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Probabilistic Reliability Analysis of Wind Turbines

(Master Thesis)

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Declaration

I hereby declare that all the information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, i worked on this master thesis independently and using only specified sources and programs which are referred.

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Acknowledgments

The past four months have been an exciting journey, dedicated to the last step in finishing my master studies. I would like to express my sincere gratitude to those who helped me during this period. Along the journey, i have met some incredible people, with whom i learned a lot about different aspects of life. Astonishingly, i also discovered a new perception towards life. These last few months will remain in some of my best days.

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Usman Zafar

Dedication

I love you beyond paint, beyond melodies, beyond words. And I hope you will always feel that, even when I'm not around to tell you so – Kiera Cass

family and friends

Abstract

Renewable energy use is on the rise and these alternative resources of energy can help combat with the climate change. Around 80% of the world's electricity comes from coal and petroleum however, the renewables are the fastest growing source of energy in the world. Solar, wind, hydro, geothermal and biogas are the most common forms of renewable energy. Among them, wind energy is emerging as a reliable and large-scaled source of power production. The recent research and confidence in the performance has led to the construction of more and bigger wind turbines around the world. As wind turbines are getting bigger, a concern regarding their safety is also in discussion. Wind turbines are expensive machinery to construct and the enormous capital investment is one of the main reasons, why many countries are unable to adopt to the wind energy. Generally, a reliable wind turbine will result in better performance and assist in minimizing the cost of operation. If a wind turbine fails, it's a loss of investment and can be harmful for the surrounding habitat. This thesis aims towards estimating the reliability of an offshore wind turbine. A model of Jacket type offshore wind turbine is prepared by using finite element software package ABAQUS and is compared with the structural failure criteria of 0.4 m deflection of the wind turbine tower. UQLab, which is a general uncertainty quantification framework developed at ETH Zürich, is used for the reliability analysis. Several probabilistic methods are included in the framework of UQLab, which include Monte Carlo, First Order Reliability Analysis and Adaptive Kriging Monte Carlo simulation. This reliability study is performed only for the structural failure of the wind turbine but it can be extended to many other forms of failures e.g. reliability for power production, or reliability for different component failures etc. It's a useful tool that can be utilized to estimate the reliability of future wind turbines, that could result in more safer and better performance of wind turbines.

Keywords: Reliability, Wind Turbines, First Order Reliability Analysis Method, Adaptive Kriginig Monte Carlo, ABAQUS

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Nomenclature

List of Symbols

A	Swept area of rotor blades	[m^2]
A_t	Projected tower area perpendicular to the wind direction	[m^2]
A_m	Cross-sectional area of member	[m^2]
B	Width of the tower, measured normal to the wind direction	[m]
C_d	Drag coefficient	[-]
C_f	Force coefficient	[N]
C_m	Inertia coefficient	[-]
C_p	Power coefficient or Betz coefficient	[-]
D	Diameter of rotor	[m]
D_m	Diameter of member	[m]
D_t	Diameter of the tower	[m]
F	Force per unit length of the member	[N/m]
F_{wa}	Wave force per unit length of the member	[N/m]
F_{wi}	Wind force acting on a tower of a wind turbine	[N]
G	Gust-effect factor	[-]
g_q	Peak factor for background response	[-]
g_r	Peak factor for resonance	[-]
g_v	Peak factor for wind response	[-]
h	Height of the structure	[m]
H_s	Design wave height in normal sea state	[m]
H_{s1}	Measured significant wave height with recurrence period of 1 year	[m]
H_{s50}	Measured significant wave height with recurrence period of 50 years	[m]
$H_{s,NSS}$	Design wave height in normal sea state	[m]
$H_{s,ESS}$	Design wave height in extreme sea state	[m]
H_1	Design wave height with recurrence period of 1 year	[m]

H_{50}	Design wave height with recurrence period of 50 years	[m]
I	Importance factor	[-]
I_{ref}	Expected value of turbulence intensity at 15 m/s	[-]
I_z	Turbulence intensity at 10 m	[-]
K_d	Directionality factor	[-]
K_z	Exposure coefficient	[-]
n_1	Natural fundamental frequency of wind turbine tower	[Hz]
P	Power contained in the wind source	[watts]
P_a	Power that can be extracted from the incoming wind	[watts]
P_f	Probability of failure	[-]
Q	Background response factor	[-]
q_z	Wind velocity pressure	[N/m^2]
R	Resonance response factor	[-]
R_s	Reliability	[-]
$V(z)$	Wind speed at height z	[m/s]
T	Wave time period	[s]
T_p	Peak spectral time period of a wave	[s]
V	Wind speed with 3 seconds averaging time	[m/s]
V_{ave}	Annual average wind speed at hub height	[m/s]
V_{e1}	Extreme wind speed with a recurrence period of 1 year	[m/s]
V_{e50}	Extreme wind speed with a recurrence period of 50 years	[m/s]
V_{gust}	Wind gust speed	[m/s]
V_{hub}	Wind speed at hub height	[m/s]
V_{ref}	Reference wind speed	[m/s]
U	Flow velocity	[m/s]
$\ddot{U}$	Flow acceleration	[m/s^2]
z_g	Gradient height	[m]
ρ	Density of air	[kg/m^3]
ρ_w	Density of water	[kg/m^3]
v	Mean wind speed at a particular area	[m/s]
σ	Standard deviation	[m/s]
Λ	Turbulence scale parameter	[m]
ζ	Structural damping ratio	[-]
β	Shape factor for Weibull distribution	[-]

β	Reliability index	[-]
η	Scale parameter	[-]
μ	Mean factor or mean values	[-]
λ	Scale parameter	[-]
γ	Location parameter	[-]

List of Abbreviations

FORM	First order reliability analysis method
FMEA	Failure modes and effects analysis
FMECA	Failure modes, effects and criticality analysis
GBS	Gravity based structure
GWh	Gigawatt hour
HAWT	Horizontal axis wind turbine
kW	Kilowatt
kWh	Kilowatt hour
MCS	Monte Carlo simulation
MW	Megawatt
MWh	Megawatt hour
SORM	Second order reliability analysis method
SLS	Serviceability limit state
ULS	Ultimate limit state
VAWT	Vertical axis wind turbine
WPD	Wind power density

List of Organizations

ASTM	American Society of Testing Materials
AWEA	American Wind Energy Association
BSH	Bundesamt für Seeschiffahrt und Hydrographie
DNV GL	Det Norske Veritas & Germanischer Lloyd

DTU	Technical University of Denmark
DWD	Deutscher Wetterdienst
EIA	Energy Information Administration
GWEC	Global Wind Energy Council
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
IRENA	International Renewable Energy Agency
NREL	National Renewable Energy Laboratory

Chapter 1

Thesis Introduction

1.1 Background

Wind is not a new term for mankind and its use has been traced back from the medieval times in which it was mostly used for propelling boats and pumping water. In earlier times, smaller windmills were also used for agriculture and electrical purposes. The reasons for the power industry to shift from traditional sources (coal, petroleum, nuclear and hydro) to renewable energy was the depletion of the resources and adverse environmental effects. Wind energy on the contrary is plentiful, clean and renewable with less problematic effects on the environment. In twentieth century, wind industry begin to flourish which evolve into onshore and offshore wind turbines. Onshore wind turbines are often criticized for aesthetics and community noise pollution. However, offshore wind turbines have resolved the aesthetics and noise pollution issues as they are constructed very far from the habitat land. New wind turbines are huge and complex machines, which are equipped with sophisticated devices and sensors which are capable of producing up to 10 MW and higher power. Countries like USA, Germany, China, United Kingdom and Denmark are among top contributing countries who are developing wind energy as a mainstream source of power generation.

From the last decade, wind turbines are getting bigger and higher. The enormous scale of these turbines has raised the concerns over safety and serviceability of these machines. Due to harsh and unpredictable marine environment, offshore wind turbines are more prone to the failure than the onshore wind turbines. Reliability analysis is often considered in the designing phase prior to the installation of offshore wind turbines. Several codes for the safer design of the wind turbines have also been prepared. The main aim of this study is to extract information and application of reliability theorems on an offshore wind turbine model so that the serviceability of the wind turbines can be predicted.

1.2 Objective and Scope

The rapid expansion in the wind industry has also increased the probability of failure of wind turbines. Different modes of failure can occur with wind turbines which include structural failure, mechanical components failure, material failure and fatigue. Any mode of failure in these massive structures can lead to the high cost of maintenance and can even affect the overall workability of wind turbines. For this research work, a 5 MW Jacket type offshore wind turbine and a structural failure mode is selected. Wind loads and Modulus of elasticity are the two parameters which are chosen for the reliability analysis. In this Master thesis, following tasks are analyzed and processed:

1. Literature review of wind turbines and their failure modes. Review of probabilistic methods to assess failure probabilities,
2. Development of a Jacket type offshore wind turbine using ABAQUS,
3. Selection of critical parameters which can contribute to selected failure modes of wind turbines,
4. Assessment of failure probabilities by applying different methods for failure probability estimation (e.g. using UQLab by ETH Zürich),
5. Application of different methods: Among them: First Order Reliability Method (FORM), Adaptive Kriginig Monte Carlo (AK–MC).

1.3 Organizational Scheme

This thesis is comprised of six chapters. The introduction, scope and organizational paradigm is presented in the first chapter. The literature review of wind turbines, their failure modes are explained in the second chapter. Chapter three is the description and review of different probability methods. Finite element modeling of Jacket type offshore wind turbine is explained in the chapter four. Chapter five includes the application of failure probability techniques along with the conclusion. Some future aspects of wind technology in Pakistan is also presented in the final and the last chapter.

1.4 Softwares Used

The following computer programs are used for this thesis:

1. **ABAQUS**, used for finite element modeling of Jacket type wind turbine,
2. **Matlab**, general purpose usage for probabilistic theorems and reliability analysis,
3. **UQLab**, a Matlab tool prepared by the ETH Zürich, used for the reliability analysis,
4. **Pyhton**, for writing scripts for ABAQUS and running simulations,
5. **Excel**, general purpose usage for calculation and graphing.

Chapter 2

Literature Review of Wind Turbines

2.1 Wind Turbines

Wind turbines are machines that use wind energy to generate electricity. They convert the kinetic energy contained in the wind into mechanical power by using strong and advanced aerodynamic rotor blades. This mechanical power is fed into the generators which in turn rotates and produces electricity. Some evidence suggests that wind has been using since medieval times some 3000 years ago. History has also shown the presence of wind vanes on the many old ships, which researchers relate to the earlier use of wind for propelling boats. In earlier times, humans were using small-scaled windmills for agricultural, irrigation and navigation purposes. The fossil fuels were the main source for power production among earlier communities. The effects of burning fossil fuels were unknown but with the evolution and development in the science and technology, it was evident that fossils fuels had damaging and adverse effects on the environment. Social and eco-environment consciousness spread around many countries demanding for a new reliable and clean source of energy. Coal and natural gas are still the most common and cheapest form of power production in the world. By the 19th century, the oil and gas industry was developing at an enormous rate and most of the early wind turbines concepts and designs were adopted from the oil and gas industry. Countries like USA, Denmark, Germany and United Kingdom invested in many research programs which evolved into modern high tech offshore wind industry. Technological advances of the the modern world is allowing wind industry to install higher and bigger wind turbines and in deeper waters than ever before. Many researchers consider wind energy as a potential source in meeting the world's future electricity demands.

Wind energy, is an alternative resource to coal, petroleum, nuclear and other resources which is more abundant, renewable, widely distributed and has fewer damaging effects on the environment. Wind turbines have proven to be efficient in their performance but one of the main hindrance in adopting it as a mainstream source of power is that they are expensive to construct and often requires advanced equipment. Usually, around 75% of the total cost of the project is the capital cost that buyers have to be pay upfront. The overall cost is decreasing at a very encouraging rate for both consumers and investors. The output of electricity is hugely dependent on the available wind speed. Oceans have generally more wind speeds as compared to the land so an average output of an offshore wind turbine is higher than its counterpart and that is the main reason that the offshore wind turbines are constructed more often than onshore wind turbines. The Figure 2.1 shows the global energy production statistics of different energy resources as of 2017.

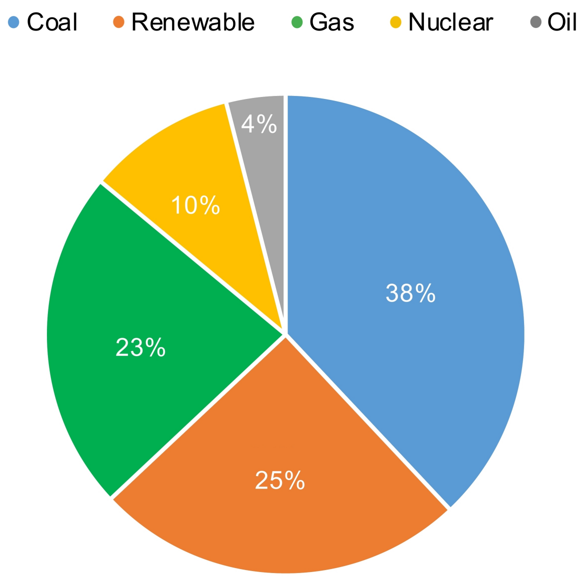

Figure 2.1: Global energy production statistics as of 2017, Source: IEA [1]

2.2 History of Wind Turbines

For thousands of years, humans have been known to use wind energy mostly for domestic and minor works. The ruins of the oldest construction site can be found in Persia dated back 6th century BC, which indicate that earlier windmills were made from wood and reeds attached to a central vertical pole [2]. The first ever wind turbine was built by the American scientist Charles Bush in 1888. New ways to use wind energy as a reliable and commercial source of power started around 1990's. In 1903, the Wright Brothers successfully invented the first airplane. The concept of onshore wind turbines blades originated from the airplane wings. Scientists and researchers were successful in adopting the technology of airplane propeller system to wind turbines. However, due to limitations in technology and machinery at that time, power generation remained limited only to onshore wind power [2].

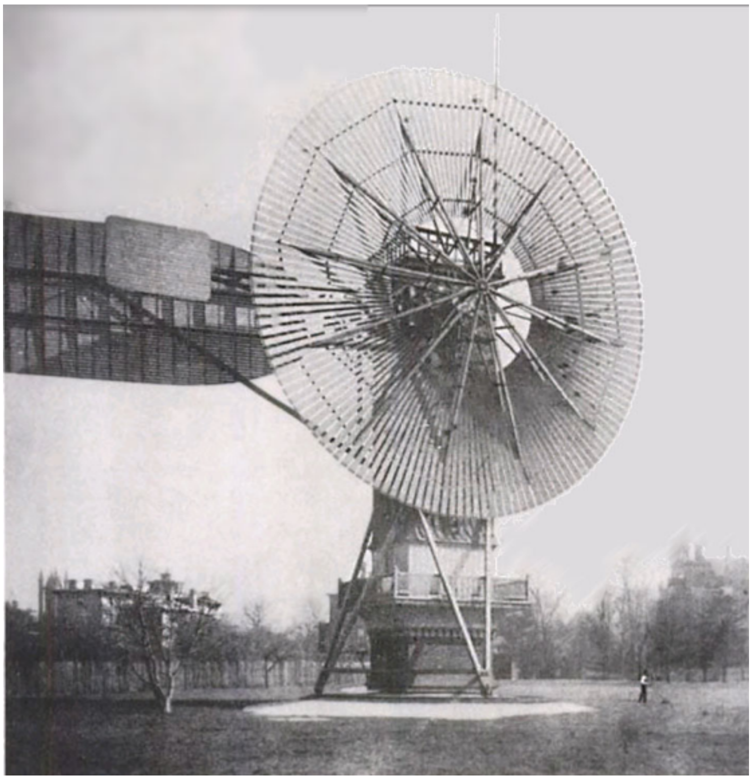

Figure 2.2: First windmill built by Charles Bush in 1888 [3]

The first commercial offshore wind farm was built in Denmark in 1991. It was named as *Vindeby* and operated 1.5 to 3 *km* off the Danish coast. It had 11 wind turbines each of 450 kW capacity capable of producing 4.95 MW. Vindeby generated 243 GWh of power in its 26 years lifespan. Dong Energy decommissioned them in February 2016. It is also worth mentioning that in 1995, after 4 years of successful operation of Vindeby, Denmark constructed its second offshore wind farm *Tunoe Knob*. This offshore wind farm had a power of 5 MW consisted of 10 Vestas wind turbines each of 500 kW. Holland was the first country to adopt to offshore wind power after Denmark. In 1994, they also constructed their first offshore wind farms in the waters of Lake IJsselmeer. After Vindeby and Tunoe Knob projects, wind industry started to expand to other countries but mostly it remained in the European waters. Still, Europe leads the wind power industry with contribution of 33% of global energy production [4]. Sweden, United Kingdom and Denmark joined in early 2000's. In 2000, Denmark constructed an offshore wind farm *Middelgrunden* which is considered the first mega and state of the art wind farm. It was constructed in the port of Copenhagen with the total cost of 54 million euros with a rated power of 40 MW [2]. *Walney Wind Farm* is the largest offshore wind farm constructed in the Irish sea, United Kingdom. It is constructed in 3 phases with 189 turbines capable of producing 659 MW to supply electricity to 600,000 homes in United Kingdom [5]. General Electric has developed a 12 MW offshore wind turbine which is the largest offshore wind turbine as of today.

Table 2.1 shows some of the earliest installed offshore wind farms in the world.

Figure 2.3: Vindeby, the first commercial offshore wind farm in Denmark [2]

Table 2.1: List of earliest installed offshore wind farms [2]

Name	No of Turbines	Rated Power	Year	Country
Vindeby	11	450 kW	1991	Denmark
Lely	4	500 kW	1994	Holland
Tunoe Knob	10	500 kW	1995	Denmark
Irene Vorrink	28	600 kW	1997	Holland
Bockstigen	5	500 kW	1991	Sweden
Blyth	2	2 MW	1998	England
Middengrunden	20	2 MW	2000	Denmark
Utgrunden	7	1.4 MW	2000	Sweden
Yttre Stengrund	5	2 MW	2001	Sweden

2.3 Important Terminologies of Wind Industry

In this section, a brief introduction of definitions and terminologies that are used in the wind industry are explained.

2.3.1 Wind Power

A measure of available energy at any location is called the Wind Power. The power contained in a wind is "P" and power that can be extracted from the incoming power of wind "P_a" power is calculated by the Eq. 2.1:

$$P_{\mathrm{a}} = \frac{1}{2}\rho A v^3 C_{\mathrm{p}} \tag{2.1}$$

where,

ρ	=	*specific density of air, (kg/m^3)*
A	=	*swept area of rotors, (m^2)*
v	=	*wind speed, (m/s)*
C_p	=	*power coefficient, (–)*

The Eq. 2.1 shows that the power output of wind turbine depends directly on the third power of wind speed, so it is more profitable to build a wind farm where the wind speeds are higher rather than constant.

2.3.2 Power Coefficient

Power Coefficient "C_p" is the measure of the efficiency of a wind turbine. The German physicist *Albert Betz* concluded in 1919 that no wind turbine can convert more than 59.3% of the kinetic energy of the wind. This is due to the reason that wind on the back side of rotors must have a high velocity to move away and allow more wind to the plane of the rotor that creates an imbalance between different wind speeds. It is also noted that the Betz limit is actually the theoretical maximum value that no wind turbine can achieve. Practically, this value is around 35% to 40% [6].

2.3.3 Wind Profile

Wind is unpredictable in nature and wind speed has a dependency on time and location. Wind speed varies during the time of the day as well as with the surface roughness of different sites. On seas and oceans, higher wind speeds are available as compared to the land. At lower altitudes, wind speeds are higher in day time than in nights and at higher altitudes, wind speeds are higher in nights than in the day time. This different behavior can be counted for the more temperature change near the surface than the higher altitudes where temperature exchange between different air layers is not very significant.

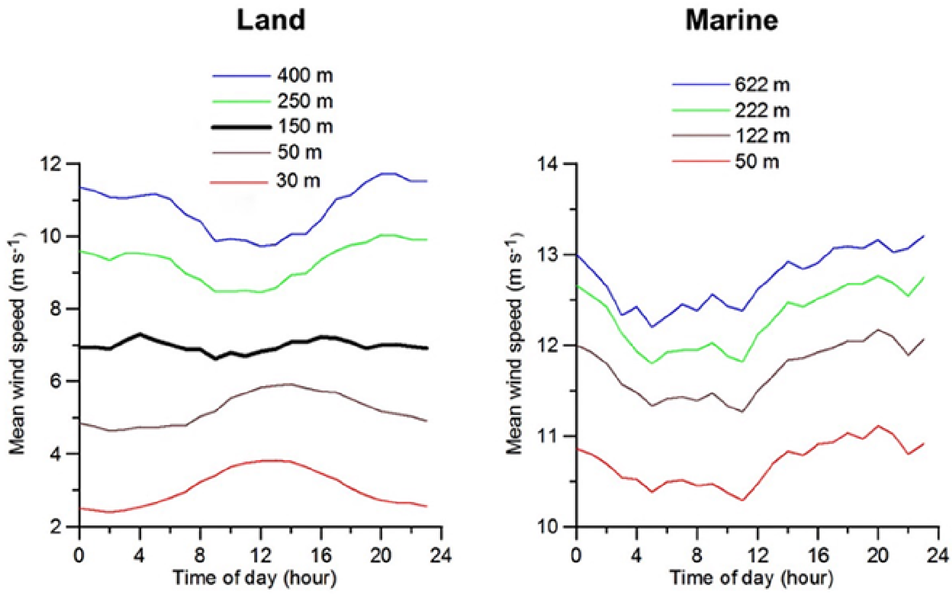

Figure 2.4: Variations of wind speeds with heights, surfaces and times of a day [7]

2.3.4 Wind Power Density

Wind power density (WPD) is an important parameter to determine the potential for harvesting wind energy at a particular area. It assists in the preliminary investigation process for the selection of best suited sites for the future wind farms. Wind turbines that are installed in areas having higher WPD will generate more electrical energy. WPD can be calculated as:

$$WPD = \frac{1}{2}\rho v^3 \tag{2.2}$$

American Wind Energy Association (AWEA) categorizes WPD into 7 different classes, which rank the resource potential from being poor to superb. The Table 2.2 shows the wind power classes and their characteristics.

Table 2.2: Wind power density classification, Source: AWEA

Wind Power Class	Resource Potential	WPD at 50 m	Wind Speed at 50 m (m/s)
1	Poor	0 - 200	0 - 6
2	Marginal	200 - 300	6 - 6.8
3	Fair	300 - 400	6.8 - 7.5
4	Good	400 - 500	7.5 - 8.1
5	Excellent	500 - 600	8.1 - 8.6
6	Outstanding	600 - 800	8.6 - 9.5
7	Superb	> 800	> 9.5

2.3.5 Wind Turbine Speed's

The performance and safety of the wind turbine depends on the wind speed. The International Electrotechnical Commission (IEC) has specified three sets of wind speeds for evaluating performance and reliability of a wind turbine. Generally, the wind turbine manufactures provide these three speeds [8],

1. **Cut-in speed**. It is the speed at which the wind turbine blades start to rotate and generate electrical power. At very low wind speeds, due to the weight and insufficient power available, wind turbine blades are unable to rotate. As the speed increases, wind turbine will get sufficient torque to rotate and generate electrical power. The cut-in speed is typically between 3 and 4 $m/$s.

2. **Rated output speed**. As the wind speed increases above the cut-in speed, the electrical output power also increases rapidly. Typically between 12 and 17 $m/$s, the power output reaches the maximum limit that the electrical generator is capable of producing. This limit of the generator output is called the rated power output and the wind speed at which it is reached is called the rated output speed.

3. **Cut-out speed**. This is the maximum operating speed of a wind turbine beyond which, turbine faces very high forces that can risk its stability. All the turbines are equipped

with automatic or manual braking system. At cut-out speed, braking system is applied which brings them to standstill. The cut-out speed is usually about 25 $m/$s.

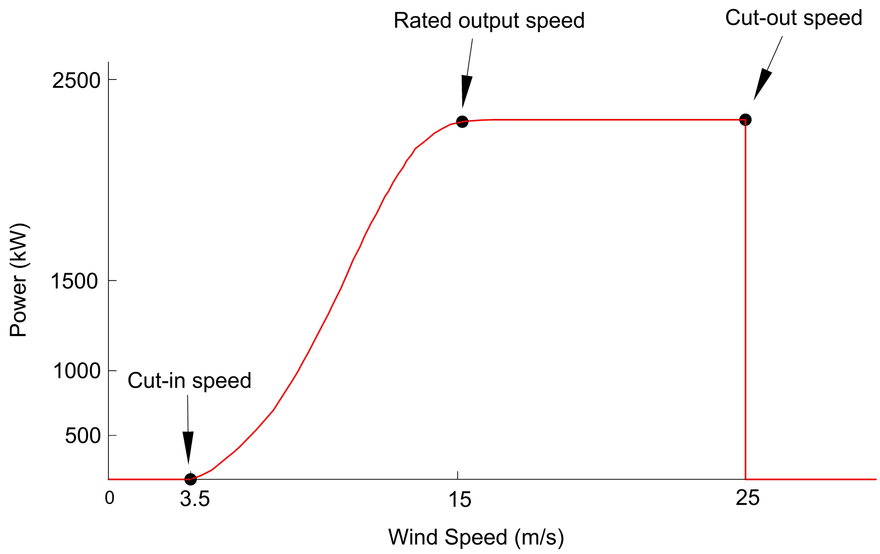

Figure 2.5: Power curve of a wind turbine [9]

2.4 Wind Turbine Cost Figures

The cost of a wind turbine varies from each design and specification but the biggest cost is the turbine itself. This is a capital investment that buyers have to pay upfront which is around 75% of the total cost of the project. The operational and maintenance costs are minimal as compared to the overall cost of the project. For the wind turbine, the largest cost components are the rotor blades, the tower and the gearbox which altogether contributes to around 50% to 60% of the cost of a wind turbine. The electrical components like generator, transformer and power converters accounts for about 13% of the turbine costs [10].

According to International Renewable Energy Agency (IRENA), the typical installation cost of an onshore wind turbine in 2010 was between 1800 to 2200 USD per kW, while offshore wind turbine stood between 4000 to 4500 USD per kW. From 2004 to 2010, the prices of wind turbines continued to rise, however since 2010 a reduction in the cost has been observed. The reasons for this reduction is the improved design, overall better performance of turbine components and reduction in steel and carbon prices in the global markets [10]. The Figure 2.6 shows breakdown of the cost share by different components of an offshore wind farm and a wind turbine.

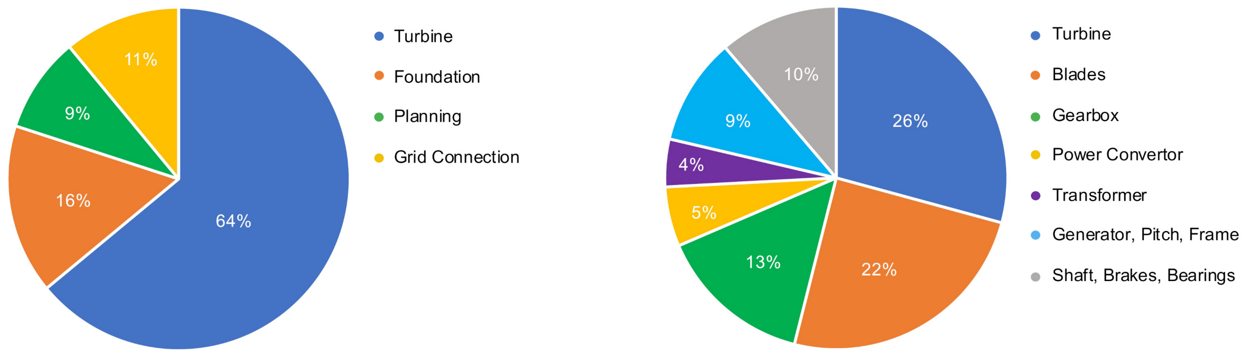

Figure 2.6: Cost breakdown of an offshore wind farm (left) and a wind turbine (right) [10]

2.5 Current Developments and Future Scope

Rapid growth was followed after Vindeby installation in 1991 and offshore wind energy expanded to the European markets. Denmark, USA and Germany were pioneers in adopting to the offshore wind energy. After Denmark and Germany, the market broadened to Italy, Netherlands, UK and Sweden. At the end of 2000, a new era begun for offshore wind energy. New and big markets were emerged from India, China, Argentina, Brazil and Mexico [4]. Global markets have seen 95% increase as of 2016 with 4,334 MW added additionally in 2017. There are now 17 active and growing offshore wind energy markets in the world producing 18,814 MW of power. 84% of the all offshore wind farms are located in the waters of 11 European countries and the remaining 16% are located in China, USA, Japan, Taiwan and South Korea. The UK is world largest offshore wind market with share of over 36% of global capacity installed, followed by Germany with a share of 28.5%, China comes third with 15% and Denmark at 6.8% [4]. According to Intergovernmental Panel on Climate Change (IPCC) report, *"by the end of 2050, 80% of the world's energy supply could come from renewable sources and wind energy will play a major role in electricity generation in 2050"* [3]. Due to the limitations of locations, visual effects, noise problem and bird's habitat issues, onshore wind industry has faced major shortfalls as compared to the offshore wind turbines. Offshore wind industry is more likely to be established as a mainstream source of energy around the world but the straight upfront capital cost has been a subject of reluctance for many countries. However, the costs have also fallen decisively with the recent research and its very likely to generate electricity at a levelized and very affordable prices [4].

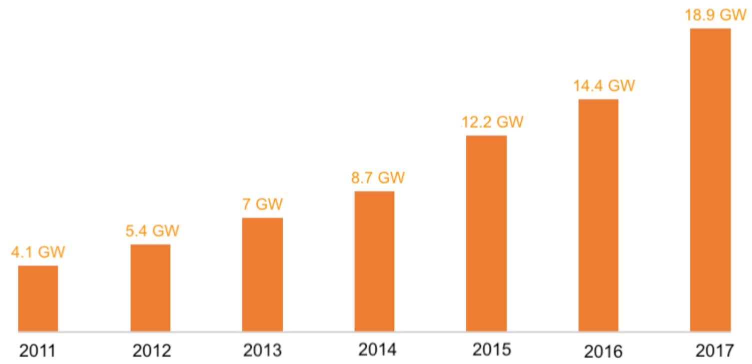

Figure 2.7: Cumulative offshore wind capacity 2011 to 2017, Source: GWEC [4]

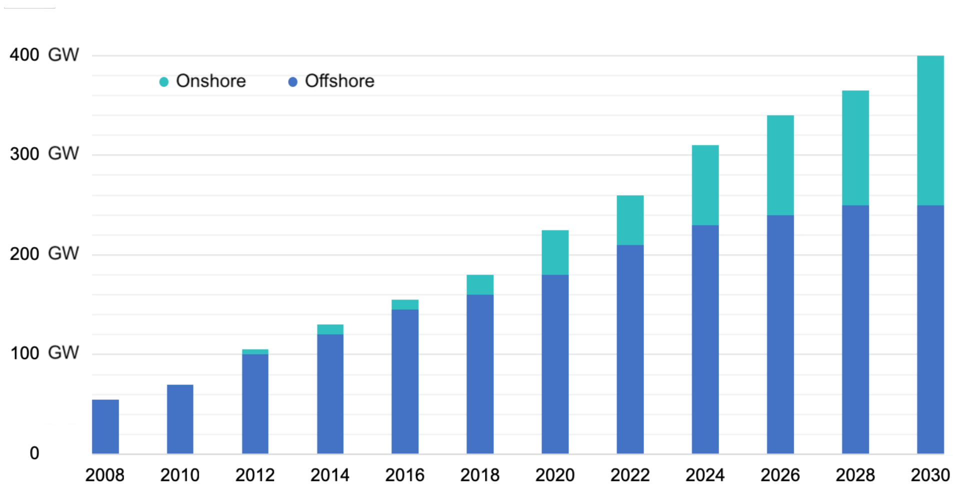

Figure 2.8: Future targets of wind energy in Europe till 2030 [3]

2.6 Foundations of Wind Turbines

The term foundation in the wind industry is considered as a whole structure which is below the water table. The purpose of the foundation is to safely transfer the loads to the seabed and ensure the stability of a wind turbine within permissible deflection limits. Foundation bears a lot of different loads including dead loads, wind loads, up thrusts, overturning bending moments, vibrations and long-term cyclic wave loadings [11]. There are various type of foundations that are used in the wind industry. They are classified on the mechanism that how they are connected to the seabed and choice of the foundation depends on the water depth at a particular site [12].

Monopile, The monopile support structure is most common type of foundation in which the tower is supported by the monopile. It is made of a hollow cylindrical steel tube with diameters up to 6 m and outer thickness of 150 mm. They are suitable for shallow to medium water depths up to 30 m [13].

Tripod, The tripod foundations are one of the heaviest foundations. Three corner piles are installed at each leg position and anchored with the seabed. The anchoring provides a good stability and stiffness against lateral loads. They are suitable for water depths up to 20 to 80 m which can become uneconomical when used for shallow water depths [13].

Jacket, A jacket structure is a three or four-legged steel structure which are interconnected with welded steel sections. They are heavy structures and installed where water depth is around 20 to 50 m. They consist of corner piles interconnected with bracings with a diameter up to 2 m. Bracings provide good stiffness against the lateral loads.The piles are driven inside the pile sleeve to the required depth to gain stability for the structure [13].

Gravity Based, The gravity type support structure is a concrete based structure and are preferred where the ground is so hard for the piles to penetrate. Gravity foundations are 2 to 3 m below the ground surface, and are rectangular, circular or octagonal in shape. In general, gravity foundations are designed to utilize the huge self-weight to prevent wind turbine from tipping over. No drilling or hammering is required in gravity based foundations [13].

Suction Bucket, This type of foundation has a reverse bucket made up of steel usually with large diameters up to 10 m. The suction bucket is lowered into the sea and water is pumped out of the bucket to lower the pressure inside the bucket skirt. The resulting negative pressure and weight of foundation causes the foundation to sink in to the sea floor. Suction bucket foundation is suitable for installing bigger turbines. It can be installed in a wide variety of site conditions including sand, silt, clay and layered strata.

Floating, The floating wind turbines are new and progressive form of structures that are adopted from the oil and gas industry. Four main types of floating foundations are known so far i.e. spar, semi-submersible, tension leg platform and barge as shown in Figure 2.10. They consist of a long cylindrical buoy at the bottom filled with ballast. They are suitable for deep waters. The tension leg platform is a semi-submerged turbine and tethered to the seabed by the vertical tension anchors. One of main reasons for the growing interest in the floating wind foundations is the saving of material specially when turbines have to install in deep waters [13, 14].

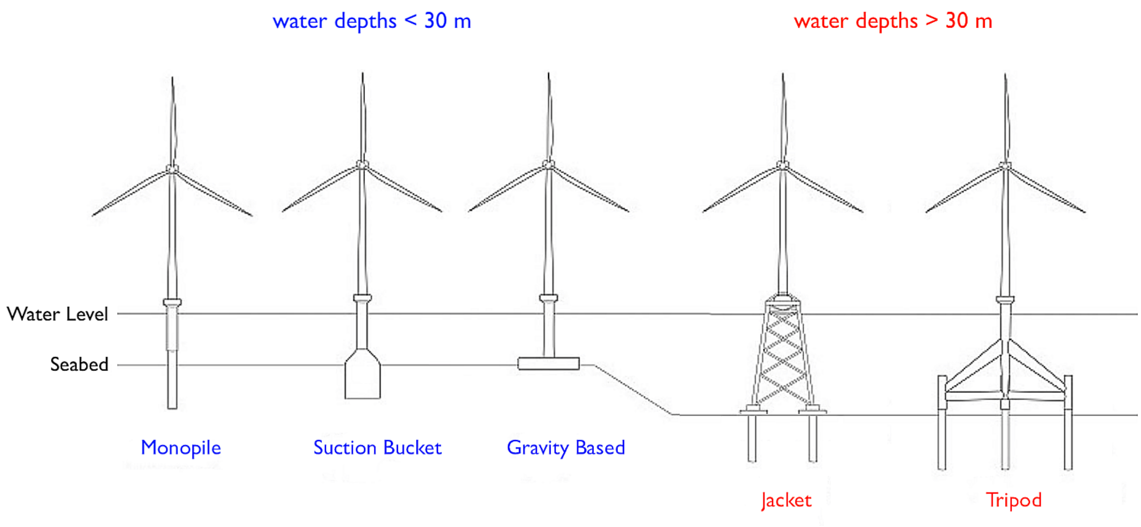

Figure 2.9: Different types of foundations for wind turbines [15]

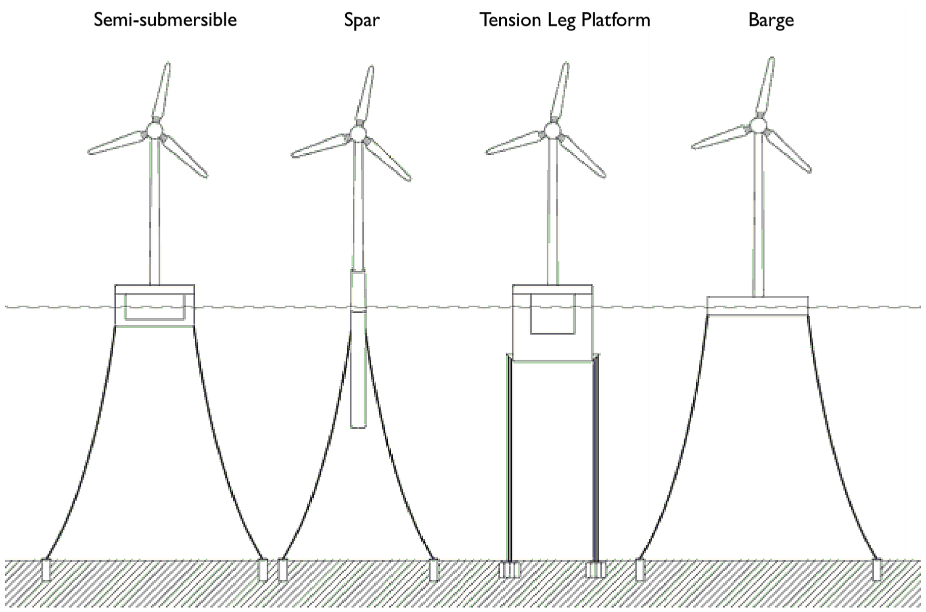

Figure 2.10: Four common types of floating wind turbines, Source: DNV GL

2.7 Towers of Wind Turbines

The purpose of the tower is to carry the wind turbine. It carries the weights of the nacelle, the rotor blades, yaw assembly and all the electrical components. It must also absorb the huge wind and vibration loads and safely transfer them to the foundation. Generally, a tubular section of concrete or prefabricated steel is used. Concrete towers are strong but expensive and steel towers allow higher turbine construction. True vertical alignment is the core part of the installation of a wind turbine tower and misalignment of the tower can result in catastrophic failure of the structure. Figure 2.11 shows the different types of towers that are used in the wind industry.

The towers are conical in shape to increase their strength and to save material. The advantage of steel towers against concrete towers is the reusability of steel after the lifespan service of wind turbine. Higher construction of a wind turbine is also possible in steel towers whereas, the concrete towers of about 80 m become uneconomical. Lattice towers are manufactured using welded steel sections. They are cheaper to construct and requires only half as much material as a tubular tower with a similar stiffness. Lattice towers have almost disappeared from the industry due to the aesthetic reasons. The hybrid tower is a combination of different tower materials. It can either be a combination of steel and concrete or steel lattice and concrete. Generally, it consists of two parts which are different from each other and are connected through an adaptor ring [16].

Figure 2.11: Types of wind turbine towers [16, 17]

2.8 Loads on a Wind Turbine

Wind turbines face a variety of loads during their entire lifespan and the design process requires special attention for the load calculations. Accurate analysis and prediction of these loads is always crucial to avoid failure of the wind turbines. International Electrotechnical Commission (IEC) and Det Norske Veritas and Germanischer Lloyd (DNV GL) are the two leading organizations that have developed international codes and standards for the wind turbines. IEC 61400-1/-2 are developed for onshore and IEC 61400-3 is solely prepared for offshore wind turbines. The wind industry has divided different loads into three major categories i.e, environmental loads, action loads and structural loads.

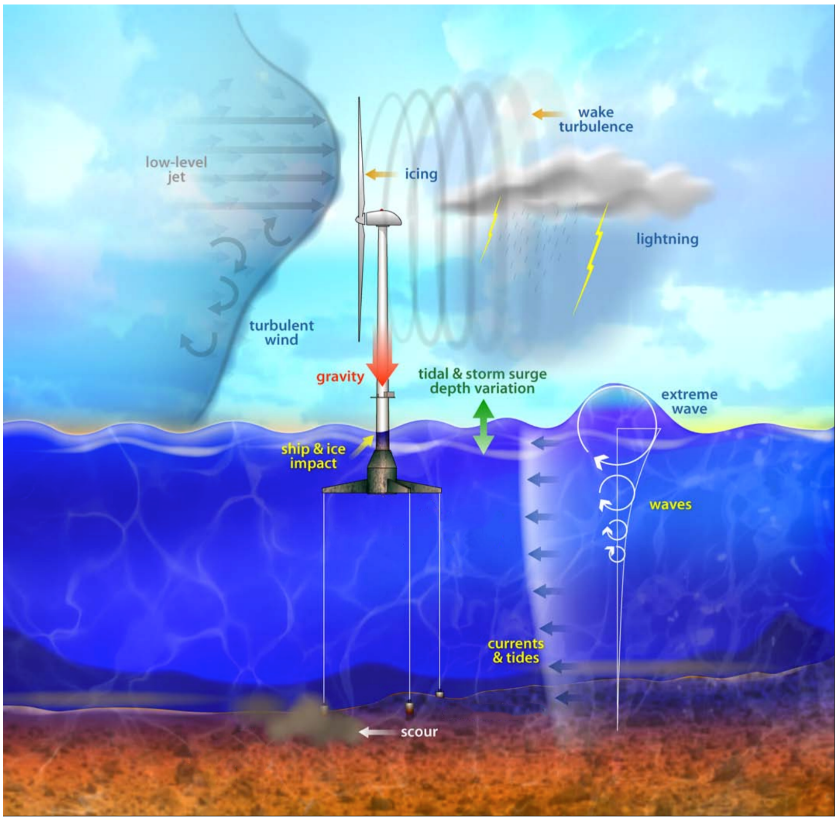

Figure 2.12: Loads on an offshore wind turbine, Source: NREL [18]

Environmental loads are mostly random in nature and often require probabilistic approach to quantify them. These include wind loads, wave loads, scour movement and snow loads. For the long-term behavior of wind turbines air temperature, humidity, solar radiation, water density, water temperature and maritime traffic loads are also included in the design calculations. **Action loads** are the response of environmental loads. The mechanical braking system, yaw motion control systems generate vibrations which are classified as action loads. In addition, aerodynamic and hydrodynamic loads are also categorized as applied loads which arise due to the wind and wave currents. Dead loads of the structure that includes foundations, tower and turbine assembly (rotor and nacelle) are classified as **Structural loads**. Auxiliary structures which are used for operation, maintenance and emergency services are also structural loads [19].

2.8.1 Wind Load

Wind turbine is a dynamic system that is subjected to huge wind loads that transforms into fatigue loads. The safety of wind turbine depends on the safe transferring of all the wind loads, which makes the wind load a critical factor in the designing of wind turbines. Wind is random and unpredictable in both speed and direction, which is always accompanied by wind gusts and wind storms. These variations of wind generates additional aerodynamic loads, which if ignored can cause failure of the turbine. According to IEC and DNV GL, wind turbines are designed with all the uncertainties and stochastic variations to withstand all the loads in their 20-year lifespan [20].

IEC characterizes two wind conditions to be inspected for a specific region i.e. normal and extreme wind conditions. Normal wind conditions are associated with the mean wind speed and extreme wind conditions take peak wind speeds into the consideration. Wind speed data at different altitudes are usually available at local metrological department or can be acquired online. Wind loads are calculated in the load-time series. During the 20-year lifespan of a wind turbine, it faces around 10 million cycles of loads, so quantify the load-time series for such long duration, it becomes impractical to process it. To overcome this time-consuming process, structural engineers use simplified load distributions models. These models require stochastic approach, which includes all uncertainties and variations to get the equivalent wind loads acting on a wind turbine [20, 21]. In a normal wind condition, Eq. 2.3 and Eq. 2.4 are used to calculate average wind speed and standard deviation.

$$V(z) = V_{\text{hub}} \left(\frac{z}{z_{\text{hub}}} \right)^{0.14} \quad , \tag{2.3}$$

$$\sigma = I_{\text{ref}} \left(0.75 V_{\text{hub}} + 5.6 \right) \quad , \tag{2.4}$$

where,

$V(z)$	=	*Wind speed at height z,*
V_{hub}	=	*Wind speed at hub height,*
σ	=	*Standard deviation,*
I_{ref}	=	*expected value of the turbulence intensity at 15 m/s*, from Table 2.3.

Return periods are important factors for extreme wind conditions. IEC has specified to take recurrence period of 50 years and 1 year [20]. Extreme wind speed with a recurrence period of 50 years and extreme wind speed with a recurrence period of 1 year can be calculated from Eq. 2.5 and Eq. 2.6 respectively:

$$V_{e50}(z) = V_{ref}\left(\frac{z}{z_{hub}}\right)^{0.11} \quad , \tag{2.5}$$

$$V_{e1}(z) = 0.8V_{e50}(z) \quad , \tag{2.6}$$

and the standard deviation for extreme wind model is given by the following equation.

$$\sigma = 0.11V_{hub} \quad , \tag{2.7}$$

where,

$V_{e50}(z)$	=	*Extreme wind speed with a recurrence period of 50 years at height z,*
$V_{e1}(z)$	=	*Extreme wind speed with a recurrence period of 1 year at height z,*
V_{ref}	=	*Reference wind speed*, can be taken from Table 2.3.

Table 2.3: Basic parameters of wind turbine classes [20]

Parameter	**I**	**II**	**III**	**S**
V_{ref} (m/s)	50	42.5	37.5	30
Annual average wind speed (m/s)	10	8.5	7.5	6
50-year return gust (m/s)	70	59.5	52.5	42
1-year return gust (m/s)	52.5	44.6	39.4	31.5
I_{ref}	0.16	0.14	0.12	-

where,

I	=	*designates the category for high wind speed characteristics,*
II	=	*designates the category for medium wind speed characteristics,*
III	=	*designates the category for low wind speed characteristics,*
S	=	*designates the category for special design cases.*

Wind gusts rarely occur in short span of time and they have large return periods. Several other parameters are required to estimate wind gust speeds e.g, diameter of rotor, standard deviation and turbulence scale parameter. Standard deviation and turbulence scale parameters are dependent on the wind classes [20]. Eq. 2.8 can be used to calculate wind gust speed.

$$V_{\text{gust}} = Minimum \left[1.35(V_{\text{e1}} - V_{\text{hub}}) \quad \textbf{or} \quad 3.3 \left[\frac{\sigma}{1 + 0.1(\frac{D}{\Lambda})} \right] \right] \quad , \tag{2.8}$$

where,

V_{gust}	=	*Wind gusts,*
σ	=	*Standard deviation*, can be calculated from Eq. 2.5
D	=	*Diameter of rotor,*
Λ	=	*Turbulence scale parameter,* which is given by:

$$\Lambda = \begin{cases} 0.7z & \text{if } z \leq 60\ m \\ 42m & \text{if } z \geq 60\ m \end{cases}$$

In extreme turbulence environments, where wind speeds are fluctuating at regular intervals, normal wind model (Eq. 2.3) can be used to estimate the wind speed but the standard deviation will be changed and following equation can be used:

$$\sigma = cI_{\text{ref}} \left(0.072 \left(\frac{V_{ave}}{c} + 3 \right) \left(\frac{V_{hub}}{c} - 4 \right) + 10 \right); \qquad c = 2m/s \quad , \tag{2.9}$$

The wind force acting on a wind turbine tower is explained in the American design standard ASCE 7-16 *"Minimum Design Loads and Associated Criteria for Buildings and Other Structures"*. The procedure for calculating wind force is governed by ASCE 7-16, which can be calculated by the Eq. 2.10 [22].

$$F_{\mathrm{wi}} = q_{\mathrm{z}} G C_{\mathrm{f}} A_{\mathrm{t}} \quad , \tag{2.10}$$

where,

F_{wi}	=	*Wind force acting on a wind turbine tower,*
q_z	=	*Wind velocity pressure,*
G	=	*Gust-effect factor,*
A_t	=	*Projected tower area, which is perpendicular to the wind direction,*
C_f	=	*Force coefficient.*

The equation that defines the wind pressure on a tower is as follows:

$$q_{\mathrm{z}} = 0.613 K_z K_{\mathrm{zt}} K_d V^2 I \quad , \tag{2.11}$$

$$K_{\mathrm{z}} = 2.01 \left(\frac{z}{z_{\mathrm{g}}} \right)^{\frac{2}{\beta}} \quad , \tag{2.12}$$

where,

z_g	=	213.36 *m is for exposure category "D" for offshore wind turbines,*
β	=	11.5 *for exposure category "D",*
K_{zt}	=	1.0 *for flat terrain,*
K_d	=	*is a directionality factor and* 0.95 *for round towers,*
I	=	1.0 *is the importance factor,*
h	=	*Height of the structure.*

The gust-effect factor value is dependent on the tower's fundamental natural frequency. Following series of equations can be used to calculate the gust-effect factor.

$$G = 0.925 \left(\frac{1 + 1.7 I_z \sqrt{g_q^2 Q^2 + g_r^2 R^2}}{1 + 1.7 g_v I_{\mathrm{z}}} \right) \quad , \tag{2.13}$$

where,

I_z = *Turbulence intensity at 10 m,*
g_q = 3.4, *the peak factor for background response,*
Q = *Background response factor,*
g_r = *Peak factor for resonance,*
R = *Resonance response factor,*
g_v = 3.4, *the peak factor for wind response.*

$$I_z = 0.15\left(\frac{10}{0.6h}\right)^{1/6} , \tag{2.14}$$

$$Q = \sqrt{\frac{1}{1+0.63\left(\frac{B+h}{L_z}\right)^{0.63}}} , \tag{2.15}$$

$$L_z = L\left(\frac{0.6h}{10}\right)^{0.125}, \tag{2.16}$$

where,

B = *Width of the tower, measured normal to the wind direction,*
L = 198.2 *m for exposure category "D".*

$$g_r = \sqrt{2\ln(3600n_1)} + \frac{0.577}{\sqrt{2\ln(3600n_1)}} , \tag{2.17}$$

where,

n_1 = *Natural fundamental frequency of the tower,*

$$R = \sqrt{\frac{1}{\zeta}R_nR_hR_b(0.53+0.47R_L)} \qquad \zeta = 0.02\ (damping\ ratio) , \tag{2.18}$$

$$R_n = \frac{7.47N_1}{(1+10.3N_1)^{5/3}} , \tag{2.19}$$

$$N_1 = \frac{n_1L_z}{V_z} , \tag{2.20}$$

$$V_z = 0.8\left(\frac{0.6h}{10}\right)^{0.11} V \quad , \tag{2.21}$$

$$R_h = \frac{1}{4.6n_1\frac{h}{V_z}} - \frac{\left(1 - e^{-2\left(4.6n_1\frac{h}{V_z}\right)}\right)}{2\left(4.6n_1\frac{h}{V_z}\right)^2} \quad , \tag{2.22}$$

$$R_{\mathrm{b}} = \frac{1}{4.6n_1\frac{B}{V_z}} - \frac{\left(1 - e^{-2\left(4.6n_1\frac{B}{V_z}\right)}\right)}{2\left(4.6n_1\frac{B}{V_z}\right)^2} \quad , \tag{2.23}$$

$$R_{\mathrm{L}} = \frac{1}{15.4n_1\frac{L}{V_z}} - \frac{\left(1 - e^{-2\left(15.4n_1\frac{L}{V_z}\right)}\right)}{2\left(15.4n_1\frac{L}{V_z}\right)^2} \quad , \tag{2.24}$$

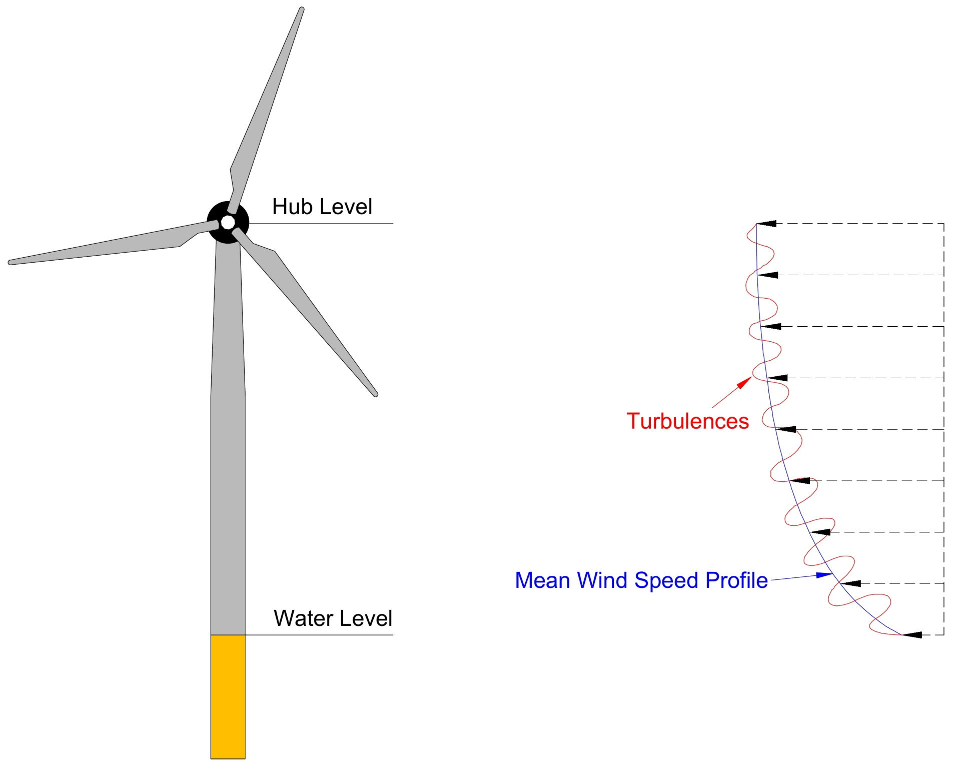

Figure 2.13: Wind speed variations along with the height of the wind turbine

2.8.2 Wave Load

Offshore wind turbines face huge hydrodynamic loads due to the marine environment. These include sea waves, sea currents, sea ice, marine growth, scour and seabed movement. Sea waves are non-linear, irregular in shape and vary with the height, length and direction of propagation. This creates a difficulty for design engineers to predict its load realistically. Design engineers have developed several sea waves models to characterize this non-linear behavior. Generally, the wave heights can be taken from a site-specific ocean meteorology data [23]. Offshore wind turbines are designed based on normal or extreme wave conditions.

Under normal sea conditions, periodic or regular wave model can be used as a resemblance to real sea state. The design wave height $\mathrm{H_s}$ and peak spectral time period $\mathrm{T_p}$ will be the same as measured or taken from ocean meteorology data. The wave period T can be assumed within a range by the Eq. 2.25 [23].

$$11.1\sqrt{\frac{H_{\mathrm{s,NSS}}}{g}} \leq T \leq 14.3\sqrt{\frac{H_{\mathrm{s,NSS}}}{g}} \quad , \tag{2.25}$$

where,

$\mathrm{H_{s,NSS}}$	=	*Design wave height in normal sea state,*
g	=	*Spectral acceleration,* $9.8\ m/\mathrm{s}^2$.

Under extreme sea conditions, the design wave height is dependent on the recurrence time period. IEC recommends using $\mathrm{H_{50}}$ with a recurrence period of 50 years and $\mathrm{H_1}$ with a recurrence period of 1 year. The design wave height's $\mathrm{H_{50}}$ and $\mathrm{H_1}$ in extreme sea state, can be calculated from equations 2.26 and 2.27 respectively. The choice of peak spectral time period is upon the designer, which should be estimated on the measured wave data. The wave period can be assumed within a range by the Eq. 2.28 [23].

$$H_{50} = 1.86 H_{\mathrm{s50}} \quad , \tag{2.26}$$

$$H_1 = 1.86 H_{\mathrm{s1}} \quad , \tag{2.27}$$

$$11.1\sqrt{\frac{H_{\mathrm{s,ESS}}}{g}} \leq T \leq 14.3\sqrt{\frac{H_{\mathrm{s,ESS}}}{g}} \quad , \tag{2.28}$$

where,

H_{50}	=	*Design wave height with recurrence period of 50 years,*
H_1	=	*Design wave height with recurrence period of 1 yea,r*
H_{s50}	=	*Measured significant wave height with recurrence period of 50 years,*
H_{s1}	=	*Measured significant wave height with recurrence period of 1 year,*
$H_{s,ESS}$	=	*Design wave height in extreme sea state.*

In order to calculate the load exerted by the ocean waves on to the wind turbine is estimated in two cases i.e. the static case and the dynamic case. The static case is applicable to structures that are stationary like Monopile, Tripod, and Jacket and floating structures are analyzed by the dynamic case. Morison's equation delivers the simplest way for estimating wave loads on the offshore structures, but it is only applicable if diameter/wavelength < 0.2 and the static case is explained below [23].

$$F_{\mathrm{wa}} = \frac{1}{2} C_{\mathrm{d}} \rho_{\mathrm{w}} D_{\mathrm{m}} U|U| + C_{\mathrm{m}} \rho_{\mathrm{w}} A_{\mathrm{m}} \ddot{U} \quad , \tag{2.29}$$

where,

F_{wa}	=	*Wave force per unit length of the member,*
C_d	=	*Drag coefficient,*
ρ_w	=	*Density of water,*
D_m	=	*Diameter of the member,*
U	=	*Flow velocity,*
$\|U\|$	=	*Time derivate of flow velocity,*
C_m	=	*Inertia coefficient,*
A_m	=	*Cross-sectional area of the member,*
$\ddot{U}$	=	*Flow acceleration.*

The values of C_d, C_m, flow velocity and flow acceleration can be measured on site or from experiments or they can be expressed as a function of Reynolds number, surface roughness, shape of the member, current / wave velocity ratio and Keulegan-Carpenter number. According to DNV GL, the value of C_d for newly coated steel structure can be taken as 0.65 and for deep waters the value of C_m can be taken as 1.6, but in shallow waters it should not be taken less than 2.0 [24].

2.9 Failure Modes of Wind Turbines

Wind turbines are getting bigger and smarter by each day. They are heavy, complex and expensive state of the art machines that throughout their lifespan face huge variable loads. These loads carry a massive momentum that can cause failure of the wind turbines. To address these concerns, several reliability studies aiming towards failure modes have been conducted. Offshore wind turbines have higher tendency of failure than the onshore wind turbines due to the presence of higher wind speeds and non-linear behavior of the ocean waves. The importance of reliability tools and sophisticated failure models is felt more often in the offshore wind industry. Reliability is defined as the ability to perform under given conditions without any failure. To improve the reliability of wind turbines, usually a categorization of known failure modes, the causes of failure and failure frequencies are required [25, 26].

Failure Mode and Effect Analysis (FMEA) is a powerful failure analysis technique to identify and classify different failure modes and its effects on the main structure. FMEA was first introduced by NASA in 1963 for their reliability requirements of the space equipment and since then, it has been widely used in many industries including nuclear, semiconductor and automotive industries. The Failure Mode, Effects and Criticality Analysis (FMECA) is more advanced form of FMEA that additionally includes the probability of occurrence of failures, severity of consequences, cost estimations and downtimes. FMEA is a reverse based bottom-up system that begins with the identification of a failure and it continues by analyzing its effects on the bigger and connected systems. To get better and more reliable FMEA models, it is recommended to breakdown a main system into many sub-systems and components [25, 26]. An overall representation of FMEA structure is explained in Figure 2.14.

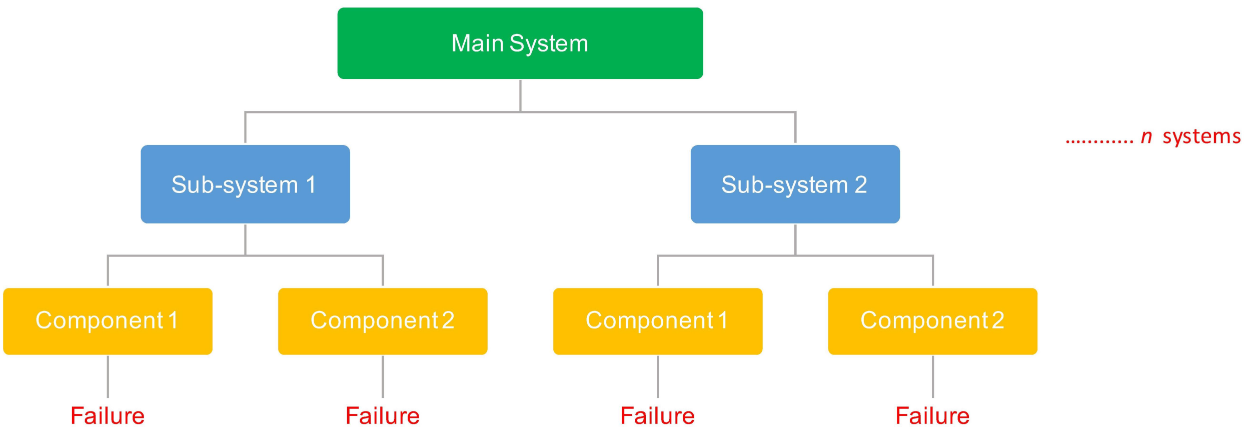

Figure 2.14: Hierarchical structure of FMEA system (regenerated) [25]

The literature shows that the traditional FMEA studies have been applied to specific regions and certain types of wind turbines. As the performance and site-specific conditions are different even for a same type of a wind turbine so, there is a need to conclude FMEA models at a certain standard. Some researchers have worked on improving the FEMA methodology. Peter J. Tanver and his colleagues [27] presented a FMEA methodology for prioritization of failures in a 2 MW wind turbine. They concluded that three different categories can be formed using FMEA models i.e. occurrence of a failure, severity of a failure and detection of a failure [25,27]. Their results are shown in the Table 2.4, 2.5 and 2.6 respectively.

Table 2.4: Wind turbine FMEA ratings for occurrence of a failure [27]

Rank	**Description**	**Criteria**
1	Level E (extremely unlikely)	Probability of occurrence is < 0.001
2	Level D (remote)	Probability of occurrence is > 0.001 but < 0.01
3	Level C (occasional)	Probability of occurrence is > 0.01 but < 0.10
5	Level A (frequent)	Probability of occurrence is > 0.10

Table 2.5: Wind turbine FMEA ratings for severity of a failure [27]

Rank	**Description**	**Criteria**
1	Category IV (minor)	Electricity can be generated but repair is required
2	Category III (marginal)	Reduction in ability to generate electricity
3	Category II (critical)	Loss of ability to generate electricity
4	Category I (catastrophic)	Major damage to the turbine

Table 2.6: Wind turbine FMEA ratings for detection of a failure [27]

Rank	**Description**	**Criteria**
1	Almost certain	Current methods will almost always defect a failure
4	High	Good likelihood of detecting a failure.
7	Low	Low likelihood of defecting a failure.
10	Almost impossible	No known methods available to detect a failure

The wind turbine failure modes can be divided into three categories i.e. structural, mechanical and electrical failures. The structural failure mostly occurs in tower and foundation and is caused by high winds. Mechanical failures happen with sub-systems like gearbox, brake system, yaw system, rotor blades, rotor bearings, hub and pitch system. Electrical failures occur very often but are not very hard to repair. Overloading, software problems, connection faults and electrical calibration errors can lead to these failures [26].

A study was conducted with a collaboration of different organizations to set a benchmark for different wind turbine failure modes in Europe. Windstats (7000 wind turbines from Denmark and Germany), LWK (650 wind turbines from Germany), WMEP (1500 wind turbines from Germany), Vindstat (80 wind turbines from Sweden), VTT (105 wind turbines from Finland), and Garrad Hassan energy consultancy (14 GW wind farms) were inspected. The results of the study are summarized below and illustrated graphically in Figures 2.15, 2.16 and 2.17.

1. Wear is the leading and most frequent cause of failure in wind turbines. It can create operational problems like misalignment and vibrations [26].
2. Control and electric sub-systems have the highest failure rates but they have less down times [26].
3. Sub-systems such as gearbox, generator, and yaw system have less failure rate but they have the longest down times [26].
4. Structure and gearbox have less failure rates but they are the most expensive to repair among all other sub-systems [26].

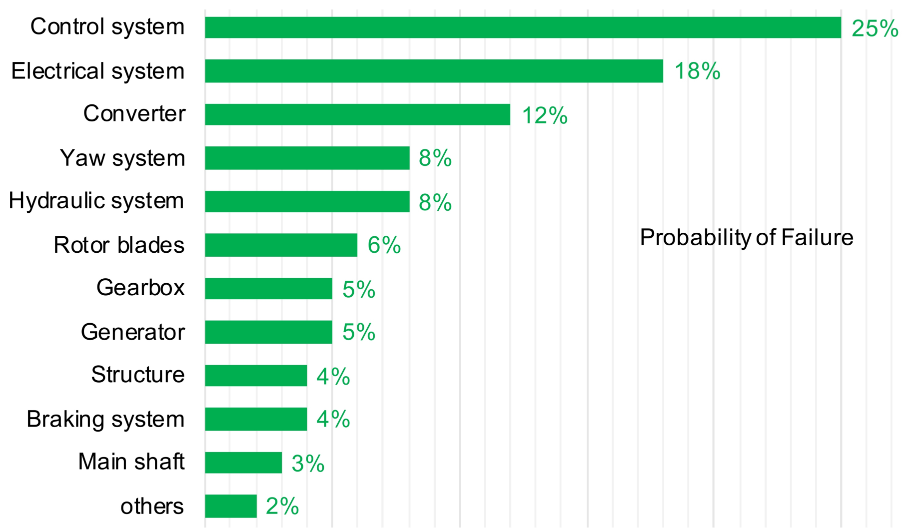

Figure 2.15: Probability of failure of different wind turbine sub-systems [26]

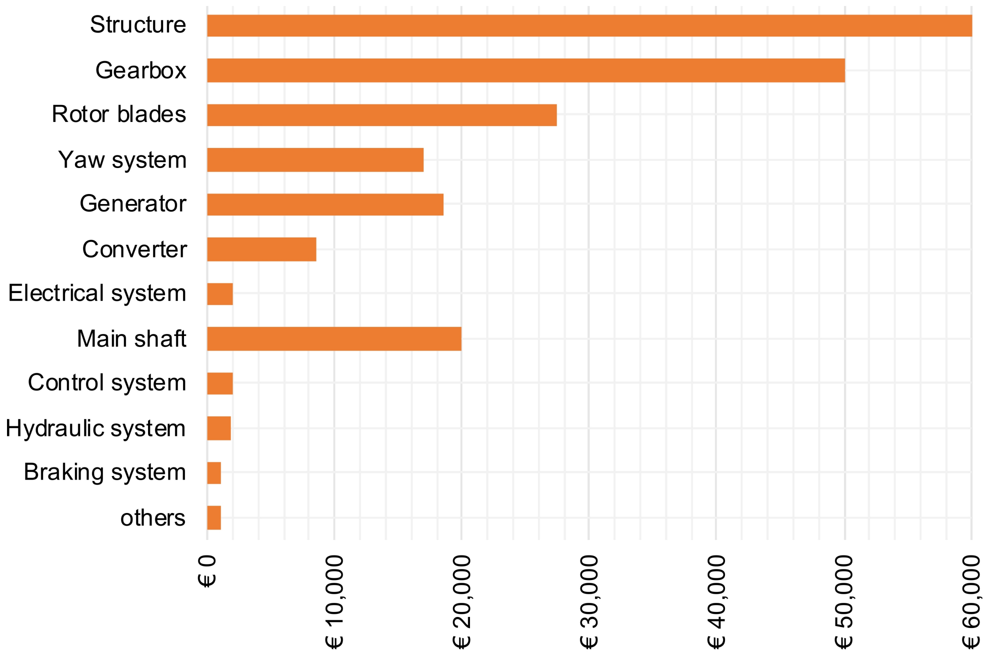

Figure 2.16: Expected cost of failure of different wind turbine sub-systems [26]

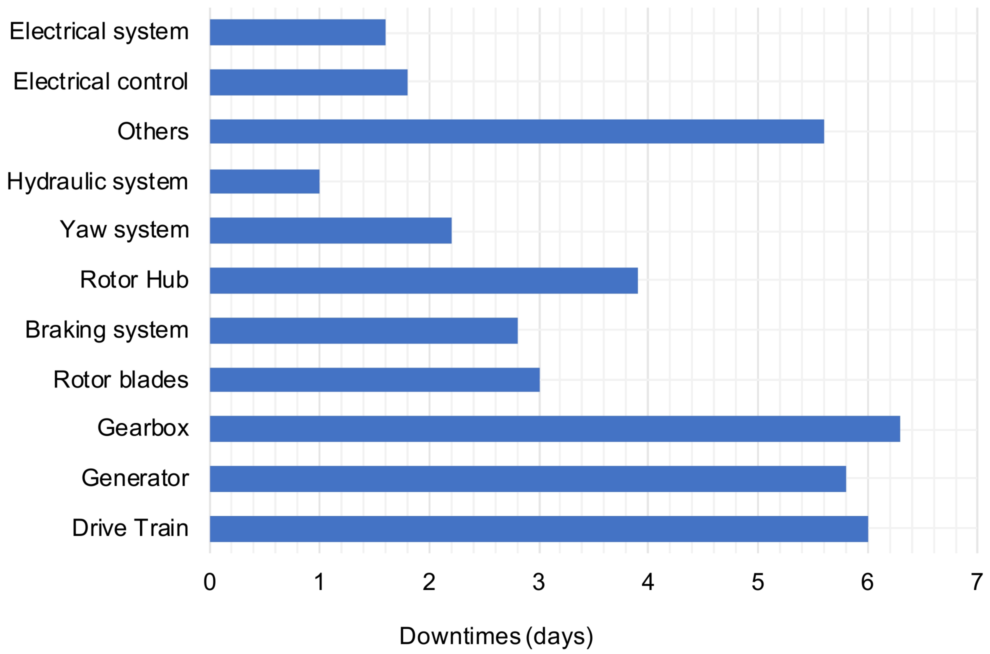

Figure 2.17: Downtimes per failure of different wind turbine sub-systems [26]

2.10 Design Criteria

The aim of the design process is to find the geometry and type of the structure that will be suitable and safe to serve the purpose for which it is built, while doing it throughout its lifetime. It is recommended to consider the following conditions when designing a structure.

1. The structure must be stable,
2. The loads must not be exceeded from the material strengths i.e, L $\leq$ S,
3. The function of the structure must be validated,
4. The structure should be aesthetically pleasing,
5. The structure has to be resistant against external factors, such as wind loads, wave loads, vibrations, bending moments, fire, earthquake, collisions, floods, frost and temperature differences.

2.10.1 Limit State

A limit state is a condition of a structure beyond which it no longer fulfills the design criteria. This limit state relates to the safety of the structure and the people. In some cases, even the safety of the content inside the structure can be seen as the limit state. Generally three types of failure are considered as a part of limit state i.e. failure due to big deformations, failure due to high stress in the material, and failure due to fatigue. Fatigue failures are very common type of failure for wind turbines, which happen due to the material deterioration under cyclic loadings. IEC, ISO and DNV GL has specified the design procedure for wind turbines. They recommend to include a factor of safety to account all the possible uncertainties. Another approach is the use of finite element software packages, which automatically simulates a model and can determine the failure, based on the very large deformations, settlements or deflections. A structure designed by limit state design is considered to sustain all the actions likely to occur during its design lifespan, and to remain in function, with an adequate level of reliability for each limit state.

2.10.2 Factor of Safety

The use of partial factor of safety is a common practice and accepted by many organizations including IEC and ISO until the sound design is achieved. The IEC 1400-1 wind turbine design specification is based on the ISO standard *"General Principles on Reliability for Structures"*. This standard specifies limit-state design procedure that uses partial factor of safety to manage uncertainties in load, material and in the analysis method. Factor of safety is applied to the design values for loads and material properties and uncertainties in load predictions. Eq. 2.30 and Eq. 2.31 defines the limit state design values of loads and material properties respectively [28].

$$L_d = \gamma_l F_k \quad , \tag{2.30}$$

$$M_d = \frac{1}{\gamma_m} F_k \quad , \tag{2.31}$$

where,

L_d	=	*Limit-state design values for loads,*
γ_l	=	*Partial safety of factor for loads,*
F_k	=	*Characteristic values of loads or material properties,*
M_d	=	*Limit-state design values for material properties,*
γ_m	=	*Partial safety of factor for material properties.*

The most basic criteria in the design of a wind structure is to make sure that the strength of the structure is greater than the loads applied, which actually defines the limit-state. According to IEC 1400-1, partial factor of safety values in limit-state for load uncertainties, material uncertainties and consequences of failure can be taken as 1.1, 1.10, and 1.15 respectively, whereas for ultimate strength, values of 1.35, 1.10, and 1.0 should be used.

Chapter 3

Probability Theory

3.1 Brief Introduction

Probability is a vital part of modern mathematics and it can be utilized to model any system. The probabilistic approach requires to define two variables, the basic variables (describing system geometry, loads or material properties) and response variables (displacement, tilting, stresses, or strains). The basic variables are the input parameters upon which the probability of a certain system is based. The response variables define the serviceability of a system, which is dependent on the input parameters. The early concepts of probability were presented first in 1749 by a French mathematician Pierre Simon and 1827 by Marquis de Laplace. Since then, the researchers have improved the concepts of probability by adding new approaches and methodologies. A large number of probability problems are solved with the help of numerical analysis and in particular, finite element method is an advanced approach for many probability solutions.

A random phenomena is defined as the observation under same conditions that leads to the changing outcomes. Most of the civil engineering applications involve uncertainties and randomness that must be incorporated in the probabilistic theorems for a reliable design. Wind turbine is a system that is structured on unpredictable and random attributes, where wind and wave forces change continuously with time. Probability theorems play a key role in quantifying those uncertain parameters. A standardized constitutive model cannot be applied to every engineering situation as material composition (soil, rock, sand, concrete or steel etc) and loads (wind, waves, earthquakes, or motions etc) vary from each location. The probability studies are widely used in mathematics, along with statistics, finance, physics, computer science, meteorology, artificial intelligence, games theory, and insurance industry [29].

3.2 Stochastic or Probabilistic Model

The stochastic or probabilistic model is a process that is constituted by a collection of random variables that are typically indexed by time. Many real-world process are random, such as bacterial growth, wind power production, and financial market rates etc, which are significantly dependent on the time. Some of the most common examples of stochastic processes are Bernoulli process, Random Walk, Wiener process, Poisson process, Markov process, Lévy process, Poisson process and Random field. Stochastic modeling is extensively used in the areas of risk management, mitigation strategies and supply chain requirements. A stochastic process can be classified in the two ways i.e, **Discrete time process**, when the time is finite or countable and **Continuous time process**, when the time is not finite.

There are typically two ways to model a system i.e, Deterministic or Stochastic approaches. Deterministic approach involves the measurements of basic variables with a factor of safety for reliable design while, the stochastic approach explicitly accounts for the uncertainties. The uncertainties in a real-world system cannot be predicted precisely however these can be statistically analyzed through probability density functions. The stochastic approach involves the identification of stochastic models for the uncertain parameters and turns the design problem into a reliability-based optimization process. A wind turbine system designed by the stochastic approach is expected to be more reliable in given site conditions [30]. A comparison between stochastic and deterministic approaches is shown in the Figure 3.1.

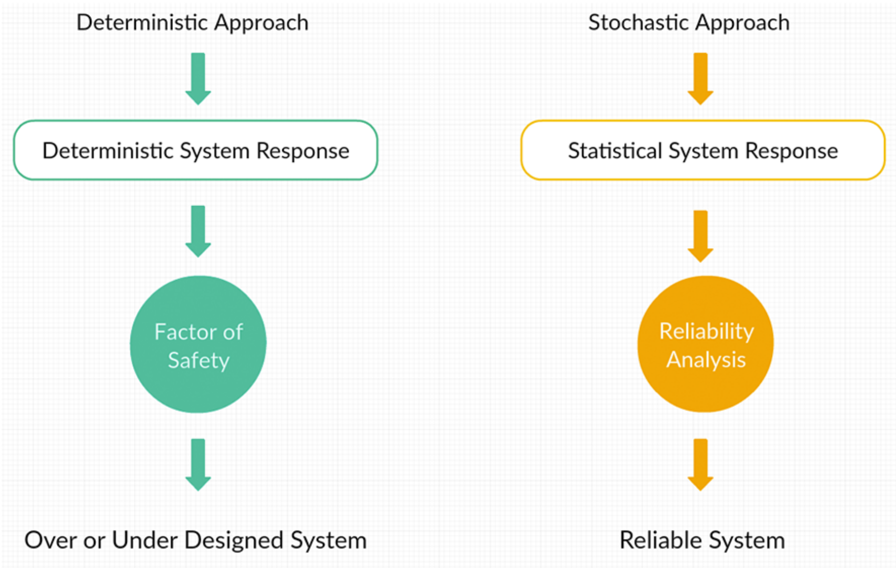

Figure 3.1: Design approaches for different systems [30]

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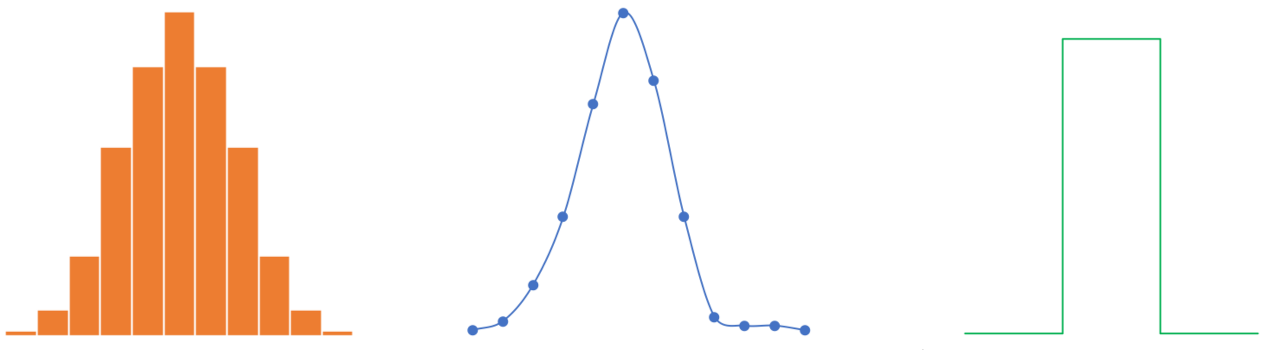
3.3 Probability Distributions

A probability distribution is a function that describes the likelihood of a random variable obtaining a certain value, which must meet two conditions. First, the sum of all probabilities for all possible values must equal 1 and second, the probability for a particular value or range of values must be between 0 and 1. In literature, two types of probability distributions are defined i.e, Discrete probability distribution for discrete variables and Probability density functions for continuous variables.

Discrete probability distributions are also known as probability mass functions and can assume a countable number of values. Some examples of discrete probability distribution are Binomial distribution, Poisson distribution and Uniform distribution.

Continuous probability functions are also known as probability density functions. Continuous variables are often measured on some scale, such as height, weight, temperature, time or speed. Most continuous distributions are used in conjunction with different parameters. These parameters include shape factor, scale parameter, location parameter, mean, and standard deviations. Specifying these parameters establishes the shape and probabilities of the distribution. The Normal distribution, Weibull distribution, Lognormal distribution and Exponential distribution are some common types of continuous distributions. Weibull, lognormal and exponential distributions can fit the skew data [31].



(a) Binomial distribution (b) Poisson distribution (c) Uniform distribution

Figure 3.2: Examples of Probability Distributions

3.3.1 Weibull Distribution

The Weibull distribution is a continuous probability density function, which was developed in 1951 by Swedish mathematician Waloddi Weibull. The distribution has three important parameters: shape, scale and location parameter, however it is frequently used with shape and scale parameters [31]. The density function of the Weibull distribution is given by the following equation:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad , \tag{3.1}$$

where,

β = *Shape factor,*

η = *Scale parameter,*

t = *is a variable representing time.*

3.3.2 Normal Distribution

The Normal distribution is also a continuous probability density function, which was introduced by French mathematician Abraham de Moivre in 1733. This distribution is one of the most widely known distribution, which is also known as Gaussian distribution and the bell curve. It doesn't require shape parameter as it is symmetric in shape and uniformly distributed. This distribution has two important parameters: mean and standard deviation. Area under the curve is of particular importance as it can be used to find out the probabilities between certain range [31]. The density function of the Normal distribution is given by the following equation:

$$f(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(t-\mu)^2/2\sigma^2} \quad , \tag{3.2}$$

where,

μ = *Mean factor ($\mu \in R$),*

σ = *Standard deviation.*

3.3.3 Exponential Distribution

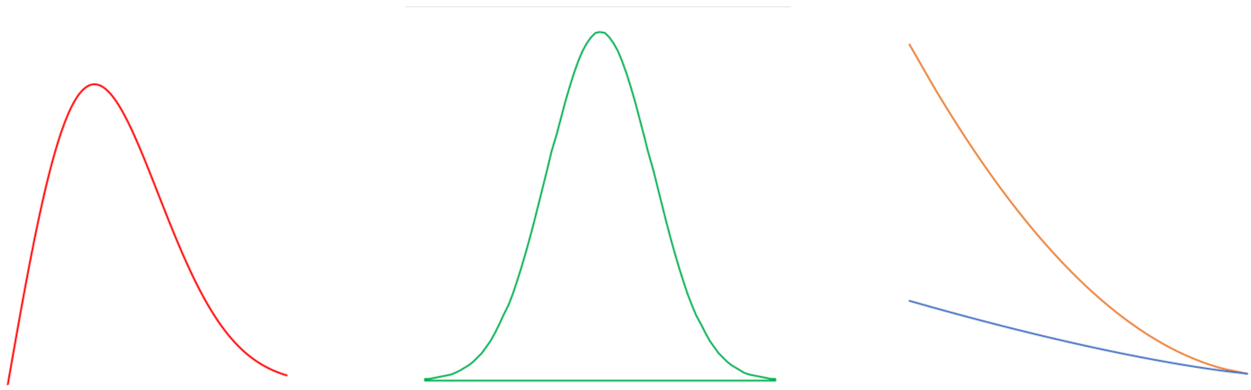
The exponential distribution is used when a constant failure rate is involved. Shape factor has no effect on the shape of the distribution curve so it is neglected from the calculations. It also generates the same shape after every analysis [31]. The density function of the exponential distribution is given by:

$$f(t) = \lambda e^{-\lambda(t-\gamma)} \qquad (with\ two\ parameters) \quad , \tag{3.3}$$

$$f(t) = \lambda e^{-\lambda t} \qquad (with\ one\ parameter) \quad , \tag{3.4}$$

where,

λ = *Scale parameter,*
γ = *Location parameter,* $(-\infty < \gamma < \infty)$.



(a) Weibull distribution (b) Normal distribution (c) Exponential distribution

Figure 3.3: Examples of Probability Density Functions

3.3.4 Generalized Extreme Value Distribution (GEV)

The generalized extreme value distribution is a type of continuous probability distribution which unites Gumbel, Frèchet and Weibull distributions. The generalized extreme value distribution is often used to model the smallest or largest values among a large set of independent variables. The GEV distribution is parameterized with a shape paramter, location parameter and scale parameter. The earlier uses of GEV distribution were in the hydrology measuring the extreme events i.e. annual rainfalls and rive discharges. It is also most commonly used in insurance industry, financial markets and often recommended for extreme values evaluations. The cumulative distribution function of the GEV distribution is given by:

$$f(x) = \frac{1}{\sigma} \exp\left(-\left(1+kz\right)^{-\frac{1}{k}}\right)\left(1+kz\right)^{-1-\frac{1}{k}} \quad , \tag{3.5}$$

where,

σ = *Scale parameter,*

k = *Shape parameter,*

μ = *Location parameter*

z = $(x - \mu)/\sigma$.

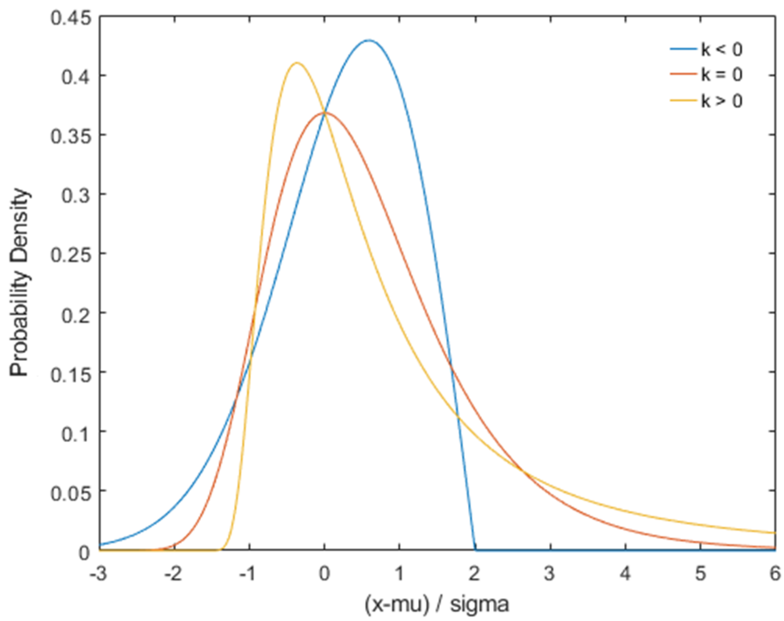


Figure 3.4: Example of Generalized Extreme Value Distribution

3.4 Reliability Analysis

Reliability is defined as the probability of a structure to be remained in the operating state within a certain defined criteria. If it falls outside the chosen domain, structure will be unreliable and will not meet the performance expectations. The reliability analysis methods aim at evaluating the probability of failure of a system. The failure criteria can be taken from the limit state design or chosen from the user requirements. Reliability studies are applied to a variety of situations especially when huge investments are involved. Reliability studies can validate results however, they always differ for unique criteria's and structures. Reliability studies for wind turbines can be applied in various modes e.g. structural stability, power production or availability of cut-in-wind speeds etc. For example, a wind turbine is said to be reliable, if it generates 1000 kW per hour, so in this case the 1000 kW per hour power generation can be selected as a criteria and the reliability analysis will only be applicable for 1000 kW per hour power generation. Reliability analysis is based on a single criteria with all uncertainties and parameters fall under that criteria, which are based on the definition of a limit state function. An illustration of reliability analysis process is explained in the Figure 3.5.

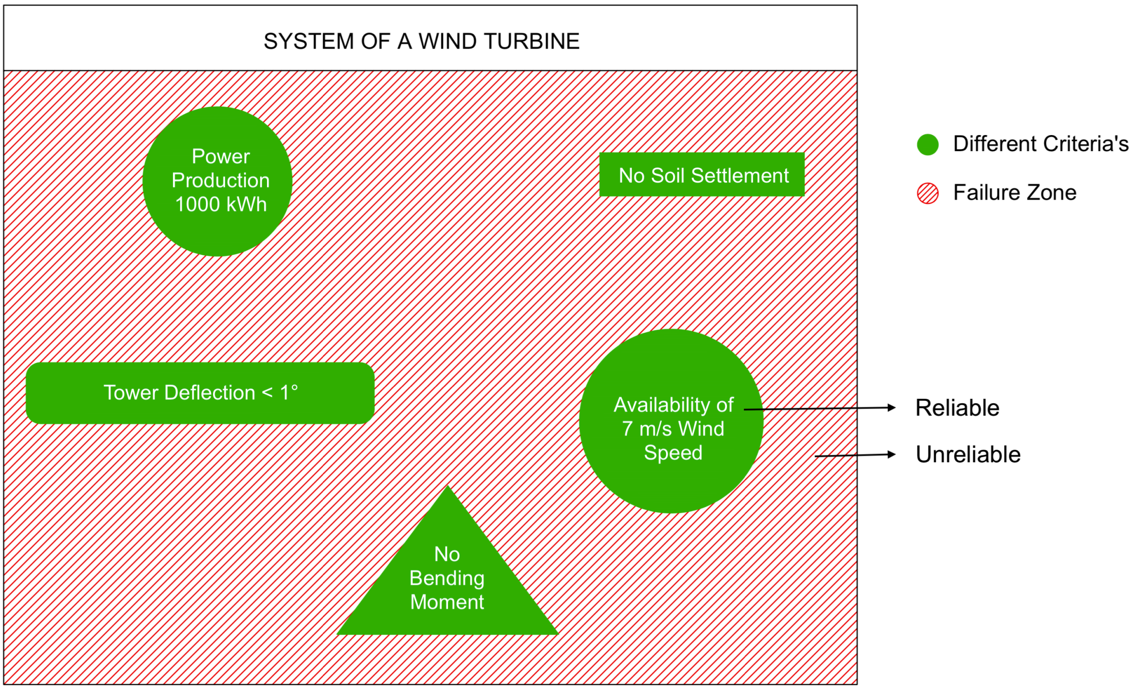


Figure 3.5: Illustration of the concept of reliability analysis for the wind turbines

The reliability of a system (R_s) can be calculated from the probability of failure (P_f) as:

$$R_s = 1 - P_f \quad , \tag{3.6}$$

For a reliable design of any system, following steps are considered, which are generally required to include in the planning phase of a project.

1. Selection of target reliability level (safety, performance or serviceability etc),
2. Identification of significant failure modes (deflection, bending or settlement etc),

3. Define the limit state functions,
4. Identification of stochastic variables and deterministic parameters,
5. Selection of probability distributions with uncertainties and deviations,
6. Estimate reliability of each failure mode,
7. Modifications in the design, if reliability does not meet the target reliability.

3.4.1 First and Second Order Reliability Methods

The first and second order reliability methods are efficient methods that deals with the limit state functions. They are considered to be one of the most reliable computational methods for structural reliability. The advantage of such analytical methods is that they provide physical interpretations and do not require much computation time. Designs based on FORM or SORM are usually performed using commercial software packages in which the underlying concept of the reliability method is hidden. Also, the available literature is not easy to read and the basic concept is buried in complex mathematical equations [30]. FORM and SORM are two standard structural reliability methods, which are based on linear and quadratic approximations, respectively. The idea is based on the joint probability density of all the factors influencing failure or non-failure, including factors controlling demand and those effecting capacity. This n-dimensional probability space is partitioned by some function into safe and non-safe regions. FORM is an analytical approximation in which the reliability index is interpreted as the minimum distance from the origin to the limit state space and the most probable point (MPP) can be searched using mathematical programming methods. The SORM is established as an attempt to improve FORM accuracy. The reliability index can be calculated from Hasofer-Lind method and the cumulative density function of the reliability index, $\Phi(-\beta)$ will give the reliability of a system [32].

$$\beta = min\sqrt{(x-\mu)^t C^{-1}(x-\mu)} \quad , \tag{3.7}$$

$$\beta = min\sqrt{\left(\frac{x-\mu}{\sigma}\right)^t R^{-1}\left(\frac{x-\mu}{\sigma}\right)} \quad , \tag{3.8}$$

where,

β	=	*Reliability index,*
x	=	*Vector representing the set of random variables,*
μ	=	*Vector of mean values,*

C^{-1} = *Inverse of a covariance matrix,*

R^{-1} = *Inverse of a correlation matrix,*

σ = *Standard deviation,*

t = *Transpose of a matrix.*

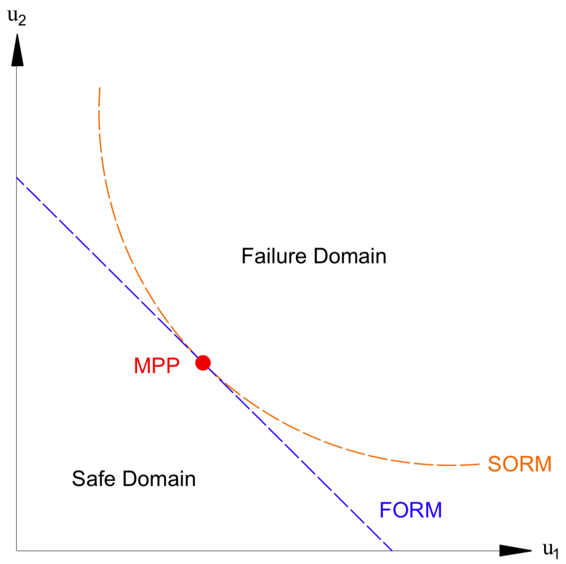


Figure 3.6: Illustration of the concept of FORM and SORM

3.4.2 Monte Carlo Simulation

Monte Carlo simulation method is based on the sampling technique, which requires multiple iterations. It's execution involves running a random number through the probability distribution and each iteration gives different results, which are categorized by the under and above the chosen criteria. MCS methods are different than FORM and SORM in a way in which the linear approximation of limit state function is disregarded. The reliability of MCS can be calculated as:

$$R_s = 1 - \frac{n_f}{n} \quad , \tag{3.9}$$

where,

n_f = *Number of failed samples,*

n = *Total number of samples.*

Monte Carlo Simulation method has been widely used in the structural reliability because it is a simple process, realistic and complex models are easily dealt with it. However, the main drawback of MCS is the significant numerical efforts in order to obtain an adequate accuracy of the failure probability. Minimum of 10,000 samples are recommended for generating accurate results [30]. The MCS procedure for wind turbines is explained below:

1. Selection of a wind turbine component (tower, rotor blades, foundation or gearbox etc),
2. Formulation of limit-state functions based on failure modes of interest (fatigue, buckling, tilting, settlement or deflection etc),
3. Uncertainty quantification (material properties, loads and statistical uncertainty etc),
4. Measurement or evaluation of results (finite element modeling analysis, dynamic analysis or instrumentation measurements etc),
5. MCS reliability analysis results.

The accuracy of Monte Carlo simulation can be measured by the coefficient of variation by the following equation [33].

$$COV = \sqrt{\frac{1 - P_f}{n \,.\, P_f}} \quad , \tag{3.10}$$

3.4.3 Adaptive Kriging Method

Reliability estimation using computer models are getting very popular nowadays due to the reason that they are reliable, more accurate and less time-consuming. Many processes are so complex that it becomes unfeasible to make physical measurements. As a result, experimental data is converted in to mathematical models. Advances in computing industry has enabled engineers to process the information with greater accuracy in less time. In industry practices, engineers often have to deal with uncertain quantities which cannot be measured directly. Estimating a statistical model often requires to measure the unobserved uncertainties in a system. The Adaptive Kriging method is useful in addressing such unobserved uncertainties as it captures the inherent uncertainties of variables. Kriging, also known as Gaussian process regression was introduced by a French mathematician Georges Matheron which, originally, was developed to deal with the geostatistics problems [33, 34].

The approach for this modeling technique is to build an accurate surrogate model (H) from a limited number of the computational model. The unique property of Kriging is its ability to determine the variance of predictions, which approximates limit state functions with good accuracy. This approach involves measuring some observed data (Y_i) and a computer model (H) that links the unobserved variables (X_i) with observed variables. In simple terms, it can be expressed as:

$$Y_i = H\left(X_i \, , \, d_i\right) + U_i \quad , \tag{3.11}$$

where,

d_i = *Known or observed quantitites,*

U_i = *Unobserved measurement errors.*

3.5 Reliability and Economics

Wind turbine designs are evolving rapidly and modern-day developments tends towards larger and heavier structures. This allows the operatives and organizations to capture large amount of wind, which results in overall higher power production. The increase in the size also increases the loads on turbine components, making them vulnerable to more failures. More often failures will escalate the operational cost of wind farms, which will eventually effect the pricing of the electricity. The cost of wind power can be reduced by improving the reliability of wind turbines. More reliable wind turbine will also reduce the operation and maintenance costs. The reliability analysis is especially useful for offshore wind turbines to reduce the high economic risks related to the uncertainties in the accessibility and loads. The key factors in the high cost of offshore wind turbines is the fact that they are situated in remote locations and the turbine components which are most likely to fail are often located at heights of around 80 m above the ground, which makes them difficult to access in transporting equipment and manpower in the downtimes of wind turbine [31, 35, 36]. A research conducted by François Besnard on maintenance optimization for offshore wind farms shows that the corrective maintenance cost was estimated to contribute 43% of the total life cycle operation and maintenance cost of the 160 MW Horns Rev offshore wind farm located 20 km off the coast of Esbjerg in Denmark. While, the failure maintenance and transportation costs remained other two major contributing factors in the operation and maintenance cost.

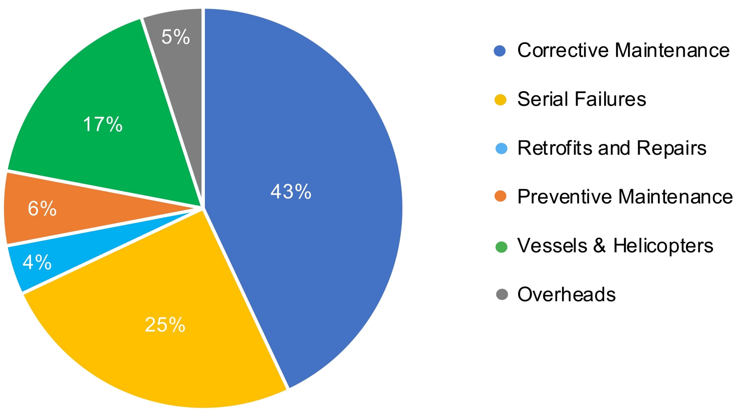


Figure 3.7: Estimation of O&M life cycle cost at Horns Rev wind farm [35]

The cost of wind power can be significantly reduced by deploying reliability analysis methods and maintenance strategies into the planning and designing phases of a wind farm project. A wind turbine based on the reliability design shows improved performance in power generation, structural safety, failures and maintenance.

Chapter 4

Finite Element Modeling and Analysis

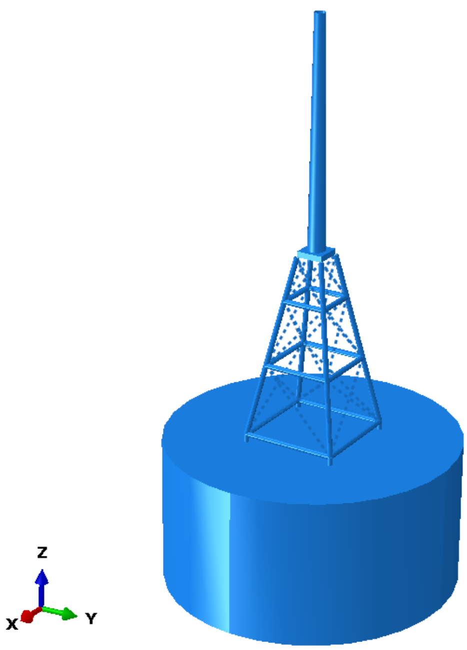
4.1 Introduction

The finite element method is a numerical method to solve mathematics and physics problems. The concept of FEM is to divide the whole model into small elements and then mathematical equations are applied to get the approximate solution. Many industries rely on finite element method to optimize their designs and to identify potential failures before manufacturing. It reduces the number of physical prototypes and experiments to refine components and develop better products more quickly. It is used in variety of fields, which include structural or fluid behavior, thermal analysis, wave propagation, or manufacturing, construction and aerospace industries etc. Large number of software packages like ABAQUS, ANSYS, ADINA, and RFEM, are available, that use finite element method for solving engineering problems. ABAQUS is a powerful engineering simulation program, developed by Dassault Systèmes, which is significantly been using in aerodynamics, defense, automobile, architecture and construction industries.

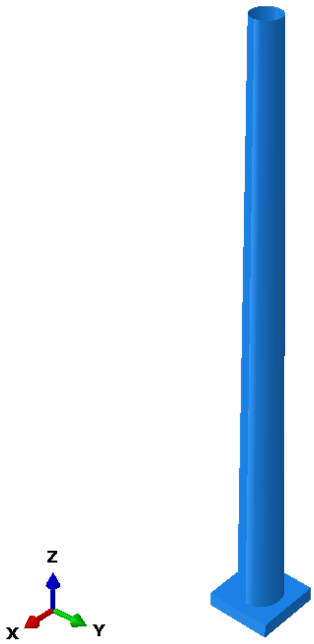
4.2 Jacket Type Offshore Wind Turbine Model

Numerical simulations of Jacket type offshore wind turbine is performed using ABAQUS. The dimensions of the Jacket wind turbine have not been specified anywhere in the patents or made publicly available from the manufacturers. However, students from National Taiwan University in 2016 conducted a research project for the design and analysis of jacket structure for offshore wind turbines and their used dimensions are chosen for this study. Furthermore, the layouts of NREL 5 MW baseline turbine model have also been selected for the current model [37, 38].

Two models are made for this study. One is the full-scaled complete model and the other one is the simplified model. Rotors and nacelle were neglected from both the models and applied separately as a dead load on the top of the both models. The complete model took between 4 to 5 hours and simplified model took around 10 to 15 minutes to complete a single simulation. As the major part of this thesis is based on the iterations, so instead of a complete model, simplified model is used for reliability analysis. The complete model is a 3D four-legged lattice structure along with the corner piles. The corner piles are interconnected with steel X-type bracings that form a supporting tower for a wind turbine. The simplified model is only a tower assigned the same specifications as of the complete model's tower. The ABAQUS generated FEM models are shown in Figure 4.1.



(a) Complete Model



(b) Simplified Model

Figure 4.1: Complete and Simplified finite element models for the study

The simplified model has neither jacket structure, X-bracings nor the seabed foundation, so a difference in the displacements between both the models was observed, which could make the results of simplified model inaccurate. To use a simplified model, the displacements should be equivalent with the complete model, which is achieved by applying a predefined force of 18.50 kN as a wave load. The displacements of complete and simplified models were 0.0450 m and 0.0443 m respectively. As the difference between both the models is 1.5%, so a simplified model can be used for further reliability studies. A visualization and comparison of displacement values of both the models in X-direction is shown in the Figure 4.2 and 4.3.

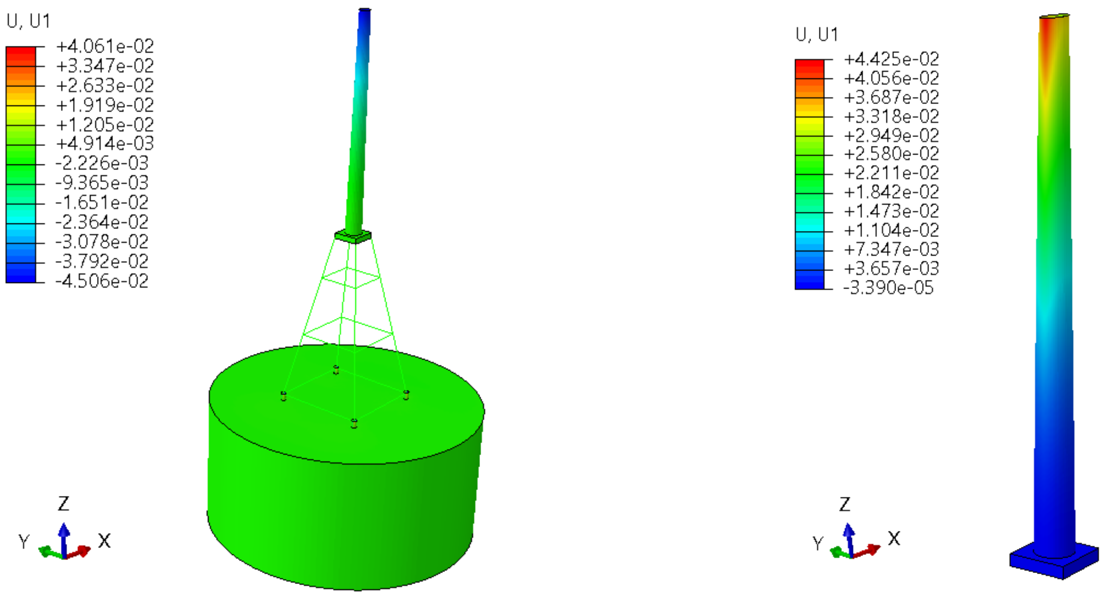


Figure 4.2: Displacement visualization of Complete and Simplified models

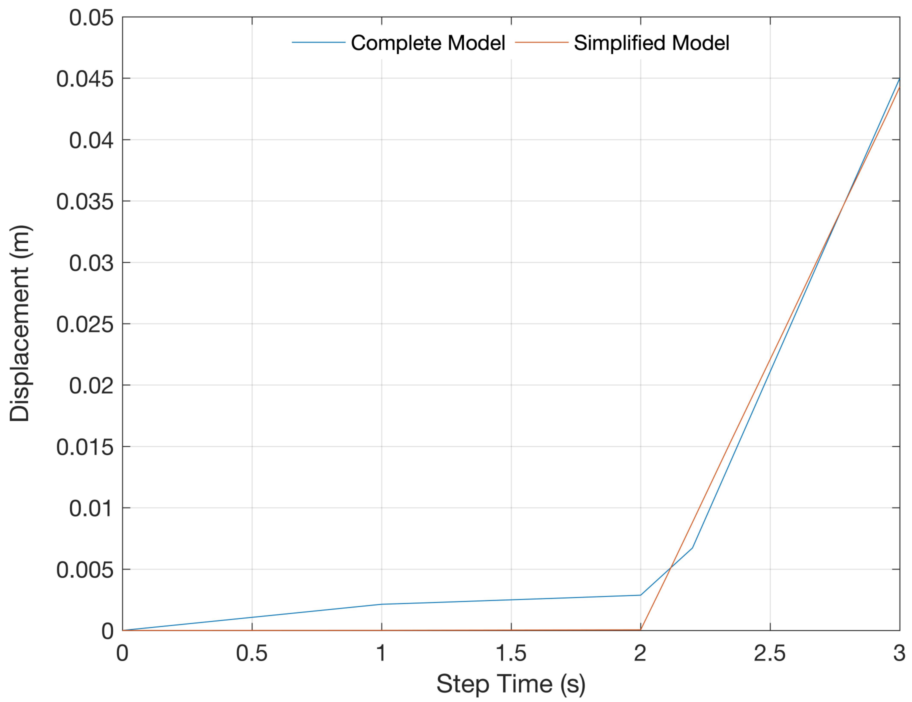


Figure 4.3: Displacement comparison of Complete and Simplified models

4.2.1 Geometry

The complete model is 100 *m* in width and 200 *m* high with ocean level at 100 *m* from the bottom of seabed. Depth of the seabed is 50 *m* which has surrounded the turbine by a radius of 50 *m*. The piles are 32 *m* x 32 *m* apart from each other, which are driven 30 *m* into the seabed with 2.5 *m* above the seabed to anchor with the jacket structure. The jacket is 66 *m* tall and legs are 10 degrees tilted towards the center, creating a distance of 9 *m* x 9 *m* at the top of a jacket structure. The structure is divided into three brackets, bottom, middle and top which contains X-bracings, which are connected through a weld joint. The bottom, middle and top are 25.5 *m*, 22 *m* and 16 *m* high respectively and the transition piece is 2 *m* high. The diameter of the piles, jacket members (legs and bracings) is 1.8 *m*. A hollow steel section is used for legs, piles and bracings with a thickness of 4 *cm*. The tower is also a hollow steel section with a base diameter of 6 *m* and top diameter of 3.84 *m*, with a thickness and height of 1.9 *cm* and 80 *m* respectively.

The simplified model is only a tower with a hollow steel section raising at a height of 80 *m* with base diameter of 6 *m* and top diameter of 3.84 *m* along with the thickness of 1.9 *cm*. The simplified model tower is grounded with a steel plate of 9 *m* x 9 *m* x 2 *m*. The geometry is explained in the Figure 4.4.

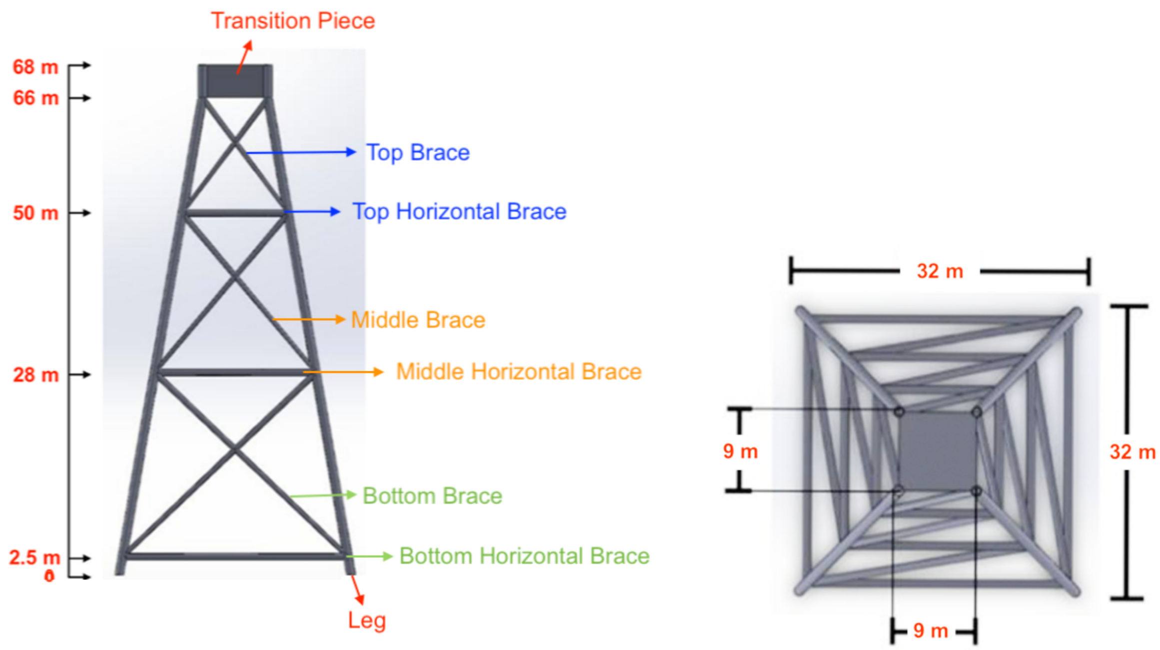


Figure 4.4: Terminologies and Geometry used for the models [37]

4.2.2 Meshing

The idea of finite element analysis is based on dividing the model into smaller domains which are called elements. The accuracy of FEM model directly depends on the finite element mesh size. Type and size of the mesh determines the overall accuracy of a model. The elements become smaller as the mesh size is refined, only then a true numerical solution is achieved. However, finer mesh size will require more computational time. One approach in minimizing the computational time is to apply the fine mesh in the areas which have high stress or which are the regions of interest. Remaining other parts can be meshed coarser. For the current study, plain strain of CPE 8 element type is used. For the complete model, jacket structure is meshed with 0.6 m size, seabed is meshed with 2 m size, while tower and piles are meshed with 0.2 m size. For the simplified model, tower and tower base plate are meshed with 0.4 m size, which is shown in the Figure 4.5.

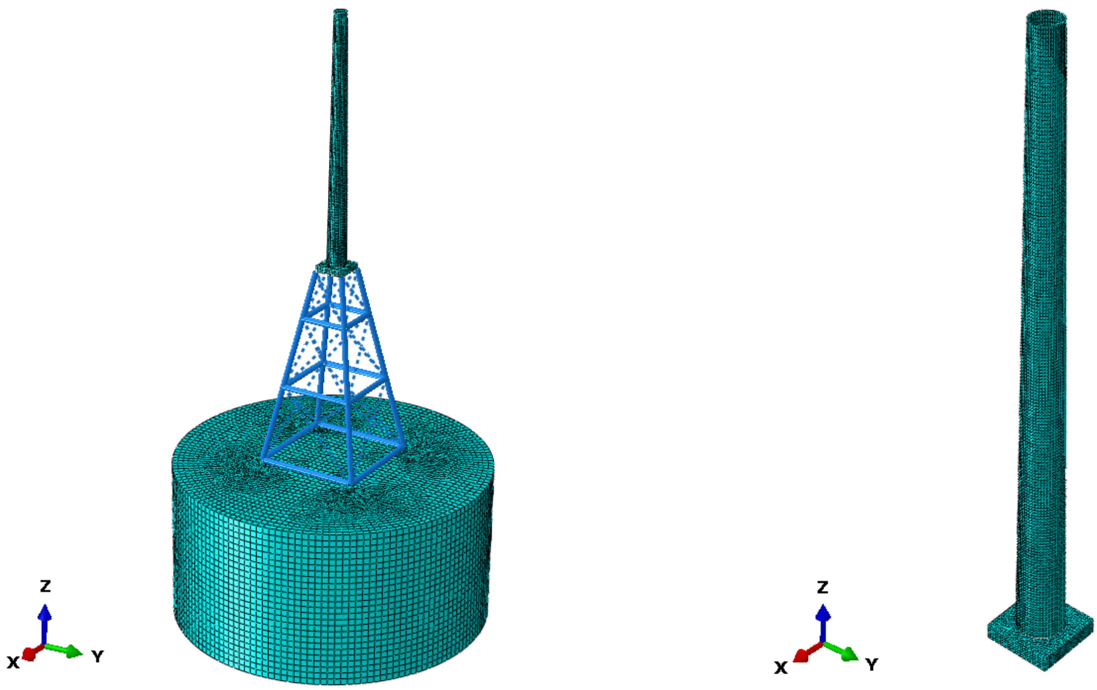


Figure 4.5: Finite element meshing of both models

4.2.3 Material Properties

Two materials are used for the current study i.e. soil and steel. Soil properties are applied to the seabed and steel is applied to the piles, legs, bracings and tower. Steel follows the linear elastic behavior whereas, soil is modeled using Mohr-Coulomb theory. Both the models are applied with the same material properties, which are summarized in Table 4.1.

Table 4.1: Material properties for modeled wind turbine [38, 39]

Material	**Units**	**Soil**	**Steel**
Density	kg/m^3	2000	7850
Poisson's Ratio	-	0.3	0.26
Modulus of Elasticity	MPa	50	2.1 x 10^5

4.2.4 Loadings

Four type of loads are applied on the each model i.e. gravity load, self-weight, wind and wave loads. Gravity load is due to the gravity itself and applied with a value of 10 m/s^2 on the whole models. As nacelle and rotors are neglected from the modeling so, self-weight of these components are applied as 240 and 110 tonne respectively. The weights are converted into kN and distributed on the top surface area of the tower as a stress with a value of 15.04 MPa. The weight of these components have taken from the NREL baseline 5 MW model [38].

Wind loads are calculated from the wind speeds and Deutscher Wetterdienst (DWD) data for the Frankfurt weather station is used for acquiring 10 minute peak wind speeds, which spanned from 2000 to 2018. The selection of the Frankfurt weather station is due to the reason that the hub height of the designed model and the station height is almost identical i.e. 98 m and 100 m respectively. For this study, wind speed is assumed to be uniformly distributed along the longitudinal profile of the turbine tower and Eq. 2.4, Eq. 2.10, Eq. 2.11 and Eq. 2.12 are used to calculate the wind loads on the top of the wind turbine tower. The weather station information is given in the Table 4.2.

Table 4.2: Wind speed measuring weather station information, Source: DWD [40]

Station ID	**Station Name**	**Station Height**	**Interval**	**Coordinates**
01420	Frankfurt / Main	100 m	10 minutes	50.0259 **N**, 8.5213 **E**

An example of wind load calculation on an assumed wind speed of 10 m/s is as follows.

$\mathrm{V_{hub}}$ = 10 m/s (Assumed)
z_{hub} = 98 m
$\mathrm{I_{ref}}$ = 0.14 (for medium wind characteristics)
σ = 1.83 (from Eq. 2.4)
C_{f} = 1.2
$\mathrm{A_t}$ = 620 m^2
G = 0.65 (for rigid structures)
V = 11.83 m/s ($\mathrm{V_{hub}} + \sigma$)
K_{z} = 1.75 (from Eq. 2.12)
K_{zt} = 1.0 (for flat terrain)
K_{d} = 0.95 (for round tower)
I = 1.0

Putting above values in Eq. 2.10 and Eq. 2.11 to get wind pressure and wind force acting on a wind turbine tower.

$\mathrm{q_z}$ = 143 N/m^2 (wind pressure)
$\mathrm{F_{wi}}$ = 69 kN (wind force)

Wave loads are generated due to the turbulence in the ocean tides, which exert forces on the wind turbine structure. For this study, ocean depth of 50 m is considered. The wave data is taken from the Bundesamt Für Seeschiffahrt und Hydrographie (BSH) portal for the FINO 1 station, which is a research platform located 40 km away from the German coast in the the North Sea. Wave loads are applied only on the complete model and the deflections were calculated, and included in the simplified model to include the effect of wave loads. Eq. 2.29 can be used to calculate the wave loads, which is as follows.

C_d = 0.65 (for newly coated member)
ρ_w = 1000 kg/m^3
D_m = 1.8 m
C_m = 1.6 (for deep waters)
A_m = 0.11 m^2
H_s = 6 m (taken from BSH portal)
T_p = 28.57 sec (taken from BSH portal)

Wave force acting on one jacket leg can be calculated by putting above values in Eq. 2.29.

F_{wa} = 35.27 kN (on one leg)
F_{wa} = 141.10 kN (on four legs)

4.3 Chosen Parameters

Wind speeds not only determine the amount of power generation, but they also play an important part in the structural safety of a wind turbine. They carry a driving force that can even overbalance the wind turbine and cause failure. Most of the structural failures in wind turbines are caused by high wind speeds and because of this significance, wind loads are chosen as the first parameter for this study.

The other chosen parameter is the modulus of elasticity. The structural steel properties used for the modeling of wind turbine confines with the A36 steel properties of ASTM standard, which are mentioned in the Table 4.1. Modulus of elasticity determines the stiffness of the material. Structures where minimal deflections are desired, are often designed with materials with high modulus of elasticity. High elastic materials tend to perform much better in vibrations and sinusoidal loads. Wind turbine are subjected to high dynamic loads and vibrations, which make the modulus of elasticity as an important parameter in the structural failure of a wind turbine system.

4.4 Failure Criteria

The limit state criteria for wind turbines have been mentioned in the *EN 1993-1-1: Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings* and are based on the factor of safety values. A deflection control approach is used to determine the failure criteria of the created model. The simplified model behaves as a cantilever beam and a deflection limit of L/180 is mentioned in the Eurocode as the maximum allowable deflection for a cantilever beam [41]. The same L/180 limit is chosen as a failure criteria for the current study. With the tower length of 80 m and a factor of safety of 1.1 for material uncertainties, the failure criteria becomes 0.40 m, which is illustrated in the Figure 4.6.

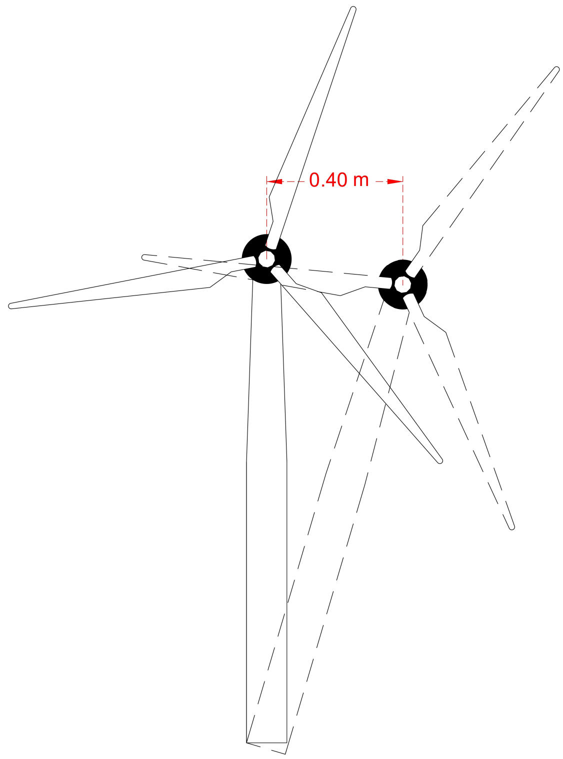


Figure 4.6: Failure limit for the current model of study

Chapter 5

Reliability Analysis

Earlier civil engineering designs were based on the deterministic way i.e. calculation of loads with given material properties. During the lifespan of the structures, it was assumed that loadings and material properties were not accurately determined in advance. For such evident reasons, a certain variability in the loadings and structural properties must have to be taken into the consideration, which resulted into the probabilistic approach. Reliability analysis is a probabilistic based methodology which takes accounts for all the uncertainties in a system and its core objective is to evaluate the ability of systems or components to remain safe and operational during their lifecycle. Structural reliability analysis deals with the quantitative assessment of the probability of occurrence of such failures (probability of failure), given a model of the uncertainty in the structural, environmental and load parameters.

The main task of this study is to estimate the reliability of a developed wind turbine model. The reliability for the current study is computed by two approaches. First approach involves the direct implementation based on the 225 ABAQUS simulations, while the other approach is to convert 225 simulations into greater number of samples and perform reliability analysis using UQLab. In the end, a comparison between different failure probability estimation methods are presented. Several different reliability methods which includes the Monte Carlo, First Order Reliability Method (FORM), Importance Sampling, Subset Simulation and Adaptive Kriging Monte Carlo Simulation method (AKMC) are considered for this study. In addition, Polynomial-Chaos-Kriging (PC Kriging) metamodel is also developed.

5.1 Failure Probability - Direct Approach

The direct approach involves 225 ABAQUS simulations performed by a random combination of wind loads and modulus of elasticity values. Displacements of all the 225 samples were calculated using python scripts and compared against 0.4 m failure criteria. The whole procedure is described below:

1. First, the wind speed data was analyzed for defining the domain. The wind data was comprised of 18 years between 2000 to 2018. The minimum and maximum wind speeds were found to be

0.2 m/s and 32.1 m/s respectively and wind loads (WL) were then calculated and found to be 0.4 kN and 650 kN. Similarly, for modulus of elasticity (E), mean value of 210 GPa and standard deviation of 12.5 GPa was modeled, which gave a domain from 159 GPa to 277 GPa. After getting the domains of both variables, histograms with probability distributions were prepared. E was modeled with Normal distribution and WL was best fitted with a Lognormal distribution as shown in the Figure 5.1. The statistical properties of probability distributions of variables E and WL are described in the Table 5.1.

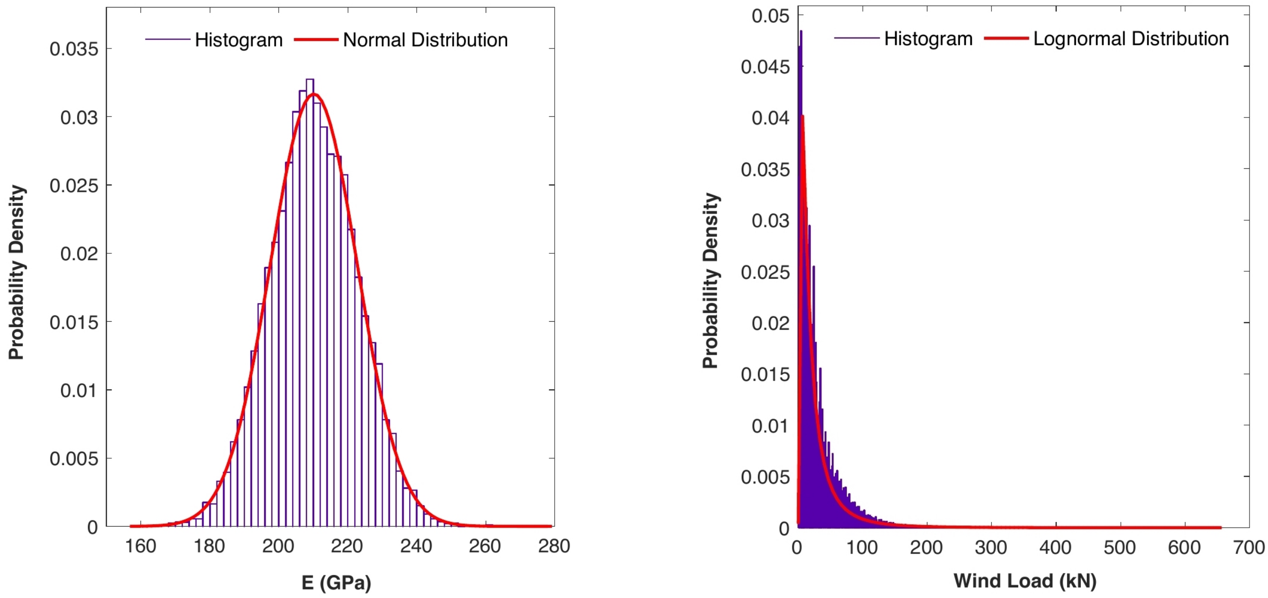


Figure 5.1: Histograms and probability distribution fits of E and WL

Table 5.1: Statistics of probabilistic distributions of E and WL

Variable	Description	Distribution	Mean	Std. Deviation
E	Elastic Modulus	Normal	210 GPa	12.5 GPa
WL	Wind Load	Lognormal	28 kN	1710 kN

2. Second step was to generate a histogram and probability distribution that fits for the displacement data of 225 samples within the combined domain of E = [159 to 277 GPa] and WL = [0.4 to 650 kN]. Python script was then used to get the displacement values of 225 simulations and transform them into Matlab import format. Generalized Extreme Value distribution (GEV) showed the best fitted results for the displacement values than any other distribution. The results are shown in the Figure 5.2. The Table 5.2 shows the statistical properties of GEV

distribution fit. Using the properties of GEV distribution, failure probability was estimated.

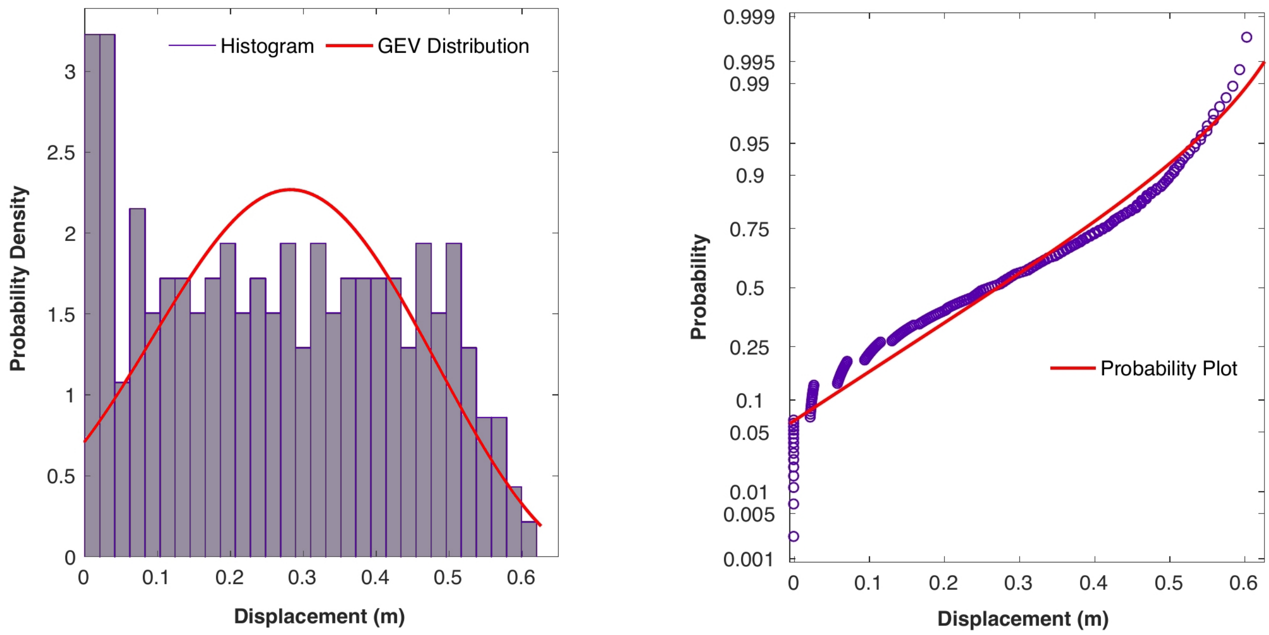


Figure 5.2: Histogram, pdf and probability plot of the 225 simulations

Table 5.2: Statistics of the GEV distribution of 225 samples

Statistical Metrics	**Observed Values**
Mean	0.265 m
Variance	0.028 m
Scale Parameter	0.174
Shape Parameter	-0.356
Location Parameter	0.211

The cumulative density function of the Generalized Extreme Value distribution is given by the equation:

$$f(x) = \frac{1}{\sigma} \exp\left(-\left(1+kz\right)^{-\frac{1}{k}}\right)\left(1+kz\right)^{-1-\frac{1}{k}} \quad , \tag{5.1}$$

where,

σ = *Scale parameter,*
k = *Shape parameter,*
μ = *Location parameter,*
z = $(x$ - $\mu)/\sigma$.

Integrating the function at the failure criteria $f(x \geq 0.4)$, reliability can be estimated as:

$$R = 1 - P_f = 1 - 0.2246 = 0.7754 \tag{5.2}$$

So, a developed wind turbine is 77% structurally reliable based on the 225 simulations under specific conditions.

5.2 Failure Probability - Alternative Approach

The idea of alternative approach is to extend the 225 simulations to a higher number to get more accuracy in the results, without being simulated again through ABAQUS. For accurate results, it is recommended to have at least 10,000 MC samples, which is unattainable for ABAQUS and can make the simulations expensive and time-consuming. The method adopted for this problem involved developing an equation, that is valid for 225 simulations. Later, that equation was used as an input in **UQLab** to estimate the probability of failure. UQLab is a general purpose uncertainty quantification framework developed at ETH Zürich. It is a Matlab based uncertainty quantification framework, which offers powerful and intuitive ways to solve many mathematical problems. Inverse analysis, optimization, reliability analysis, surrogate modeling, sensitivity analysis, regression models and many other advanced topics are included in the UQLab framework. The front end interface of UQLab is quite simple and easier to understand but the back end underlying interface is where all the working and coding is done [42]. The procedure of alternative approach is explained below:

1. First, the displacement data of 225 simulations were processed through a regression analysis. Regression analysis is a predictive modeling technique to represent a relationship between dependent and independent variables. Different types of regression models are available e.g. linear, polynomial, logistic, ridge, lasso or elasticnet regressions etc. The choice between different types of regression models depends on the data type. After getting the equation, the goodness of the fit is performed with statistical metrics i.e. R-squared, Adjusted R-squared and standard error. For the current study, linear regression model with two variables is used. **Y** represents the displacements (m), while $\mathbf{X_1}$ is the wind load in kN and $\mathbf{X_2}$ represents the modulus of elasticity in GPa. The equation after regression analysis is shown below:

$$Y = 0.254 + 0.000855X_1 - 0.00127X_2 \tag{5.3}$$

The statistics of the regression analysis shows that the 225 ABAQUS simulations data is well fitted with the equation as the R-square and Adjusted R-square values are close to the unity. The goodness of the fit statistics are presented in the Table 5.3.

Table 5.3: Regression statistics of the 225 samples

Statistical Metrics	**Observed Values**
R-Squared	0.995761
Adjusted R-Squared	0.995722
Standard Error	0.011312
Difference in Values	6.7%

2. The Eq. 5.3 will give the displacement values against any given value of E and WL. It will not define the limit state function. To do so, the Eq. 5.3 was modified by adding 0.4 m as a failure criteria to get the displacements in the form of a function $g(x)$ and the probability of failure becomes $g(x) \leq 0$. The equation 5.4 is a modified equation with a limit state function.

$$g(x) = 0.4 - 0.254 - 0.000855X_1 + 0.00127X_2 \tag{5.4}$$

3. In the third and the last step, equation 5.4 is imported in the UQLab for MC and other reliability analysis methods. The general methodology of uncertainty quantification underlying UQLab is show in the Figure 5.3. Objects does not require any specific configurations instead they only requires minimum syntax, which mostly are the input model parameters. The UQLab framework requires three components to proceed with the reliability analysis.

    - A model input that defines the limit-state function, $g(x)$,
    - An input model that describes the probabilistic model of variables (E and WL),
    - A reliability analysis method (MC, FORM or AKMC etc)

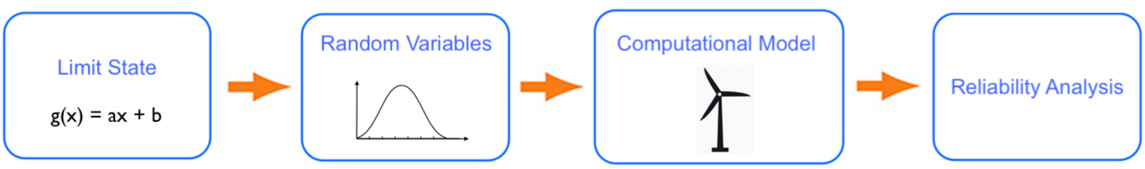


Figure 5.3: The general uncertainty quantification framework underlying UQLab [42]

Table 5.4: Input parameters for UQLab

Index	Name	Variable	Type	Parameters	Moments
1	X_1	Wind Load	Lognormal	[2.754, 1.076]	[28.03, 41.40]
2	X_2	Elastic Modulus	Gaussian	[210, 12.5]	[210, 12.5]

Reliability analysis using UQLab is performed for 1 million samples. The Monte Carlo method utilized all the samples, while the other methods FORM, Importance Sampling, Subset Simulation and AK-MCS achieved convergence with less number of samples. This is due to the intelligent algorithms of UQLab, that uses the results of MCS to identify the failure regions and perform simulations only for those critical regions. The results of UQLab are expressed in terms of probability of failure (P_f), reliability index (β), covariance (COV) and number of model evaluations. The results are presented in the Table 5.5. The graphical illustration of the results also include the convergence plots of P_f and β as shown in Figures 5.4, 5.5, 5.6 and 5.7.

Table 5.5: Results of the reliability analysis using UQLab

Reliability Method	P_f	β	COV	No. of Simulations
MCS	0.000741	3.1785	0.0367	1,000,000
FORM	0.000735	3.1804	-	22
Importance Sampling	0.000791	3.1595	0.0566	1022
Subset Simulation	0.000910	3.1194	0.2828	3518
AK–MCS	0.00088	3.1280	0.1066	14

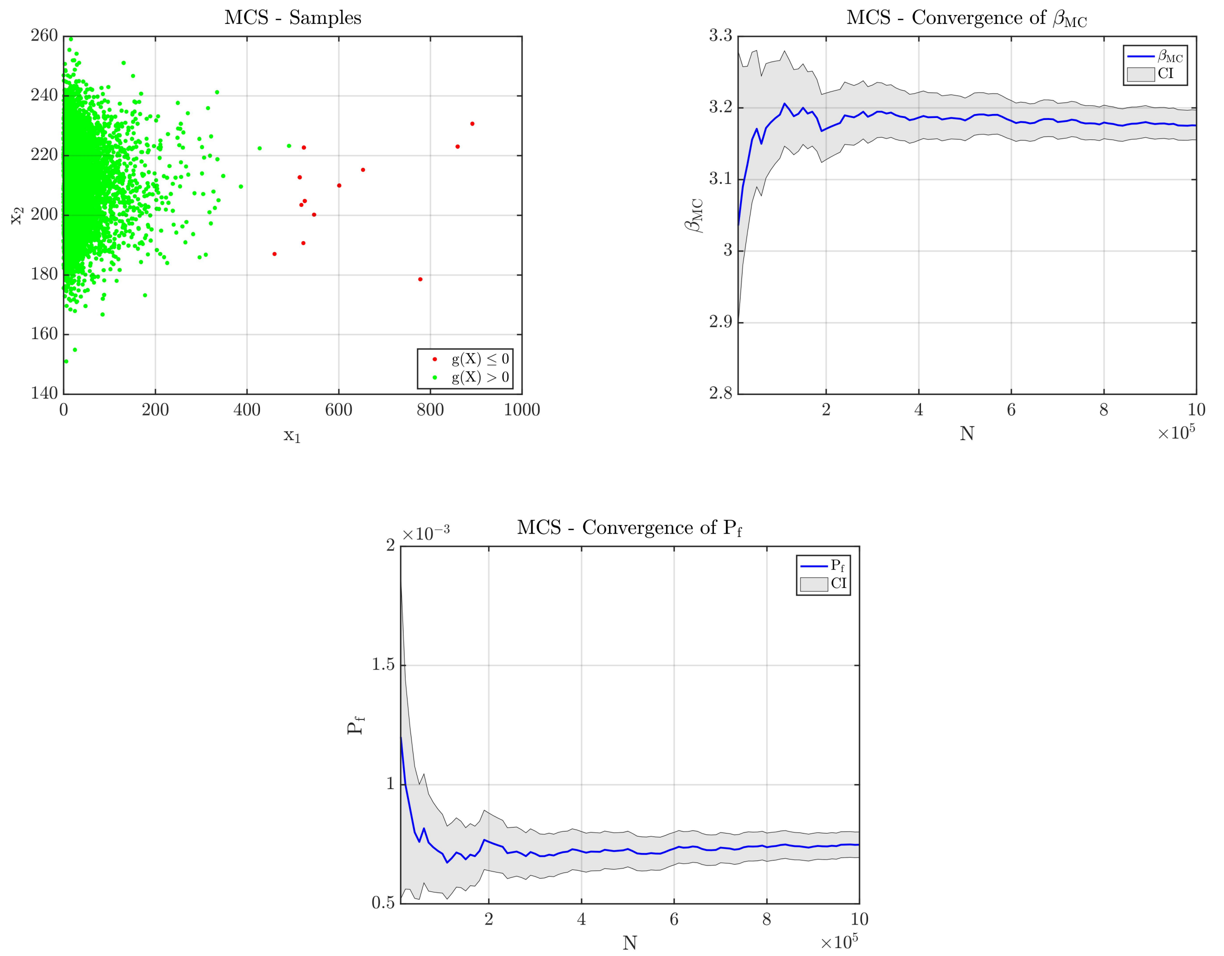


Figure 5.4: Monte Carlo Simulation results (samples and convergence of the results)

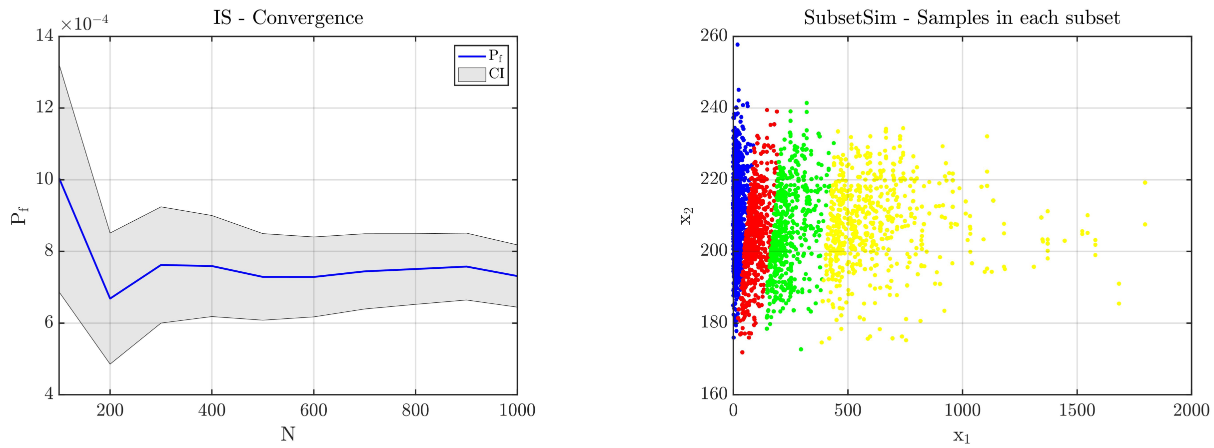


Figure 5.5: Importance Sampling and Subset Simulations results

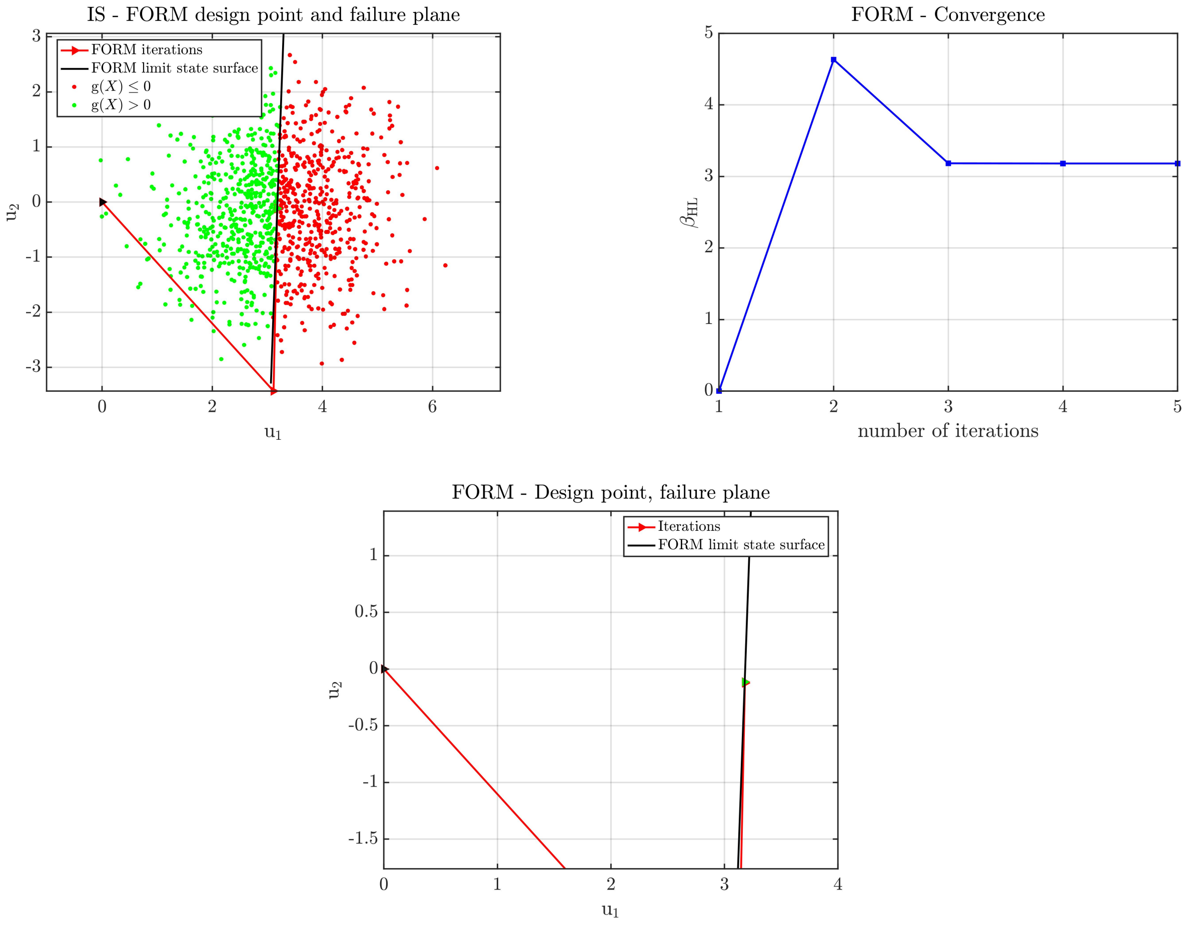


Figure 5.6: FORM results

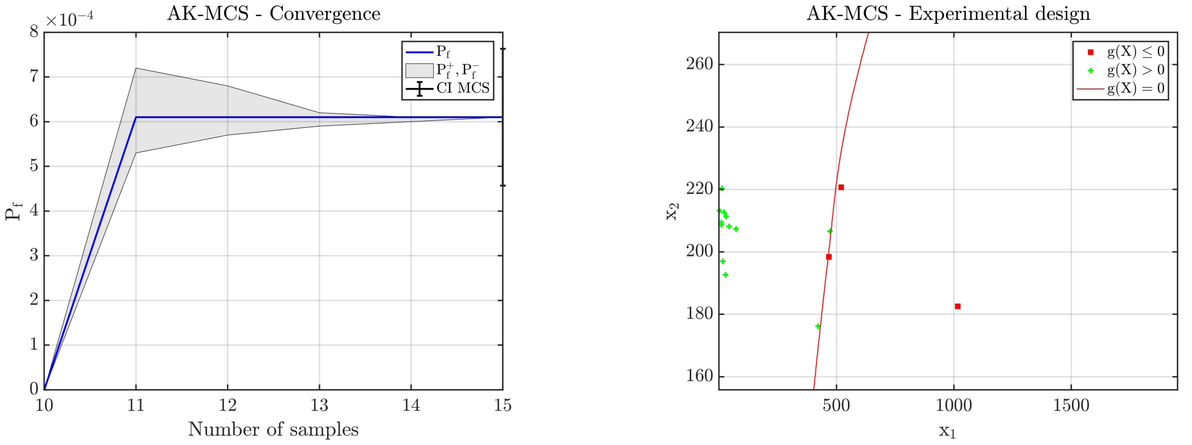


Figure 5.7: Adaptive Kriging Monte Carlo Simulation results

The Table 5.6 compares the reliability analysis results at different number of samples.

Table 5.6: A comparison of probability of failure at different number of samples

Reliability Method	**P_f at Different Number of Samples**				
	5000*	**10,000***	**50,000***	**100,000***	**500,000***
MCS	0.00040	0.00090	0.00060	0.00077	0.00073
FORM	0.000735	0.000735	0.000735	0.000735	0.000735
Importance Sampling	0.00084	0.00075	0.00072	0.00070	0.00075
Subset Simulation	0.000492	0.000956	0.000710	0.000827	0.000690
AK–MCS	0.00075	0.00075	0.00088	0.00078	0.00084

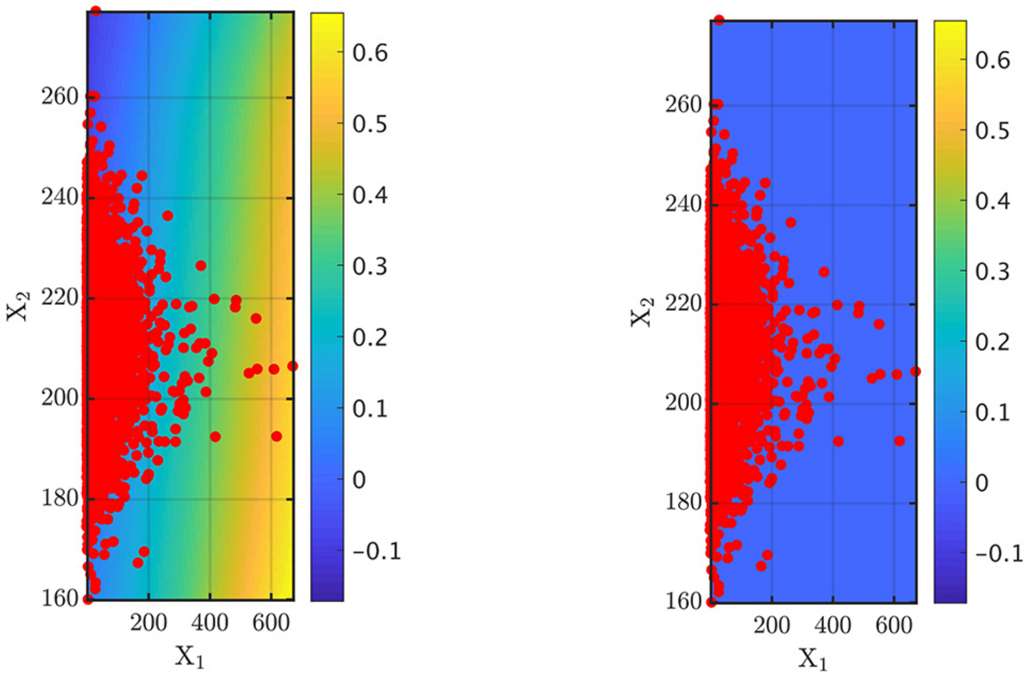
* Number of Samples

5.3 Polynomial-Chaos-Kriging Metamodel

A surrogate model is an engineering method, which is used for the approximation of input and output functions. It is significantly useful when an outcome of the model cannot be directly measured due to time-consuming or expensive simulations. Many civil engineering models are complex and often requires experiments or simulations for the optimum design. These experiments or simulations can take several hours to even days to complete a single dataset. Since design optimization requires a large number of simulations, so it becomes unfeasible and impossible to process large number of simulations. The engineers came up with a solution for such problems by constructing approximation models, which are known as surrogate or metamodels that resembles the simulation results as closely as possible while being computationally cheaper to evaluate. The main aim of these surrogate models is to reduce the computational costs and allow for more sophisticated analyses, such as reliability analysis and design optimizations. A metamodel is constructed from the response of the simulations at a limited number of chosen data points. Surrogate models are often used in other areas of science, where there are expensive experiments or simulations are involved. The main challenge for the engineers is to build these surrogate models, that accurately represents the experimental model by using few simulations. The accuracy of the surrogate depends on the number and location of samples [43].

Polynomial-Chaos-Kriging (PC-Kriging) is a state-of-the-art metamodeling algorithm which was developed by the *Stefano Marelli* and *Bruno Sudret* at ETH Zürich, which is based on the well-established Polynomial Chaos Expansions and Kriging. Due to the integration of Polynomial Chaos Expansions and Kriging, PC-Kriging is transformed into the most sophisticated and advanced algorithm, which allows to capture the global behavior of the computational model as well as the local variations. This combination in a metamodeling technique is more efficient than Polynomial Chaos Expansions and Kriging separately [42]. The PC-Kriging surrogate model of the current study is shown in the Figure

5.8, which includes the mean and variance plots of the variables X_1 = Wind Load and X_2 = Modulus of Elasticity.



(a) Mean

(b) Variance

Figure 5.8: PC–Kriging surrogate model

5.4 Conclusion

Reliability analysis, which offers the mathematical framework for considering uncertainties in engineering systems, plays very important role in the design of wind turbines. Wind industry is thriving towards cheaper production and better performance of the wind turbines, which cannot be achieved without the reliable wind turbines. Reliability studies of the wind turbines are being performed on a larger platform to identify and counter the uncertainties in their system, that can significantly improve the performance of the wind turbines. This study has evaluated the reliability of a Jacket type offshore wind turbine under specific conditions. The present study considers only the structural failure of the wind turbines but it is not limited to the structural failure. It can be expanded to other failure modes of wind turbines as well. Following are the conclusions of this study.

1. Research on the wind turbine reliability assessment focuses mainly on rotor blades and gearbox. Very less research is performed on the structural failure of wind turbines,
2. The number of samples is a key factor in determining the probability of failure. A large number of samples will result in more accurate results. The reliability of 225 samples is 77.5% and for 1 million samples is 99%. The reason for these difference in reliabilities is because a single number can create a huge impact on the outcome in a small domain,
3. For the current model, the mean displacement value is 0.265 m, which lies fairly within the limit state,
4. The reliability index β for this research is 3.20, which coincides with the excellent reliability index threshold between 2.7 to 3.1, is deemed good,
5. The reliability method, Importance Sampling, is a method to improve the efficiency of Monte Carlo simulation. It changes the sampling density so as to focus only regions of importance. The importance regions in reliability problems can be seen as the failure regions,
6. It is seen from the results that coefficient of variation (COV) decreases as the sample size increases. Therefore, accurate solution can only be obtained by using sufficient large sample size,
7. FORM, Importance Sampling and Adaptive Kriging methods showed very consistent results as compared to the MCS and Subset Simulation methods. The convergence of failure probability and reliability index of FORM and AK–MC is very impressive than the other reliability methods.

Chapter 6

Future Aspects of Wind Energy in Pakistan

Pakistan, as a developing country has seen its growing energy demands over the past recent years. Currently, natural gas, oil, hydropower and coal still remains the major sources of power production in the country. Due to the recent unstable economic conditions, Pakistan has seen the worst shortfall of energy ranging between 4 to 6 GW in 2012. The deficit of energy has been controlled somehow but still due to the lack of energy policies by the government of Pakistan, the energy crisis can spike anytime. The current power production resources are diminishing and also effecting the environment, which raises the need for an alternative source. Still, Pakistan has no clear renewable energy plans and policies which on many occasions expressed by the policy makers. However, the government has acknowledged the urgent needs and started to invest in research projects and policy building for future country's electricity demands [44].

Fortunately, Pakistan lies in a region where wind speeds are much higher specially due to the presence of Indian ocean, high wind speeds are available around coastal regions. Mean annual wind speeds are generally between 6 to 8 m/s, which are sufficient enough to generate a steady power throughout a year. Ministry of Energy has put research efforts in collaboration with IRENA, Wold Bank, DTU, USAID and NREL to identify the wind potential of Pakistan. The results were validated by DTU, which indicated a potential of 346 GW. The government of Pakistan has decided to develop wind power energy sources due to its problems of deficit of electricity. Around 250 MW wind power projects are undergoing or operating that are undertaken with the cooperation of government of China. Pakistan is developing onshore wind power plants in *Jhimpir, Gharo, Keti Bandar and Bin Qasim* regions which are located in the southern part of the country which are estimated to have a potential of 50 GW alone. Wind projects cannot grow without the assistance and cooperation from the government. Pakistan is also developing policies and infrastructure for foreign companies that will smoothen their plans and strategies to come and invest in the wind sector of the country. These major developments include the policy reforms, regulatory transformations, infrastructure development, research projects with other international agencies and investment incentives to continue wind power production industry in the country. The government of Pakistan has also taken initiative in making policies for the implementing the wind projects by facilitating them in tax leverages [44]. Tables 6.1 and 6.2 shows the current and future planned wind energy projects in Pakistan.

Table 6.1: List of on-going wind energy projects in Pakistan [44]

Sr. No.	**Name of Project**	**Capacity**	**Location**
1	Hydrochina Dawood Power	49.5 MW	Gharo
2	United Energy Pakistan	99 MW	Jhimpir
3	Sachal Energy Development Pvt.	49.5 MW	Jhimpir
4	Jhampir Wind Power	49.6 MW	Jhimpir
5	Hawa Energy Pvt.	50 MW	Jhimpir

Table 6.2: List of future planned wind energy projects in Pakistan [44]

Sr. No.	**Name of Project**	**Capacity**	**Location**
1	Three Gorges Second Wind Farm	49.5 MW	Jhimpir
2	Three Gorges Third Wind Farm	49.5 MW	Jhimpir
3	Tricon Boston Consulting Corporation	99 MW	Jhimpir
4	Western Energy Pvt.	50 MW	Jhimpir
5	Burj Wind Energy Pvt.	14 MW	Jhimpir
6	Hartford Alternative Energy Pvt.	49.3 MW	Jhimpir
7	Shaheen Foundation	50 MW	Jhimpir
8	Trans Atlantic Energy Pvt.	50 MW	Jhimpir
9	Norinco International Thatta Power Pvt.	50 MW	Jhimpir
10	Act 2 Wind	50 MW	Jhimpir
11	Artistic Wind Power Pvt	50 MW	Jhimpir
12	Harvey Wind Power Project	50 MW	Jhimpir
13	Zulikha Energy	50 MW	Jhimpir
14	Gul Ahmed Electric	50 MW	Jhimpir
15	Din Energy	50 MW	Jhimpir

Pakistan is now preparing to use other energy resources, including renewables, to meet further increasing demand in power needs. The Government of Pakistan is devising policies, plans and programs to include clean, affordable and sustainable energy supply based on higher shares of renewables in the energy mix. Pakistan's total energy demand as of today is around between 23 to 25 GW. Installed capacities of alternative and renewable energy sources has already risen from 0.2% to 5.2% from 2013 to 2018. Energy generated from the wind power projects has a current share of 5% and authorities expect that by the 2030, the wind energy will constitute the larger share in the overall power generation than the 5% [44].

The current study can also be useful in implementing the wind projects in Pakistan. Reliability of wind turbines are of utmost importance for developing countries like Pakistan, where any failure or idle wind turbines can cause significant loss to the economy. Figure 6.1 shows the wind speed map of Pakistan which also indicates a bright future of wind energy in the country. However, it is majorly up to the government to make policies and facilitate these on going and future wind energy projects to make a stable economy in the world.

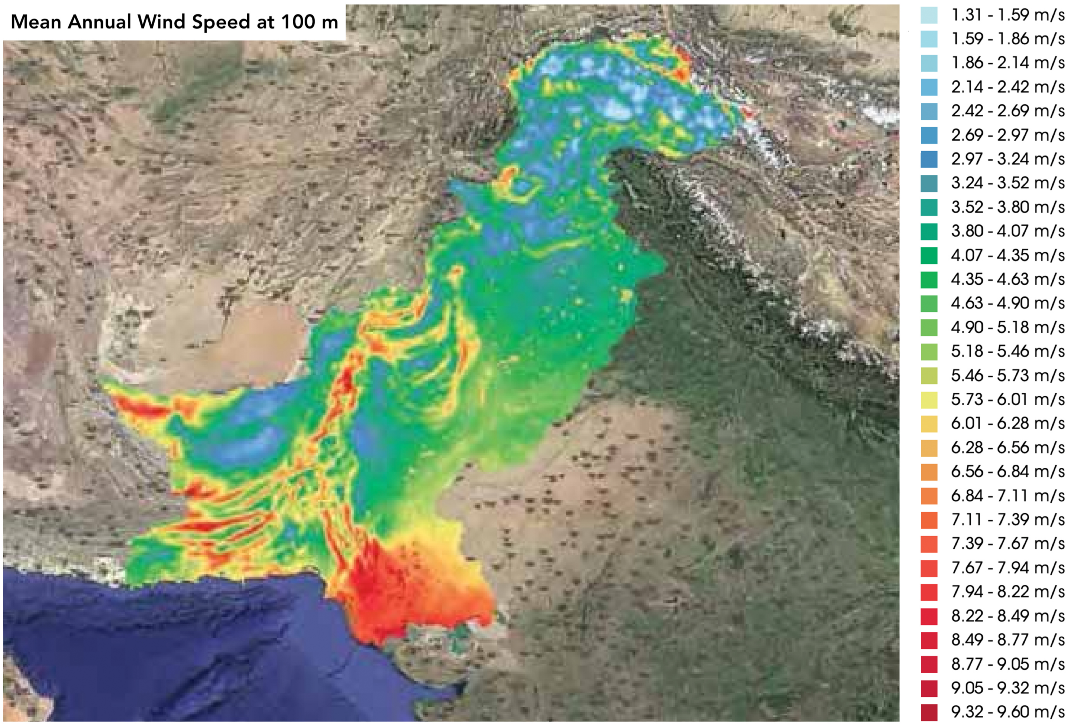


Figure 6.1: Wind speed map of Pakistan, Source: IRENA [44]

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Listings

Annex – 1: Matlab Code for Reliability Analysis by using UQLab

```
% Initialize UQLab
close all
clearvars
uqlab

% Limit State Module
ModelOpts.mString = '0.4 - 0.2544 - 0.000855*X(:,1) + 0.00127*X(:,2)';
ModelOpts.isVectorized = true;
myModel = uq_createModel(ModelOpts);

% Probabilistic Input Module of Variables
InputOpts.Marginals(1).Name = 'X1';
InputOpts.Marginals(1).Type = 'lognormal';
InputOpts.Marginals(1).Parameters = [2.754 1.076];
InputOpts.Marginals(2).Name = 'X2';
InputOpts.Marginals(2).Type = 'Gaussian';
InputOpts.Marginals(2).Parameters = [210 12.5];
myInput = uq_createInput(InputOpts);
uq_print(myInput)

% Reliability Analysis using Monte Carlo Simulation
MCSOptions.Type = 'Reliability';
MCSOptions.Method = 'MCS';
MCSOptions.Simulation.MaxSampleSize = 1e6;
MCSAnalysis = uq_createAnalysis(MCSOptions);
uq_print(MCSAnalysis)
uq_display(MCSAnalysis)

% Reliability Analysis using FORM
FORMOptions.Type = 'Reliability';
FORMOptions.Method = 'FORM';
FORMAnalysis = uq_createAnalysis(FORMOptions);
uq_print(FORMAnalysis)
uq_display(FORMAnalysis)
```

```
% Reliability Analysis using Importance Sampling
ISOptions.Type = 'Reliability';
ISOptions.Method = 'IS';
ISAnalysis = uq_createAnalysis(ISOptions);
uq_print(ISAnalysis)
uq_display(ISAnalysis)
SSimOptions.Type = 'Reliability';

% Reliability Analysis using Subset Simulation
SSimOptions.Method = 'Subset';
SSimAnalysis = uq_createAnalysis(SSimOptions);
uq_print(SSimAnalysis)
uq_display(SSimAnalysis)

% Reliability Analysis using Adaptive Kriging Monte Carlo Simulation
AKOptions.Type = 'Reliability';
AKOptions.Method = 'AKMCS';
AKOptions.AKMCS.MaxAddedED = 50;
AKAnalysis = uq_createAnalysis(AKOptions);
uq_print(AKAnalysis)
uq_display(AKAnalysis)
```

Annex – 2: Matlab Code for PC–Kriging Metamodel

```
% Initialize UQLab
close all
xSamp
xsamp = [X2 X1];
ysamp = Y;
uqlab;

% Input Module
input.Marginals(1).Name = 'WL';
inputopts.Marginals(1).Type = 'lognormal';
inputopts.Marginals(1).Parameters = [2.754 1.076];
input.Marginals(2).Name = 'E';
inputopts.Marginals(2).Type = 'gaussian';
inputopts.Marginals(2).Parameters = [210 12.5];
myInput = uq_createInput(inputopts);

% Creation of Metamodel
metaopts.Type = 'Metamodel';
metaopts.ExpDesign.X = xsamp;
metaopts.ExpDesign.Y = ysamp;
metaopts.MetaType = 'PCK';
metaopts.Mode = 'sequential';
metaopts.PCE.Method = 'LARS';
metaopts.PCE.Degree = 2:5;
metaopts.Kriging.Corr.Family = 'Matern-5_2';
dmodel = uq_createModel(metaopts);
```

Annex-3: Python Code for Parametric Study for 225 Simulations

```
% Creation of Parametric Study
wind = ParStudy(par=(('par1'), ('par2')))

% Defining Wind Load as a Parameter
wind.define(CONTINUOUS, par='par1', domain=(0.4., 650.))

% Defining Modulus of Elasticity as a Parameter
wind.define(CONTINUOUS, par='par2', domain=(159., 277.))

% Defining Number of Samples
wind.sample(NUMBER, par='par1', number=15)
wind.sample(NUMBER, par='par2', number=15)

% Combining the Parameters
wind.combine(MESH, name='1')

% Generating the Job
wind.generate(template='Job-1')

% Executing the Job
wind.execute(ALL)
```

Annex-4: Python Code for getting Displacements from ABAQUS

```
from ABAQUS import *
from ABAQUSConstants import *
from caeModules import *

session.Viewport(name='Viewport: 1', origin=(0.0, 0.0), width=200, height=160)
session.viewports['Viewport: 1'].maximize()

txt_Folder='C:/Users/justo/Desktop/Usman/Parametric study/Mix/Displacements/'

for i in range(1,226):
  o1 = session.openOdb(name='C:/Users/justo/Desktop/Usman/Parametric study/Mix
    Job-1_example_1_c'+str(i)+'.odb')
  session.viewports['Viewport: 1'].setValues(displayedObject=o1)
  session.xyDataListFromField(odb=o1, outputPosition=NODAL, variable=(('U',
    NODAL, ((COMPONENT, 'U1'), )), ), nodeLabels=(('PART-2-1',('11', )),))
  x0 = session.xyDataObjects['U:U1 PI: PART-2-1 N: 11']
  session.writeXYReport(fileName=txt_Folder+'Displacement'+str(i)+'.txt',
    appendMode=OFF, xyData=(x0, ))
  del session.xyDataObjects['U:U1 PI: PART-2-1 N: 11']
  session.odbs['C:/Users/justo/Desktop/Usman/Parametric study/Mix/Job-1
    _example_1_c'+str(i)+'.odb'].close()
```