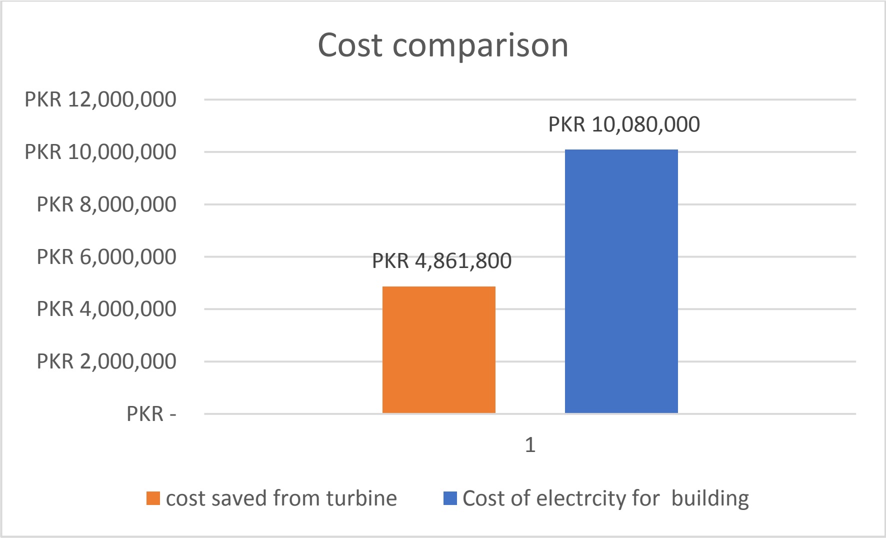

Figure 71 *Cost Saved from Turbines VS Cost Incurred using WAPDA*

This saving in cost is significant when a large number of BAWT’s are incorporated in the constructed buildings **Hagen (2014)**. Also, the return on investment for our case based on the study from Hagen shows that our project could give us a return within **2 years,** the calculations are shown in Appendix - 2.

CHAPTER 5

CONCLUSIONS

1. Based on the observed results and the energy calculations as shown in appendices , Model 2 shows the maximum power generation obtained per turbine. That is
2. Small increase in input velocity led to a large increase in power generation e.g., as observed for model #2, the power output increases from 3.7 kW @ 7m/s increased to 5.58 kW for 8 m/s. thus, confirming the findings of Y.G. Heo about geometrical concentration and how the geometrical configuration will greatly affect the power generation.
3. The observed power generation has been for one turbine only. However, if we increase the number of turbines the power generated could be increased at least by 3 folds for each model by increasing the number of turbines to a suitable limit.
4. The obtained results indicate that the roof and the edges of the building are the most optimum locations for turbines to be placed.
5. Facade of existing building needs to be properly optimized to harness maximum possible wind for power generation.
6. Based on the results from figure 37 and 48 the building has positive pressure on the front face of the building only and negative pressure on the remaining three sides. With our building located in Karachi where the climate is relatively hot and humid throughout the year. Positive pressure applied on the building is essential to keep the hot and humid air outside the building. Whereas the negative pressure will cause the outside hot and humid air and pollutants to be sucked inside the building. Thus, the temperature in the building would almost always be hot and humid throughout the year and will cause mold to form. This will cause property damage. Even the HVAC system would find it difficult to maintain a relatively cooler temperature and dry condition inside the building.

RECOMMENDATIONS

- Since building is under construction, yet to be completed. The devised model can be optimized to meet the geometrical configurations of model 2 to meet the geometrical requirements in order to produce sufficient electricity and making the building sustainable. The circular geometry could be used as overhead water storage tanks.
- The building should be analyzed against actual wind pressure to optimize structural design. Structure should be designed such that minimum negative pressure is observed on the building surface. This will help in reducing the cost incurred by extensive use of HVAC system in the building.
- To analyze experimentally the obtained results using wind tunnel experiments.
- Solar panels could be placed on the face of building to harvest solar energy and make building more sustainable

Prospects

- Studying the effect of downstream vortices generated on nearby buildings.
- Implementing Building Augmented Wind Turbines in construction.

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APPENDICES

APPENDIX - 2: DETAILED CALCULATIONS OF COST ESTIMATIONS

No. of Turbines Possible	6

Annual Energy Obtained for 6 Turbines			
Power (kW)	Energy (kWh)	Rs. Per unit	Cost Saved
3.7	194472	25	PKR 4,861,800

Turbines Installation Charges		
Turbine Cost $	Exchange Rate USD - PKR	Total Cost
55000	154	PKR 8,470,000

No. of Apartments	96

Annual Energy Consumption for whole building			
Power (kW)	Energy (kWh)	Rs. Per unit	Yearly Cost Rs/-
-	403200	25	PKR 10,080,000