Application of Monte Carlo simulation for the assessment of the availability of an offshore substation

Master thesis - MSc. Risk and Safety Management

The Faculty of Engineering and Science

Aalborg University – Esbjerg

Luca Emanuele Seresina

January 2020

Abstract and thesis information

Thesis title	Application of Monte Carlo simulation for the assessment of the availability of an offshore substation
University	Aalborg University
Education	Msc.Risk and Safety Management
Semester	4th
Supervisor	Jannie Sønderkær Nielsen
Members	Luca Emanuele Seresina
Hand-in-date	10 January 2020
Report language	English
Number of pages	52
Word count	16.968

Abstract

The project presents a Montecarlo simulation in the non-dedicated programming software environment R to analyse the availability of a substation and provide support to the develop of tools for the assessment of availability calculation based on failures of components and availability of O&M resources. The work uses Montecarlo simulation to ensure variability in calculation and include uncertainty. A generic model of an offshore substation is prepared, and a case study is built from it. The availability of a substation is calculated based on failures of components and mobilization of resources and reparation time of components. Data and information are gathered with the support of experts from the industry. A sensitivity analysis is carried out to develop a discussion around the model and the results. The availability and other economic measures are calculated from the case study. The thesis work and the results provide a glance on the potential of the utilization, even at its early stage of development, of Montecarlo modelling technique to help to improve the confidence of experts in the evaluation of the availability for projects development.

Preface

This work is the result of the thesis project of 30 ECTS points developed during the education in Risk and Safety management at the Aalborg University, campus of Esbjerg in the autumn of 2019. The project has been carried out in the period from the 1st of September until the 10th of January 2020. The project has been developed together with the collaboration of Semco. The thesis is intended for persons who are interested in the wind industry, offshore substation availability, RAM, quantitative risk assessment, Montecarlo simulation and the use of software and tools for the assessment of uncertainty.

I want to say thank you for the support during this period to my supervisor Jannie Sønderkær Nielsen for being supportive and patient with me and for reading all the material I sent her. I also want to thank Michael Korshøj Dalstrup, Peter Rex Drescher and Søren Krøyer Gundersen from Semco for their support as Semco experts for letting me use their knowledge, information and expertise and for using their time to listen to me and to answer to all my questions.

The valuable inputs from peer students Santa Gatere and Stefan Petroiu from RISK4 were also greatly appreciated.

Lastly, I wish to thank my mother for the unlimited support throughout these years and for having me helped to be who I am today.

Nomenclature – Acronyms

EU	European Union
GW	Gigawatt
MV	Megawatt
LcoE	Levelized Cost of Energy
CAPEX	Capital Expenditure
O&M	Operation and Maintenance
BoP	Balance of Plant
WTG	Wind turbine
HVAC	High Voltage Alternate Current
MV	Medium voltage
HV	High voltage
T	Transformer
SCADA	Supervisory Control and Data Acquisition system
LV	Low Voltage
UPS	Uninterruptible power supply system
EN	European Standard
CTV	Crew Transfer Vessel
SOV	Service Operation Vessel
OPEX	Operational expenditure
CRF	Capital Recovery Factory
AEP	Annual Energy Production
IEC	International Electrotechnical Commission
MTBF	Mean Time Between Failures
MTTR	Maximum Time To Repair
RAM	Reliability, Availability, Maintainability
Hs	Critical wave height
FTA	Fault Tree Analysis
AC	Alternate Current
SF6	Sulphur Hexafluoride
GIS	Gas Insulated Switchgear
kV	Kilovolt

Contents

1 Introduction ... 1
1.1 Renewable energy ... 1
1.2 Wind energy ... 3
1.3 Wind project cycle ... 3
1.3.1 Development ... 3
1.3.2 Commissioning ... 4
1.3.3 Operation and maintenance ... 4
1.3.4 Decommissioning ... 4
1.4 Offshore Wind energy ... 4
1.4.1 Offshore wind farm balance of plant ... 4
1.4.2 Offshore wind turbine ... 5
1.4.3 Offshore substation ... 7
1.5 Offshore O&M ... 10
1.5.1 Maintenance ... 10
1.5.2 O&M facilities ... 11
1.5.3 O&M resources ... 11
1.6 Offshore wind energy costs ... 12
1.7 Availability ... 16
2 State of the art – literature ... 19
2.1 Problem formulation ... 21
2.2 Problem delimitation ... 21
3 The availability assessment model ... 22
3.1 Main assumptions of the model ... 22
3.2 Availability assessment model algorithm ... 23
3.2.1 Preventive maintenance time function ... 25
3.2.2 Downtime function ... 26
3.2.3 Availability function ... 26
3.2.4 Accessibility modelling ... 27
3.2.5 Waiting time modelling ... 28
3.2.6 Failure modelling ... 30
3.3 Expert opinion modelling ... 31
4 Case study ... 32
4.1 Case study Model results ... 35
5 Sensitivity analysis ... 42
6 Discussion ... 46

7 Conclusion 49
8 Bibliography 50
9 Appendix) 53
9.1 R code 53
9.1.1 R code, preventive time maintenance block function**Error! Bookmark not defined.**
9.1.2 R code, Downtime function 79
9.1.3 R code, Availability function 82
9.2 Collection of plots 83
9.3 Thesis contract 89

List of figures

Figure 1-1 Gross consumption by fuel,EU 28 1990-2017: [2] 1
Figure 1-2 Primary energy production in EU-28, million tonnes oil equivalent, 1990-2017 [2] 1
Figure 1-3 :Primary production of energy from renewable sources EU-28 1990-2017 [3]...... 2
Figure 1-4 Wind offshore balance of plant.. 5
Figure 1-5 Schematic representation of a generic wind turbine, self-made........................... 5
Figure 1-6 Nacelle components representation 6
Figure 1-7 simplified external layout of a wind offshore substation on the left, actual picture of a substation on the right [13] 8
Figure 1-8 Generic model of a substation scheme components – made by the author - [10] 8
Figure 1-9 Type of transport vessel, CTV on the left [15], SOV on the right [16]................. 12
Figure 1-10 Support vessel example [17] 12
Figure 1-11 Wind project cycle cost and timing, made by the author [18] 13
Figure 1-12 Downtime time formation diagram... 17
Figure 2-1 Literature review methodology [23] 19
Figure 3-1 Generic overview of the availability model – Made by the author 23
Figure 3-2 More detailed overview of the availability assessment algorithm – made by the author 24
Figure 3-3 Preventive Maintenance function detail – made by the author............................ 25
Figure 3-4 Downtime function detail 26
Figure 3-5 Availability function detail 26
Figure 3-6 Accessibilty flowchart – made by the author... 27
Figure 3-7 Visual representation of Vessel operation limit 27
Figure 3-8 Visual representation of a weather window (e.g. repair time = 4) 28
Figure 3-9 Visual representation of waiting time.. 28
Figure 3-10 Waiting time plot – made by the author 28
Figure 3-11 Waiting time frequency histogram – made by the author.................................. 29
Figure 3-12 Waiting time lognormal fit – made by the author... 29
Figure 3-13 Poisson failure distribution for component.. 30
Figure 3-14 - Example of two triangular distribution representing the vessel time – made by the author.. 31
Figure 4-1 Component representation for the case study 32
Figure 4-2 Medium voltage Switchgear of the Biomass power Plant Steyr [31] 33
Figure 4-3 Plot for waiting time for MV component.. 35
Figure 4-4 Histogram for waiting time for MV component 35
Figure 4-5 Histogram for vessel time for MV component 36
Figure 4-6 Histogram for waiting time for Transformer component 37
Figure 4-7 Histogram for spare part time for MV component 37
Figure 4-8 Histogram for spare part time for Transformer component 38
Figure 4-9 Figure 4-10 Histogram for spare part time for HV component 38
Figure 4-11 Histogram for preparation time for MV component 39
Figure 4-12 Histogram for preparation time for Transformer component 40
Figure 4-13 Histogram for preparation time for HV component 40
Figure 4-14 Histogram of life time availability 41
Figure 5-1 Montecarlo simulation sensitivity analysis for failures of component MV 42
Figure 5-2 Sensitivity analysis, availability result 42
Figure 5-3 Histogram for AEP calculation from case study.. 44

Figure 5-4 Histogram for LCoE calculation from case study 45
Figure 9-1 Plot for vessel time for MV component - made by the author 83
Figure 9-2 Plot for vessel time for Transformer component - made by the author 83
Figure 9-3 Plot for vessel time for HV component - made by the author.............................. 84
Figure 9-4 Histogram for vessel time for HV component - made by the author.................... 84
List of tables
Table 3-1 Simplified example for formation of total downtie.. 25
Table 4-1 MV component specification 33
Table 4-2 Transformer component specification.. 34
Table 4-3 HV component specification.. 34
Table 5-1 Availability results due to decrement of reliability 43

List of attachments

File	File type
availabilitycalculationcode_thesisRisk4_Luca Seresina	R
LucaSeresina_availabilityfunction_Risk4_montecarloavailability	R
LucaSeresina_downtimefunction_Risk4_montecarloavailability	R
LucaSeresina_preventivetimefunction_Risk4_montecarloavailability	R
LucaSeresina_sensitivity analysis_Risk4_montecarloavailability	R
datatxt	Text

1 Introduction

In the introduction the role of wind energy and the structure of wind offshore energy production are presented.

Climate change is indisputably a problem that humankind must face and solve. The society is changing towards a higher awareness of this issue and changes in the means of production systems are required to government and companies all over the world to reduce to production of CO2. For this reason Europe decided to act and face the challenge of the energy transformation from non-renewable to renewable sources of energy with a series of legislative changes and embracing vision for the future with political programs built on purpose, such as Europe 2020 [1].

1.1 Renewable energy

Today renewable energy is a key component of the energy consumption all over Europe with its relevant and constantly increasing share of the energy market consumption as shown in. Figure 1-1.

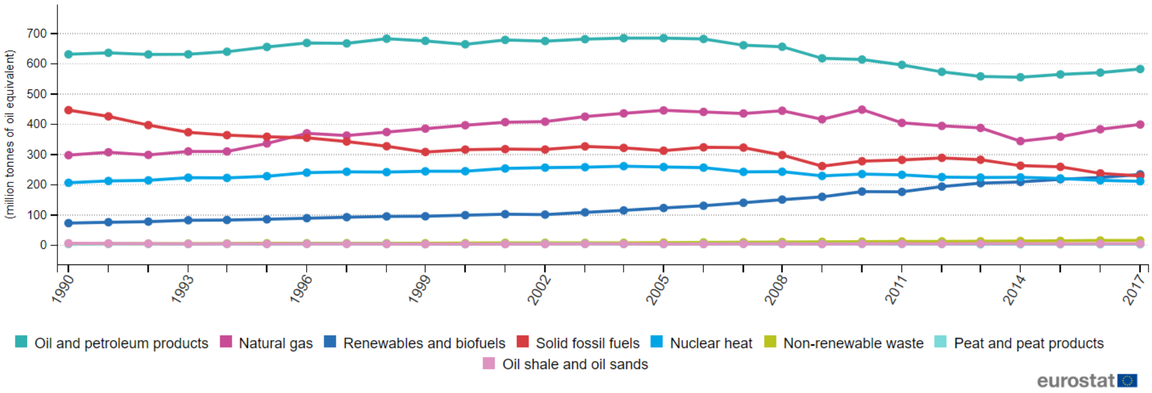


Figure 1-1 Gross consumption by fuel, EU 28 1990-2017: [2]

Renewable energy in 2017 had the biggest share in primary energy production in EU-28 (29,9%) representing an increasing trend over time, as shown in Figure 1-2

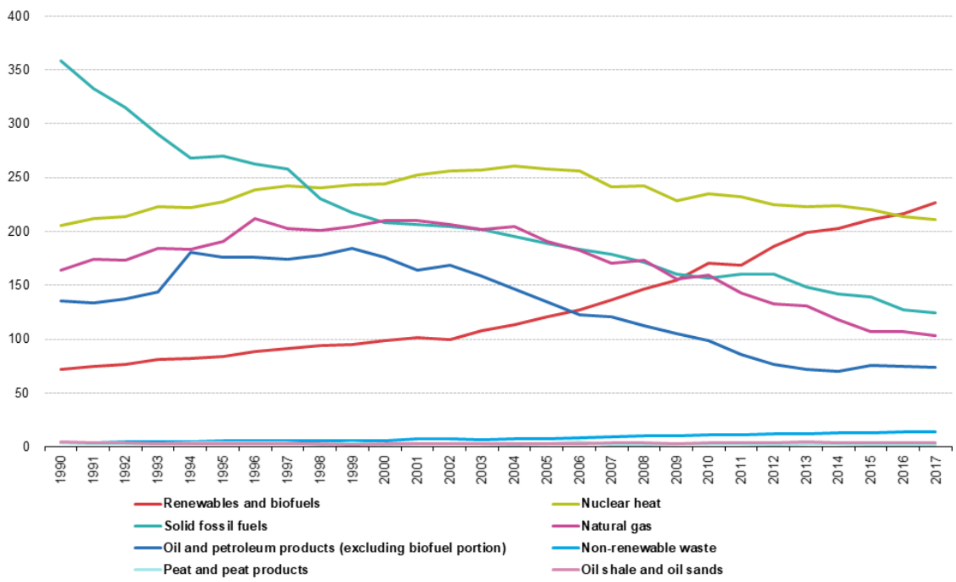


Figure 1-2 Primary energy production in EU-28, million tonnes oil equivalent, 1990-2017 [2]

In 2017 the second biggest component of the renewable energy was wind energy, represented with 13.8 % of the total of the primary production of energy from renewable sources [3] as shown in Figure 1-3

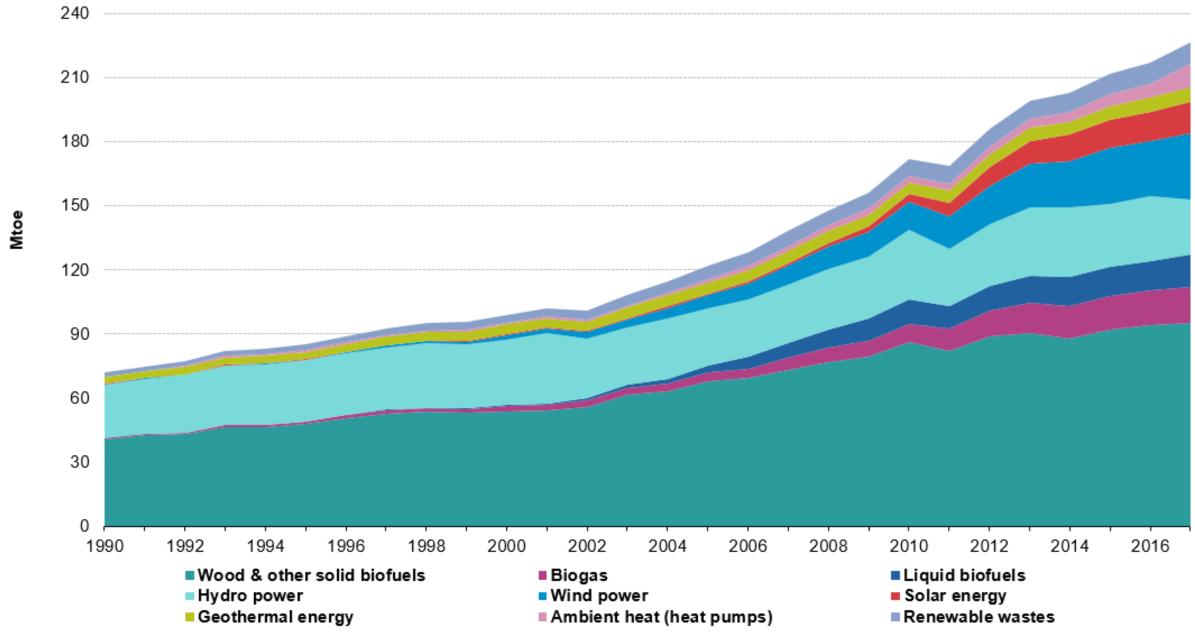


Figure 1-3 :Primary production of energy from renewable sources EU-28 1990-2017 [3]

As a matter of fact, among the renewable sources, wind has become the most important in 2017, providing 30.7 % to the total gross electricity consumption of the European countries [3] and reaching an overall installed capacity of 178.8 Gigawatt (GW) in 2018 [4].

Wind energy comes from both onshore and offshore installation. Currently there are 189 GW of installed wind plant power capacity all over Europe, divided in 170 GW onshore and 19 GW offshore with the offshore part increasing every year in its share [4]. Together onshore and offshore wind production cover 14% of European energy demand, divided in 12% for onshore and 2% for offshore [4]. Looking only at the wind energy installation capacity the 91.8% is onshore and only the 12% offshore [5]. The foreseeable trend for the future installations is to focus more on offshore. The reasons for this choice are different. Among these reasons there are:

- Offshore installations have a higher average rate of production [4]
- It is easier to find suitable locations if compared with onshore where the public and the legislation resist to the installation of big plants near households
- Offshore represent bigger expansion possibilities in terms of space and potential, compared with onshore installation.
- The subsidy schemes are moving from promoting onshore towards facilitating offshore plants [5].

In 2018, 409 new offshore installation were deployed and connected in Europe over eighteen projects, bringing 2649 Megawatt (MV) of additional capacity and adding up to the installed offshore wind capacity amount of 18,499 MW. During 2018 in Europe 4543 offshore wind turbines were connected in more than eleven countries [6].

Regarding wind energy utilization, Denmark is the country with highest share of wind energy in its electricity demand [4]. In 2018, in Denmark, 220 new onshore and 61 new offshore installations were deployed and at the same time 13 installation were decommissioned [4].

The increasing trend in demand of wind energy and linked increasing trend in demand of offshore plants bring the challenge of need for more projects to be start and deployed and x need for more operation and maintenance. The increasing number of projects and installations also bring the need for more attention on the profitability of each wind park. In this context the attention for strategies and tools to increase, monitor and foreseen the production of a wind farm is also increasing.

1.2 Wind energy

Wind energy production relies on the ability to catch the potential energy entrapped in the wind and transforming it into electricity. In order to do so a set of engineering solutions has been developed in time. The more common solution today, it is to design, develop and install wind farms, both onshore and offshore. The caught wind energy is then distributed through the grid to final users, both companies and private.

1.3 Wind project cycle

The structure of a wind plant construction project is not the focus of this work, however a brief introduction to it is given below to help better understand the system and its relationships.

To ensure a wind farm can produce energy, either onshore or offshore, four stages are followed:

- Development
- Commissioning
- Operation and maintenance
- Decommissioning.

Each of the four above listed stages can be divided into more detailed stages briefly introduced below.

1.3.1 Development

Wind farms are usually developed through governmental tenders. Governments set tenders and assign contract to project based on the best Levelized Cost of Electricity (LCoE) [5]. Subsidiaries are constantly lowered across the world, which will force the wind industry to compete on liberal basis with other energy sources [7], therefore to obtain the lowest LCoE both capital and operational costs must be reduced as much as possible. The Capital expenditure cost (CAPEX) are maintained low with a good planification in the development phase. This phase involves the planning phase, the design phase and the permit phase. In this stage all the decisions about the size, the power, the location, the infrastructures, the budgets and the partners are made.

The development phase can be broken down into:

- Feasibility study
- Basic design
- Detailed design.

1.3.2 Commissioning

After the details are established, the agreements are in place and the contract is won the wind farm is delivered and installed. Further on the installation tests are carried out to verify the functionality and safety of the installation.

The commissioning phase can be broken down into:

- Transport and installation
- Commissioning.

1.3.3 Operation and maintenance

The objective of the Operation and Maintenance phase (O&M) is to run the wind farm and ensure that it will provide the expected level of production together with maintaining its lifetime expectation and containing the costs.

The operation phase can be broken down into:

- Warrantied operation and maintenance
- End of warranty
- In-house operation and maintenance
- End of lifetime

1.3.4 Decommissioning

Once the wind farm has reached its lifetime there is a need to decide whether to decommission the wind farm or proceed with a repowering of it. That would mean upgrading the plant with new equipment.

The decommissioning phase can have two different endings:

- Decommissioning and dismantling
- Repowering [5].

1.4 Offshore Wind energy

As previously mentioned, the production of electricity by means of the wind power can happen both onshore and offshore. For the purpose of this thesis the structure of the offshore wind energy industry is briefly introduced in section 1.4.1.

1.4.1 Offshore wind farm balance of plant

An offshore balance of plant (BoP) is a construction at sea made from the combination of four main elements:

- The wind turbines (WTG)
- The inner grid
- The offshore substation
- The external grid [8]

As mentioned before the purpose of the BoP is the one of harvesting wind energy and produce electricity. A schematic representation of a wind offshore balance of plant is illustrated in Figure 1-4 below.

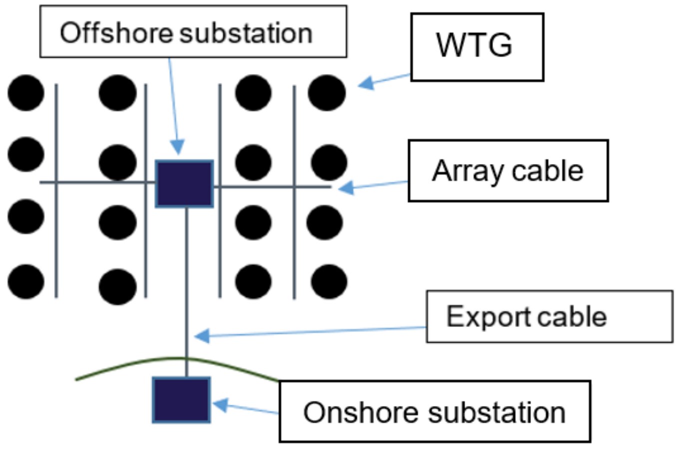


Figure 1-4 Wind offshore balance of plant – made by the author

The layout of wind turbines can be displayed in several ways, depending on the climatic conditions and the depth of waters and the WTG can be divided in several groups as well. One substation can serve more than one windfarm. The distance from shore can vary from very close to several kilometres away. In the following subchapters a brief introduction to the WTG and to the substation is given. The grids are represented by the cables and by the connections from the turbines to the substation and from the substation to shore.

1.4.2 Offshore wind turbine

A wind turbine is a device able to capture the wind energy, transform it and transfer it on shore to use it as source of energy production. The Figure 1-5 illustrates a profile schematic representation of a generic wind turbine.

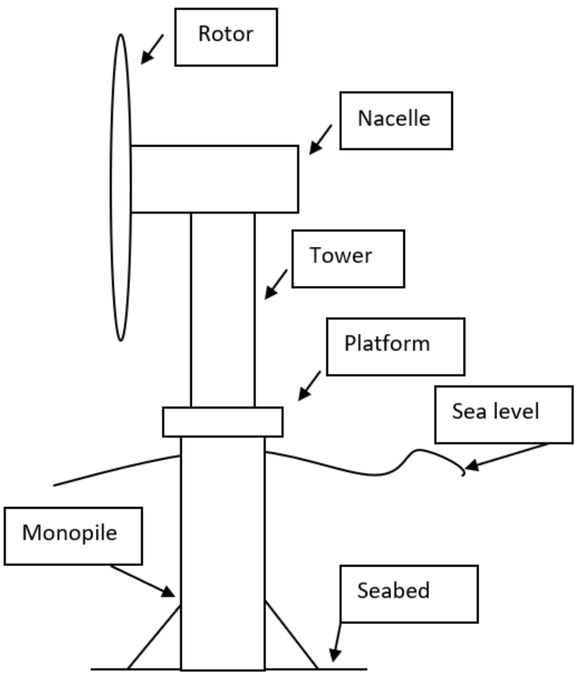


Figure 1-5 Schematic representation of a generic wind turbine - made by the author

The main elements that compose a wind turbine are:

- Rotor
- Nacelle
- Tower
- Support structure.

A standard representation of the components found inside the nacelle are illustrated in Figure 1-6.

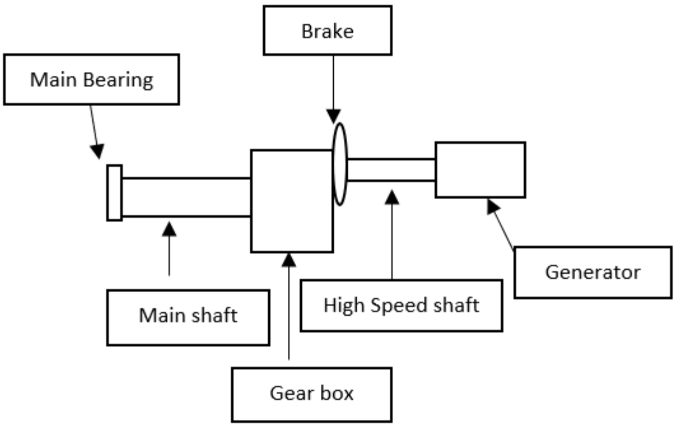


Figure 1-6 Nacelle components representation- made by the author

Nacelle components are:

- the main bearing,
- the main shaft,
- the gear box,
- the brake ,
- the high-speed shaft,
- the generator.

The blades of a wind turbine start spinning, and producing energy, only when the wind speed is above a cut-in-speed. For example, the V164/9500 (MHI Vestas Offshore) wind turbine model has a cut-in speed of 3,5 m/s [9] and it will reach the rated wind speed approximately at 14 m/s [9]. Over the rated wind speed there is no increment in the production and over the cut-out-speed of 25 m/s [9], the components will be loaded and therefore will suffer damages, for this reason the turbine will be stop at that mark. In order to catch more energy as possible the hub, illustrate above in Figure 1-6, is provided with two main system:

- The Yaw system, that allows the nacelle to face the direction of the wind by rotating the entire nacelle.
- The Pitch system, that allows the blades to rotate between 0 and 90 degrees to increase and or reduce the wind load on the blades.

The transformation from wind to energy eventually occur in the generator. The main shaft rotates accordingly with the rotation of blades. It is the gear box that transmits the rotation to the high-speed shaft and then into the generator. In the generator the mechanical energy is transformed into electrical energy. After the generator the flow of electricity pass through other components such as a frequency converter, with the aim of generate a steadier flow suitable to the grid and a transformer, to ramp up the voltage to facilitate the transmission from the wind turbine to the substation and then to shore.

1.4.3 Offshore substation

The following chapter aims to provide the description of a generic high voltage alternate current (HVAC) offshore substation which will define the boundaries of the model and of the case-study later in the following chapters. The substation generic reference model is based on a simplified representation of the main components of a substation from a usual installation in the Danish offshore system. The model is based on the input received from Semco experts [10] and finding in literatures.

Following the indication of the BVG Associates report [11] a typical HVAC substation is placed 25 meter above the sea level and has total area of 800-meter square. Normally a substation can support the generation input of about 500 MW. The electrical system of a HVAC substation integrates alternate current (AC) power output from individual turbines and ramps up the voltage for exports it to onshore. According to the BVG Associates report [11] the key components of the system include:

- HV/MV switchgear to isolate and protect each array and export connection to the substation
- Transformers in order to transform to higher voltage for onward transmission. A typical offshore substation will have two or more transformers to improve availability. Transformers are oil cooled, requiring the use of fire and blast protection
- Passive and active reactive power compensation
- Earthing systems including lightning protection connecting electrical components and the substation structure
- Cable trays, tracks, clamps and supports to protect electrical items [11].

In the following chapters the structure of a generic HVAC substation is further investigated to provide more details on the topic.

The structure

As introduced in 1.4.1, an offshore wind substation is the link between the wind turbines generating electricity from wind power and the shore, receiving that energy. The purpose of a substation is to modify the energy received from the wind turbines, usually very discontinue in terms of quality and quantity, to provide a steady unique flow of energy and to send it onshore through export cables. For this reason the main components of a substation are transformers and converters that increase, decrease or modified the electricity accordingly with the needs of the grid and or the distance from shore. A substation can be identified in two main parts:

- The support structure (sub-structure)
- The top side [12]

In Figure 1-7 the external layout of a substation is illustrated next to an actual picture of a substation.

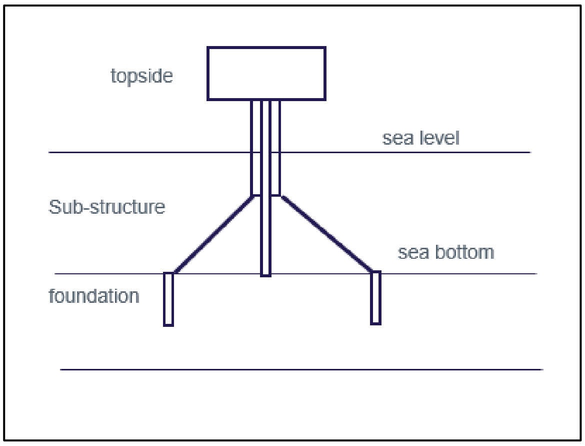


Figure 1-7 simplified external layout of a wind offshore substation on the left, actual picture of a substation on the right - made by the author [13]

The topside is usually a square shaped structured allocated on top of the support containing all the electrical equipment [12]. The provided illustration above represents only one of the many possible combinations in terms of configurations and therefore must not be seen as actual example of an existing solution. The explanation of the many possible combinations and design is beyond the scope of this thesis and therefore will not be treated.

1.4.3.1 Offshore wind substation's scheme

The final content and configuration of the substation depends, and it is mainly determined, by the importance of the plant in relation with the power grid. The design for an offshore substation is more focus not on keeping a continuous power flow but rather on achieve a higher availability for the installation. However, in most of the current substation, develop at today this consideration has not taken place and therefore little or none redundancy has been applied. It was rather common that only vital and cheaper systems like communications, cooling and firefighting systems were implemented as redundant. Following to this, some of these installations incurred in important losses of income when some important failure has happened. [12]

As mentioned before all the components of the substation are usually contained in the top-side. Figure 1-8 illustrate the generic scheme of the main components found in the top-side of a generic substation.

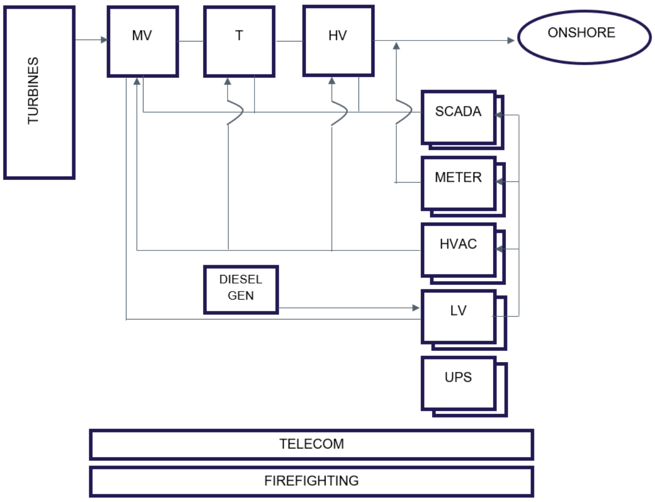


Figure 1-8 Generic model of a substation scheme components – made by the author - [10]

The elements illustrated in Figure 1-8 are the following:

- Offshore wind turbines
- Medium voltage components (MV)
- Main Transformer (T)
- High voltage components (HV)
- Supervisory Control and Data Acquisition system (SCADA)
- Metering system
- Heating Ventilation and Air Conditioning (HVAC)
- Low voltage power distribution components (LV)
- Uninterruptible power supply system (UPS)
- Diesel generator
- Telecommunication system
- Firefighting system
- Cables and arrays
- Onshore substation.

The wind turbines and the onshore structures are not part of the substation itself. However they represent the beginning and the end of the journey the energy goes through.

Medium voltage components (MV)

The medium voltage components receive the energy from the wind turbines and provide it to the transformers so that it can be transformed in high voltage current to be send later to shore.

Main transformer (T)

The main transformer manipulates the energy and transform it from medium to high current to send it onshore.

High voltage components (HV)

The high voltage components receive the electricity from the transformer and transmit it onshore through export cables.

Supervisory Control and Data Acquisition system (SCADA)

The Supervisory Control and Data Acquisition system (SCADA) provides real time information on errors happening at the substation regarding the components health.

Metering

The metering system represent the combination of measurements that provide reading on the production of energy on the substation.

Heating Ventilation and Air Conditioning (HVAC)

Heating Ventilation and Air Conditioning (HVAC) is the system that helps to dissipate the heat generated by electrical components on the offshore substation and helps to prevent failures of the components from over-heating.

Low voltage power distribution component (LV)

The low voltage components ensure the functioning of the component on the substation providing them with electricity.

UPS

The uninterruptible power supply system (UPS) is the emergency system that, together with the diesel generator, provide energy in case of a main power fail.

Diesel generator

The diesel generator provides energy to the system in case of a mail power fail, together with the UPS system.

Telecommunication system

The telecommunication system provide communication from and to the substation maintaining connection with the onshore base.

Firefighting system

The firefighting system ensure that possible fires on the substation are controlled and extinguished.

Cables and arrays

Cables and arrays connect the subcomponents of the substation and the substation itself from the wind towers to shore ensuring the flow of electricity.

1.5 Offshore O&M

The following chapter aims to provide a brief introduction of the components of the Operation and Maintenance phase of a wind offshore substation. The chapter focuses mainly on the terminologies utilized later in the work to provide clarification and instruments to understand the thesis work.

1.5.1 Maintenance

Main scope of the O&M phase, as introduce above in 1.3.3, is to reduce the operative costs, prevent major failures and ensure operability of the plant. Maintenance is a very important part of this phase. In the EN13306:2010 maintenance is described as ."*combination of all technical and administrative actions, including supervisory actions, intended to retain an item in, or restore it to, a state in which it can perform a required function"* [5] and it also includes definitions of all the possible application of maintenance. An introduction to the preventive and corrective maintenance is provided in the following chapters.

Preventive maintenance

Preventive maintenance is a category of maintenance performed as an active action with the purpose of ensuring the conditions of the system and prevent failure and degradation to lengthen the life time of the substation.

Preventive maintenance can be carried out following different approaches.

- Scheduled maintenance
- Predetermined maintenance
- Condition based maintenance

In this thesis work only scheduled maintenance is taken in account. Scheduled maintenance is a type of maintenance carried on fixed intervals without considering lifetime measurement of the degradation of components or previous failures events. It differs from predetermined maintenance and condition-based maintenance which both try to maximise the efficiency of the interventions considering the condition of the components and modelling their intervention based on that. Despite this, scheduled maintenance is easier to perform and for this reason it is widely used in the industry if compared with other types [14].

Standard EN 13306:2010 defines preventive maintenance as *"maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item"* and it describes scheduled maintenance as *"maintenance carried out in accordance with an established time schedule or established number of units of use"* [5].

Corrective maintenance

Corrective maintenance is the other main division in the branches of maintenance types. It is a reactive measure and its aim is to restore components after failures. Corrective maintenance can be defined as:

- Remote
- Immediate
- Deferred.

In the thesis work only immediate maintenance is taken in account. Immediate maintenance is the maintenance that is performed without allowing delay from the time of the failure to reduce downtime and loss of production.

1.5.2 O&M facilities

The structures that support the O&M phase are mainly of two types:

- The Operation hub
- The Maintenance hub.

The operation hub is the main control point for the offshore operation. The main responsibility of the operation hub is to control and monitor the wind farm SCADA. The maintenance hub is responsible for the logistics of the O&M activities.

1.5.3 O&M resources

To carry out the maintenance activities there is the need for educated technicians, spare parts and transportation. In the thesis work spare parts and transportation vessels are taken in consideration while technicians' availability is given.

Spare parts

In the thesis work spare parts are represented as items that can replace failed components. Some spare parts can take longer than others to be retrieved and, therefore lengthen the time of maintenance operation.

Transportation

Transportation from the shore to the wind farm can be ensured mainly in two ways, by vessels and by helicopter. The transportation of component can require the utilization of two different type of vessels, an access vessel or a support vessel depending on the size of the parts and the operation to be performed. The helicopter option is not taken in consideration in the development of this thesis work. Therefore, no further information about the helicopter will be provided.

Access vessel

An access vessel is a smaller type of vessel to transport technicians and spare parts from shore to the BoP. Vessels that belong to this category are, for example, crew transfer vessels (CTV) visible in Figure 1-9, and service operation vessels (SOV) also visible in Figure 1-9.

Figure 1-9 Type of transport vessel, CTV on the left [15], SOV on the right [16]

Support vessel

Support vessels serve the same goal as the access vessels, but their main mission is to transport heavy parts and provide support for the installation. Support vessels have greater operation capacity and are usually not owned by the wind farm but rather leased [5]. An example of a support vessel is provided in Figure 1-10

Figure 1-10 Support vessel example [17]

1.6 Offshore wind energy costs

Wind farm project cycle costs

Now that an overview on the technical details of what a wind farm is composed of and how it works, it is possible to provide a short introduction to the costs of running a windfarm and therefore introducing the importance of the O&M part from the cost-perspective of the availability of a substation.

As mentioned in chapter 1.3 the construction of a wind farm is the result of four main stages. Development, Commissioning, Operation and Maintenance and Decommissioning. Figure 1-11 below show an example of the breakdown of these stages.

The Development part is mostly a management process aiming to identifying the right site for the construction, achieving the needed finances and engaging the public. It can take up to ten years to be completed and the final cost of it is usually a combination of outsourced assessment costs, campaign costs, permission and licence costs, initial design costs, legal framework study costs and environmental study costs [18]. Usually the project development costs weigh for the 10% of the CAPEX [5].

The Commissioning stage is the shortest phase in the whole wind project cycle but is also the most expensive. The objective of this phase is to build the wind farm; turbines, foundations, substation and the connection to the grid. The whole operation can take one or two years and it is very much linked with the development part. For example, for a 50 MW plant the Development and Implementation phases together can have an approximate cost of 65 million Euro [18]. Usually a 90% of the CAPEX is covered in the commissioning part while the remaining 10% is due to project development costs as said before [5].

The Operation and Maintenance phase is the longest period of the whole cycle. It takes the whole life time span of the wind farm, nowadays around 20, 25 years. The costs of this phase are represented by the expenses for management, technicians, spare parts, vessels and administrative costs needed to run the wind farm. The highest are the failures and the unavailability in this phase the highest the costs will be. This phase, due to its length, its subject to a great uncertainty and it plays a big role in the cost effectiveness of the whole wind farm in the long term. Approximately it is possible to estimate a 40.000 Euro a year per a 2 MW machine as O&M costs. Therefore the costs will vary according to the size of the windfarm [18]. Most of the Operation Expenditure (OPEX) cost derive from this stage of the project cycle [5].

The Decommissioning phase is of course the last part of the entire cycle and its goal is to remove the wind farm from its location and restore the site. Sometimes the decommissioning is a re-powering of the wind farm. The usual time to cover this operation is of one year and an estimation cost is around three million Euro [18].

All the above estimations and figures are approximation utilized with the aim of providing an example. The real costs and timing for each part can vary greatly depending on the single project.

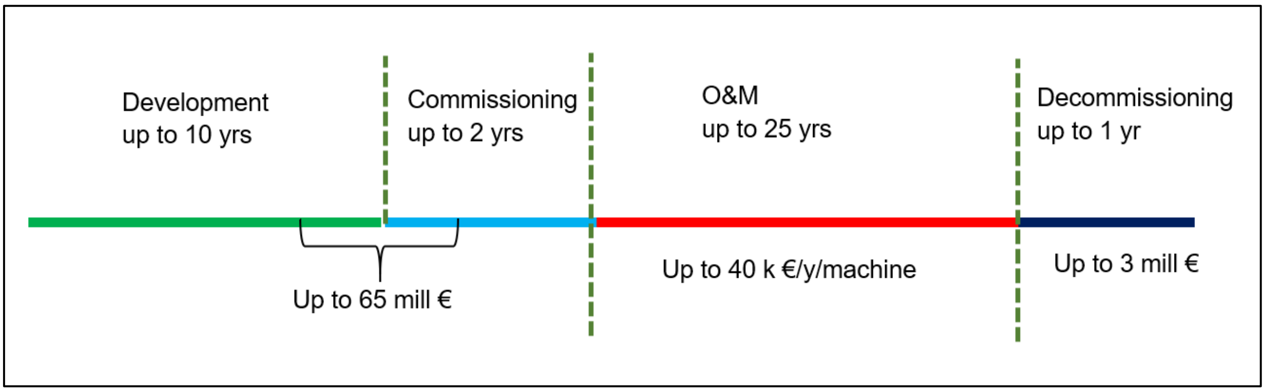


Figure 1-11 Wind project cycle cost and timing, made by the author [18]

Moving from the above introduction and the information already provided in chapter 1.4 it is possible to understand that a wind farm is a complex structure that require complex management to be delivered and operated. From this understanding now a brief look at the economic profile of a wind farm project is provided and the role of the availability in the framework of the costs is made clearer.

Economic profile

As introduce in the Development chapter Wind farm tenders are won based on the best levelized cost of energy (LCoE). In this chapter the LCoE is introduced and the importance of the availability of the substation as measure of good profitability of a wind farm project is highlighted.

The LCoE is defined by the U.S Energy Information Administration as "*a convenient summary measure of the overall competitiveness of different generating technologies*" [19] and it is a tool that attempts to describe the kW per hour cost of building and operating an energy production plant over its entire lifetime. It is a widely applied measure in the industry. The particularity of this measure is that it levelized all the costs that are spread over the project lifetime and it summarizes them in a rather convenient measure easy to be compared with other solutions. The UK department of Energy and Climate defined the LCoE as "*the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life*" [20].

To express the LCoE there are different formulas, with different level of complexity, a much rather simple formula is shown below in equation 1.1 [5]:

$$LCoE = \frac{(CAPEX * \ CRF + OPEX)}{AEP_{potential} - AEP_{loss}} \qquad 1.1$$

Where:

- CAPEX are the fixed costs for the initial capital
- OPEX are the cost due to the operability of the project
- CRF is the Capital Recovery Factor
- $AEP_{potential}$ is the Annual Energy Production in Watt hour
- AEP_{loss} is the lost energy production due to the unavailability of the wind farm.

The Capital Expenditure (CAPEX) represent the summation of all initial cost to establish the wind farm. It can vary greatly from plant to plant.

The Operational Expenditure (OPEX) represent the costs during the full lifetime of the wind farm. It covers fuel costs, management costs, administrative costs, personnel costs, the maintenance cost, and so on.

The Capital Recovery Factor (CRF) is the mathematical device used to discount the costs to the net present value. Its formula is represented below in equation 1.2 [5]:

$$CRF = \frac{i * \ (1 + i)^n}{(1 + i)^n - 1} \qquad 1.2$$

Where:

- The interest rate is i
- The lifetime is n.

The Annual Energy Production (AEP) is usually calculated as an average. A simplified formula is shown below in equation 1.3:

$$AEP = MW * \ Lifetime(h) * \ Cf \qquad 1.3$$

Where:

- MW is the power produced by the plant in MW
- The lifetime in hours is the life span we want to take in consideration to perform the calculation
- *Cf* is the capacity factor

As showed in the Offshore wind turbine chapter a wind turbine produce energy according to the wind availability. Because of this, the production of energy from a wind farm is not constant in time but rather it changes over different periods such as days, seasons and years. To perform the AEP calculation the Capacity factor is then used. The factor represents the percentage of time the wind farm is assumed to produce at 100% of its own nominal capacity. As said previously wind turbines produce energy thanks to wind energy that is discontinue. Therefore, for example, a 50 MW plant will not always produce at its own maximum capacity of 50 MW, but assuming a 25% of the time where this target is hit, it is possible to set 25% of maximum production capacity over an entire year and the resulting simplified annual AEP calculation is:

$$AEP = 50\ MW * \ 8760 * \ 0.25 \qquad 1.4$$

The above AEP equation shown in 1.4 is assumed to be calculated as the production is maintained continuously throughout the whole period at the 100% of its capability. However, this is not true, sometimes due to failures and intervention on components the wind farm will not be able to produce at the same level. To take account of this it is required to subtract the $AEP_{potential}$ the AEP_{loss} that represent the possible unavailability moment suffer by the wind farm, both from windfarm issues and substation problems. The AEP_{loss} is usually represented as a percentage of the $AEP_{potential}$ [5].

The afore illustrated calculation does not take in consideration of the unavailability of the plant and therefore lacks representativeness in the matter. Accurate calculation of AEP can be performed using specific modelling tool such the one use in the RMA studies analysed in literature review [21], that however miss to take in consideration variability and uncertainty performing a deterministic fault tree analysis, and such the one developed in this thesis work where the AEP can be evaluated more correctly taking in consideration the unavailability of the plant calculated with a risk risk-based approached. The higher unavailability the lower the AEP and therefore the higher (and unfeasible) the LCoE.

It is a well-known fact that the availability modifies the profitability of an offshore plant investment [21]. Furthermore, as introduce in the Introduction, offshore plants receive subsides from governments to be installed and be operational. These economic incentives for windfarm are measured by the availability of a wind farm [22]. Moreover the economic fines for the non-production of an offshore wind farm plants are greater than those applied to a typical onshore instalment [22].

Lastly, it is worth to mention that usually substations design focus on maintaining continuous power. This means a higher initial CAPEX investment to cover redundancy and control systems. The higher initial investment must then be made up with the provided electricity capacity. An interruption in the availability, as short as it can be very significant for the economic output of the plant [22]. It is clear then how the availability of the substation over the period of O&M plays an important role on the final profitability of the project.

1.7 Availability

In the previous chapters an introduction to the parts that contribute to run a wind farm and the components of the cost of electricity were explained. The importance of reducing cots in the O&M was also made clear and the relevance of the availability component in the economic calculation was defined. In the following chapter an explanation of the concept of availability is given.

The availability of a substation can be described as the time in which the substation is operating, not suffering downtime that would prevent it from transmitting electricity onshore. A formula to summarize the availability is provided below in equation 1.5:

$$Availability = \frac{(total\ time - total\ downtime)}{total\ time} \qquad 1.5$$

Where:

- The availability is the resulting percentage of the time the substation is operating over the entire period
- The total time is the life time considered for the calculation
- The total downtime is the total downtime in the considered life time for both failures and planned intervention of scheduled maintenance.

In a more technical definition, as defined from IEC Standard 61400-26 the availability can be described as the following equation 1.6 [5]:

$$Availability = 1 - \frac{(Unavailable\ Time)}{(Available\ Time + Unavailable\ Time)} \qquad 1.6$$

The total downtime can be illustrated in formula as the equation 1.7:

$$Total\ downtime = time\ to\ repair + vessel\ time + spare\ part\ time + waiting\ time + scheduled\ maintenance\ intervention \qquad 1.7$$

Where:

- The time to repair is the time used by the technicians to perform a repair on the substation (Tr).
- The vessel time is the time required to retrieve a vessel (TV).
- The spare part time is the time required to retrieve spare parts (Ts).
- The waiting time is the time that the maintenance team must wait before sailing due to the condition of the sea (Tw).
- The scheduled maintenance intervention time is the time required every year to perform the scheduled maintenance interventions (Tm).

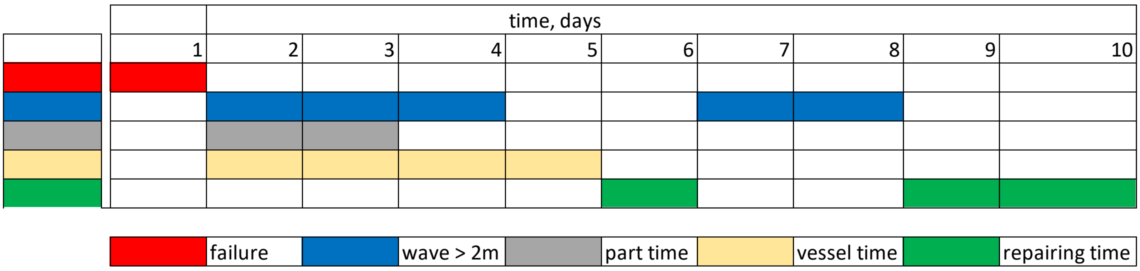


Figure 1-12 Downtime time formation diagram - made by the author

The above Figure 1-12 depicts how the downtime due to the failures in the system is formed. The different time windows can be overlapping. For example the time needed to gather the spare parts can overlap with the time to retrieve a specific vessel. For this reason it is necessary to divide the down time caused by the failures in two main time. From the above considerations it is possible to rewrite the formula for the downtime as equation 1.8:

$$\textit{Total downtime caused by failure} = \textit{preparation time} + \textit{operation time} + \textit{waiting time} \qquad 1.8$$

Where:

- Preparation time is the longest time to be waited when combining the time to retrieve spare part and the vessel as shown in equation 1.9:

$$\textit{Preparation time} = \max(\textit{vessel time}, \textit{spare part time}) \qquad 1.9$$

  This is true because in case one of the two components in the calculation is available it is always necessary to wait for the other before proceeding with the maintenance intervention. Therefore the selected time to define the entire preparation time is the max (the longest) of the two.

- Operation time is the time required after the preparation time to perform the repair as shown in equation 1.10:

$$\textit{Operation time} = \textit{repair time} \qquad 1.10$$

- Waiting time is the time, after that spare parts and vessel are retrieved, that the technicians crew must wait before sailing due to the meteorological condition.

The availability then can be resumed in the following formula in equation 1.11:

$$\textit{Availability} = \textit{total downtime cause by failure} + \textit{scheduled maintenance} \qquad 1.11$$

This calculation applies for every single failure causing a downtime at the substation. Therefore the formula 1.6 can be rewrite as the summation of all the failures in a period as shown in equation 1.12:

$$\textit{Availability} = \sum_0^f (\textit{total downtime cause by failure}) + \textit{scheduled maintenance} \qquad 1.12$$

Where:

f represents the number of failures over the lifetime of interest and it is a random realization dependent on the quality of the component, expressed in the mean time between failures (MTBF).

To better clarify the calculations provided above an example of deterministic one-point estimation of the annual availability is given below in equation 1.15:

- Time period of one year (8760 hours)
- Number of failures in the life time period is assumed to be five hours
- The vessel time (Vt) is assumed to be zero hours for all the failures
- The spare part time (St) is assumed to be from one hour to five hours for each failure.
- The waiting time (Wt) is assumed to be on average 6 hours
- The repair time (Rt) is assumed to be of 8 hours each
- The total scheduled time (Mt) for maintenance is of eight hours

$$Downtime = (Vt + St + Wt + Rt) + (Vt + St + Wt + Rt) + (Vt + St + Wt + Rt) + (Vt + St + Wt + Rt) + (Vt + St + Wt + Rt) + Mt \quad 1.13$$

And this become:

$$Downtime = (0 + 1 + 6 + 8) + (0 + 2 + 6 + 8) + (0 + 3 + 6 + 8) + (0 + 4 + 6 + 8) + (0 + 5 + 6 + 8) + 8 \quad 1.14$$

$$Downtime = (15 + 16 + 17 + 18 + 19) + 8 = 93\ hours$$

Therefore

$$Total\ annual\ availability = (8760\ hours - 93\ hours) / 8760\ hours = 98{,}93\% \quad 1.15$$

2 State of the art – literature

The research for this thesis work has been carried out on the widely and commonly used research engine Google. By means of Google the research of grey literature was performed and collection of interesting pieces of information was made. Once identified a trend of interest the use of the more specific and specialized Google scholar engine was performed to refine the previous research. Later, the research moved on to more specialised databases such as The Aalborg University library database. The collected literature of interest was then analysed by abstract and refine to be read. If the paper was found to be of interest for the purpose of the thesis was then selected to be part of the sources. The flow to refine the literature is shown in Figure 2-1 below.

Figure 2-1 Literature review methodology [23]

There is a vast literature with the interest to model wind farm, wind turbines and substations to provide suggestions on how to improve the offshore wind industry. Much of this literature focus on the effort of modelling failures of wind turbines and try to identify possible better cost-efficient solution to improve the O&M phase. This is the case for example of "*On risk-based operation and maintenance of offshore wind turbine components"* [24] and "*Methods for Risk-Based Planning of O&M of Wind Turbines"* [7] which both propose a Bayesian risk approach to predict failures of components and switch from a scheduled fixed maintenance type to a preventive type of.
Another interesting article that focus on wind turbines failures is "*Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines"* [25]. The article provides an interesting overview of failures of components of wind turbines and aim to provide information to reduce the O&M cost for offshore wind farm industry.
Of more interest for the subject of this thesis are those articles which the focus is the whole modelling of a wind farm, comprehensive of wind farm elements, O&M and management decisions, such the following:

1. *A probabilistic approach to introduce risk measurement indicators to an offshore wind project evaluation – improvement to an existing tool Ecume* [26]
2. *Marine logistics decision support for operation and maintenance of offshore wind parks with a multi method simulation model* [27]
3. *NOWI cob – A tool for reducing the maintenance costs of offshore wind farms* [28]
4. *Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms* [29]
5. *Risk and Reliability based O&M Planning of Offshore Wind Farms* [5]

In the first work the authors review an already existing tool (Ecume) used to evaluate the profitability of investment in offshore windfarm business and improve it by introducing a risk approach to it. Ecume provides the result as a mean estimate solution. The proposed model improves this condition with the implementation of the use of Hamiltonian Montecarlo method and classic Montecarlo simulation. In the article The Net Present Value (NPV) is used as measure to prove the utility of the risk approach. The based model Ecume permit the user to insert the deterministic cash flows consisting of CAPEX and OPEX, costs such as fixed costs, preventive maintenance costs, standard exchanges, costs for monitoring condition-based maintenance, etc. Moreover uncertainty is added to the model by mean of the corrective maintenance cost due to the failures and degradation of system detected by condition-based maintenance. Those costs are proportional to the failure rate given by the user.

The unavailability is composed of the maintenance interventions itself and of the waiting time before the maintenance operation can be performed. The waiting time is the results of the inaccessibility due to access complications. The improvements brought in the paper are of the sort that the constrains, such as, the meteorological condition at the geographical location of the windfarm, are simulated with Hamiltonian Montecarlo and combined with simulated failures in Montecarlo, using a Weibull process, to predict the final costs and Net Present Value of investment.

In the second article a tool to select the best O&M strategy for a wind farm is illustrated. The authors use an object-based modelling technique and discretization of value to simulate weather data, O&M resources and decision-making strategy. The use of statistical analysis is then made to verify the best solution among possible decision strategies. The article takes in account Wind turbines modelled with 19 components each, failures modelled following a Poisson process with a time dependent failure intensity expressed as a Power Law process following a Weibull-function, and both preventive maintenance (annual service, inspection, etc.) and corrective maintenance. Other inputs that the model allows are weather data, Wind Turbine data, vessel data, spare part data, cost data, marine logistic and maintenance strategy data. Decision-making methodology is taken account as well. The model provides results for a various set of measure:

- Time-based availability (available time/total time)
- Energy-based availability (actual production/theoretical possible production)
- Technical availability (available time/theoretical available time)
- Lost production
- Marine logistics cost
- Vessel utilization (days used/days chartered)

The third article is a review of the NOWI cob tool. The author performed an analysis of the strength and weakness of the model and made a summary of it.

The fourth article is a comparison of the above three articles with a reference wind farm. The authors want to provide a reference wind farm to facilitate the verification and validation of models for future work.

The fifth article is an extensive work where the author uses a risk-based approach to model the costs of running a generic offshore plant model. This work has been fundamental for many of the aspects and most of the work that is found in the thesis.

Of extreme interest is also the Preliminary RAM (Reliability, Availability and Maintainability) study performed by Siemens on Dogger Bank [21]. This study addresses the availability issue from a more structure point of view but without taking in consideration variability and uncertainty. A full and extensive analysis of the design and the system is carried out and a fault tree analysis is performed. The authors did not, however, considered some aspects and addressed some others in a different manner they have been advocated in this current work. Therefore it is of interest to briefly review those points. In the RAM study cited above it is assume that all maintenance personal is available and mobilized in within 12 hours for the offshore platform. All the spare parts are always available at appropriate time. All the remediation measures are conducted completely within the allocated time and without delay. Scheduled outages are not considered. Forced outages that can be deferred close to the next scheduled outage are not considered. No variation for none of the above measure is considered.

2.1 Problem formulation

The introduction provided an overview on the offshore wind energy production reality and made clear how complex of an industry it is. The offshore wind energy competition relies on small margin and face high risks and operate in harsh condition. It is a challenging industry with many obstacles and great uncertainty. For these reasons it is of certain relevance to aim to the development and introduction of a more risk-based approach to the industry. When estimating parameters and calculating margin or possible profits industries must take in account uncertainty, variability and risks. The gap between the work done in the academia environment and the methods used in the everyday life industry reveals challenges in the account of this matter. For this reason this project wanted to develop a model for assessing the lifetime availability of an offshore substation in a Danish wind farm moving from the classical one-point estimation or three point what if analysis and developing a complete risk-based tool. The work combines failure components modelling, incident modelling, sea condition modelling, platform accessibility assessment and repairing time, and uncertainties related to these are propagated to estimate the resulting uncertainty on the annual availability. These conditions make it relevant to state the following main question for this thesis:

At the light of the above consideration and of the information presented in the introduction part, how is it possible to implement and improve the use of a risk-based approach in the calculation of the availability of a substation using Montecarlo simulation compared with more classical one-point estimations?

The objective that will be elaborated through the project and are the results of the problem analysis are:

- Develop a generic model of an offshore substation.
- Develop a model for failures of components.
- Develop a model for platform accessibility depending on meteorological conditions.
- Develop a model for repairing time and mobilization time based on expert opinions.
- Combining all the above information to estimate the distribution of the availability of a substation offshore for the wind energy sector.
- Estimate economic cost from the results of the model and compare them with classical one-point estimation.
- Develop a discussion and conclusion around the results

2.2 Problem delimitation

The scope of the thesis is limited only to cover the calculation of the availability of the substation. This involved the calculation for accessibility and the combination of all the mobilization time and repair time. Other aspects such as failures on wind turbines, problem related to energy transmission, onshore substation problems, etc are outside the scope and will not be covered. Other aspect is that the model does not take in consideration all the non-failure related outage, e.g. due to ship collision, fire outbreak, occupational accidents, human errors, extreme load, earthquake, collapses, dropped objects etc. Moreover, this project is a feasibility study with the main purpose of testing a methodology - not to develop a full operational model. The project does only utilize simple modelling to reveal the potential of the models developed within the project and make use of an empirical approach and approximations for calculating its own results.

3 The availability assessment model

The following chapter describes the availability assessment model used to provide the results of the thesis work. The model is developed in the non-dedicated programming language environment R, and it makes use of Montecarlo simulation to consider uncertainty and variability. Specific R libraries are used to perform the calculation.

The model allows the user to explore changes in the availability of a substation by modifying multiple variable such as:

- Time reference of interest
- Location of reference of the substation
- Maintenance strategy applied to the substation
- Component characteristics
- Quantity of components

The time reference refers to the reference time of interest and can vary in its length, for example 5 years availability or a lifetime availability. The location reference can be modified by providing different oceanographic data to the model, therefore reflecting a different geographical area and different wave conditions such as for example, using oceanographic data retrieved from the North Sea or from the Philippine Sea. The maintenance strategy can be changed by modifying the number of preventive repairs per year and their duration, for example, one preventive maintenance intervention per year or five preventive maintenance interventions per year. An arbitrary number of components can be represented in the model, and for each component, a fixed set of required information is needed to describe each of them properly. Each component is assumed independent of each other, and its failure represents a downtime with a consequential loss in availability. Each component is described by:

- the critical wave height reference to be transported by vessel (Hs),
- the maximum time to repair (MTTR),
- the mean time between failures (MTBF),
- the expert opinion on the minimum, mode and maximum time to retrieve a vessel,
- the expert opinion on the minimum, mode and maximum time to retrieve spare parts,
- the expert opinion on the minimum, mode and maximum time to perform a repair,

The model makes use of triangular distribution to model the expert opinion input that would cope with the lack of reliable and trusted collection of data.

3.1 Main assumptions of the model

As previously illustrated in the Introduction, an offshore substation is a structure at sea that allows to send electricity from the offshore wind farms to the substation onshore. This structure requires to be regularly maintained to reduce the degradation of components and prevent failures. However, failures can occur regardless of the maintenance where in that case, technicians are sent to perform the required repairs. As stated in 1.4.1 a substation is a complex system made of several components and many different levels of systems and subsystem connected between each other, forming a rather complex engineering system. However, due to the limited resources in terms of manpower, time and knowledge of complex electronic system and to embrace simplicity in the modelling design, the thesis work relies on the main assumption that the components are independent from each other. Moreover, it is considered that a total shutdown would occur in case of a failure of even only one of the represented components. This approach can be somehow justified when looking at the failure as a result of a subsystem failure. However, despite the above consideration, the data used to proceed with the calculations refer to single components. The failures are modelled following a Poisson process.

Another aspect that is worth highlighting is that repairs cannot be performed in multiple steps. When looking for an available window to go out and perform the repairs the model will only search for a total available time without interruptions, without taking in consideration the possibility that a repair might be terminated in two or more visits at the substation.

Regarding preventive maintenance strategy, only one kind of approach with a fixed visit to the substation is allowed. The frequency and the duration of the repair are free to be chosen.

When it comes to spare part time, vessel time, and actual repair time, the absence of available data is counterbalanced by the utilization of a triangular distribution to model expert opinion over the minimum, maximum, and mode of the variable of interest.

Other events that might cause suspension of the production at the substation and decrease the availability are not taken into consideration.

The components are assumed to be repair as new. The mean time between failure of components is considered constant over the whole selected period. The initial wear in and the wear out forming the bath tub are disregarded.

3.2 Availability assessment model algorithm

The following chapter describes the steps the model goes through to perform the calculations and provide the results. The various part of code which the algorithm refers to can be found in appendix 9.1. The following Figure 3-2 shows the general functioning of the algorithm.

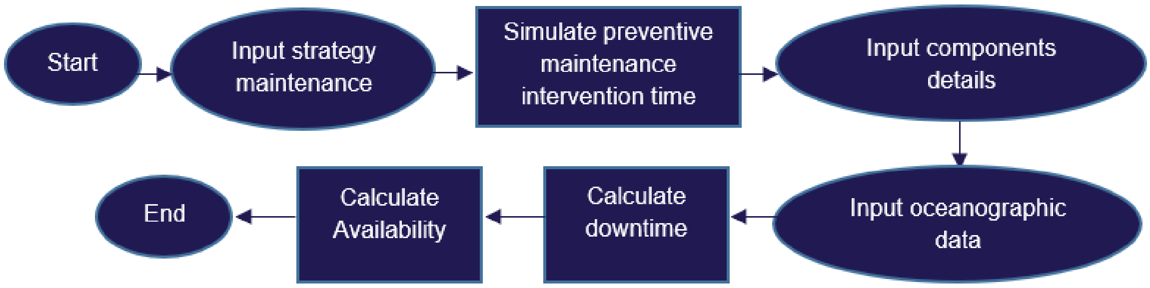


Figure 3-1 Generic overview of the availability model – Made by the author

As shown in Figure 3-1, the model is mainly composed of three blocks. The first block consists of calculating the preventive maintenance downtime. The input of the maintenance strategy reference is required. The inputs for all the components and the oceanographic data must be provided as well and based on these the downtime and the availability can be calculated as second and third blocks.

The following Figure 3-2 shows a more detailed flowchart of the algorithm steps.

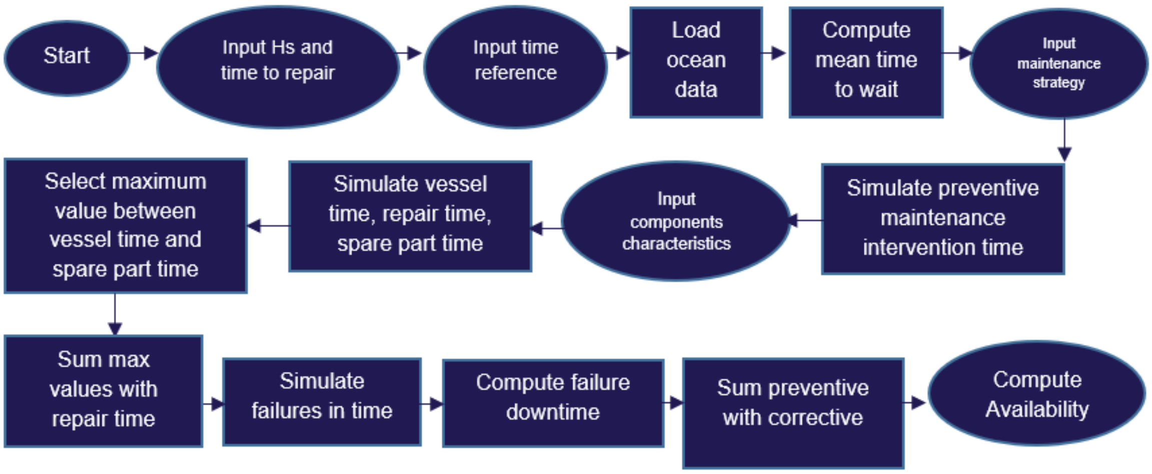


Figure 3-2 More detailed overview of the availability assessment algorithm – made by the author

The first block, preventive maintenance downtime, requires providing the maintenance strategy in terms of how many interventions there are per year, their length, and it simulates the total maintenance intervention time in the selected period. The second block, calculating the downtime, is made of several sub-steps. First, the characteristics of the component must be provided. The components characteristics as mentioned in previous chapters are:

- Maximum time to repair (MTTR)
- critic wave height for transportation with vessel (Hs)
- mean time between failures (MTBF)
- expert opinion in the form of minimum mode maximum for the time to retrieve vessel
- expert opinion in the form of minimum mode maximum for the time retrieve spare parts
- expert opinion in the form of minimum mode maximum for the time perform a full repair.

After all this information is gathered, it is possible to simulate vessel time, repair time and spare part time. Once this is done the maximum time between vessel time and spare part time is selected and it is used as preparation time, the other value is discarded. Further on, all the time values are added to form the possible total waiting time in case a failure. The possible total downtime in case of a failure is then replicated as many times actual failures are simulated to happen in the selected time, forming the downtime failure in case of a failure due to a failure. The table illustrate a simplified example to clarify the passages. The simplification reported in the is since in the model the value of time is not simply multiple by the number of failures, but it is rather replicated as many times as a failure occurs, to preserve variability in the randomization of the data and representation of uncertainty.

Preparation time	Repair time	Possible total downtime in case of a failure	Simulated failures	Total downtime in case of a failure due to a failure
10	5	15	0	0
10	5	15	1	15
10	5	15	2	30

Table 3-1 Simplified example for formation of total down time- made by the author

The values represented in the last column of the above table and labelled as total downtime in case of a failure due to a failure represent the downtime that the substation encounters in case of an actual failure. These values differ from the total downtime failure due to a failure, because the takes in account the number of failures, that can be a number from 0 to n, depending on the MTBF of the components. In the third block, the total downtime in case of a failure due to a failure is added to the preventive maintenance time to form the total downtime in the selected time for the substation, both for preventive and corrective maintenance. From this point it is possible to assess the availability.

The algorithm, as mentioned previously, is divided into three main blocks. In the following chapters, a more detailed view will be provided in the form of flowcharts and it will be commented to provide a better understanding and clearness.

3.2.1 Preventive maintenance time function

The calculation of the preventive maintenance time requires input to define the maintenance strategy. This means to set the number of maintenance interventions over the period and to provide the minimum, the mode and the maximum time needed for a single intervention to simulate a triangular distribution to be able to perform a Montecarlo simulation. The code related to this block can be found in the appendix **Error! Reference source not found.**.

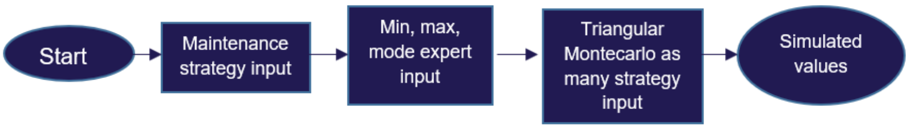


Figure 3-3 Preventive Maintenance function detail – made by the author

3.2.2 Downtime function

The downtime block works following the flow as shown in the below Figure 3-4.

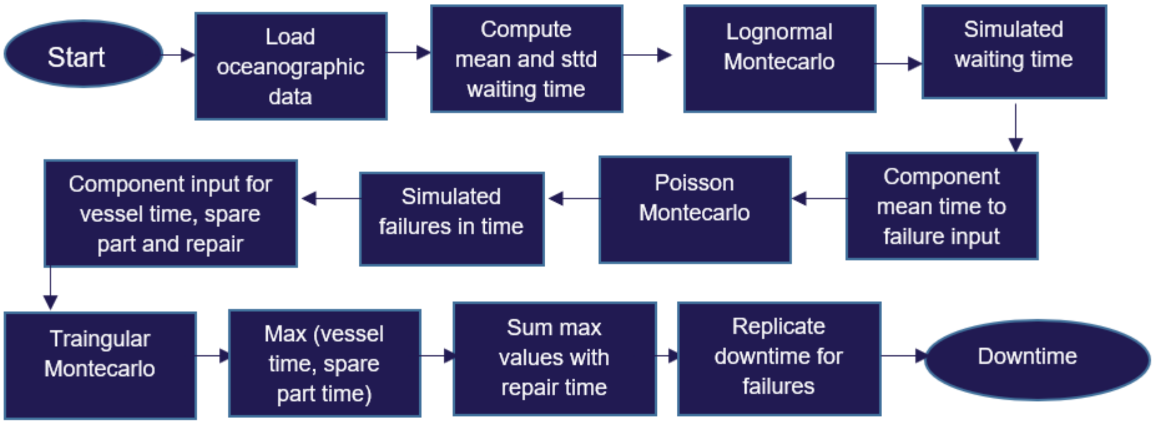


Figure 3-4 Downtime function detail- made by the author

The functioning principle is as follows, the oceanographic data are loaded and passed to compute the mean and standard deviation of the waiting time. Using the mean and the standard deviation it is possible to simulate the waiting time by means of a lognormal distribution as shown in chapter Waiting time modelling. Further on, the failures are simulated based on the mean time to failures input. The time component for a vessel, spare part and repair time are simulated by means of triangular distributions and the maximum values between vessel time and spare part time is selected. These values are afterwards summed and replicated as many times failures are simulated to happen. In this way, the downtime for failure, in case of a failure for each component, in the selected period is calculated. The code related to this calculation can be found in the appendix 9.1.1.

3.2.3 Availability function

The last part of the algorithm is the availability function and it has the task of combining all the possible components inserted in the previous steps and to sum all the corrective downtimes with the preventive downtime coming from the strategy that was previously modelled. The availability is calculated subtracting the total downtime from the expected time where the substation should operate. The figure below shows the steps for the availability function. The relative code can be found in the appendix R code, Availability function.

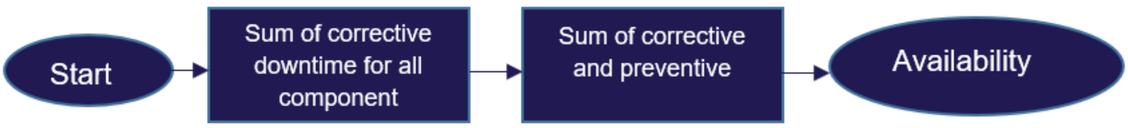


Figure 3-5 Availability function detail- made by the author

3.2.4 Accessibility modelling

To accurately model the waiting time to access the substation with the vessel, as previously mentioned, there is a need to model the accessibility to the platform depending on the vessel operational limit (Hs), the repair time (Rt) and the weather conditions at the location (Wh). In this sub-chapter, the detail of the accessibility algorithm is discussed. The following Figure 3-6 shows the flowchart of the steps used to calculate the accessibility and thereafter summarized as the waiting time mean and standard deviation to access the substation, given the wave height, vessel operational limit and required repair time window (Rt).

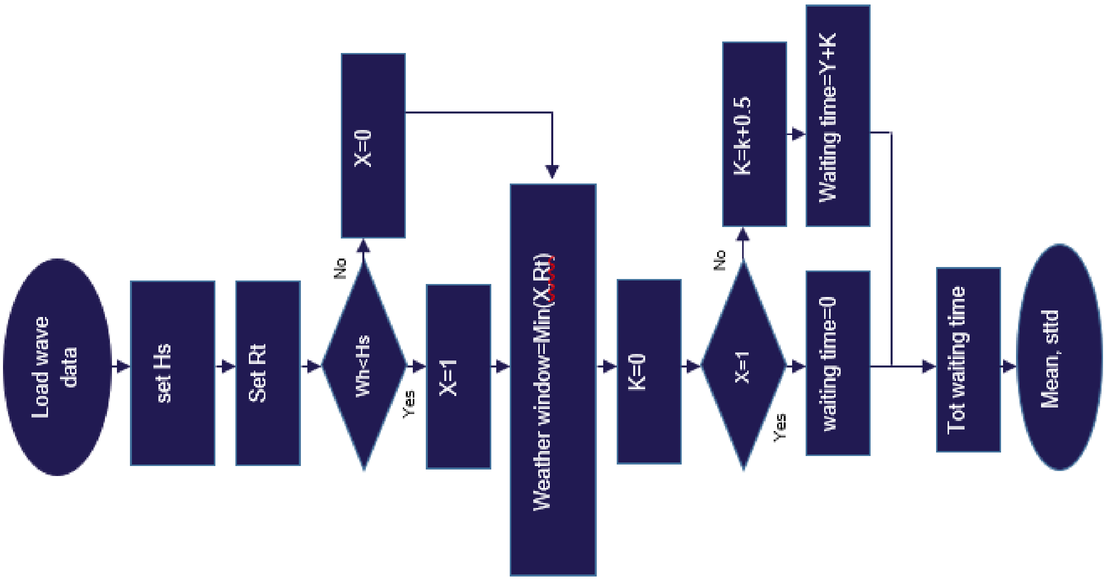


Figure 3-6 Accessibility flowchart – made by the author

The oceanographic data reflects the wanted position of the substation in terms of wave height. The critical height for vessel operation (Hs) is set. The window needed to perform the repair (Rt) is set. The height of the waves is passed for each time steps and compared with the critical height for vessel operation. Whenever the Hs is above the Wh it means that the vessel can sail in those conditions, therefore a positive 1 is assigned, otherwise a 0 is assigned, an example is provided below in Figure 3-7.

Wh (m)	2	2.5	3	1.5	2	2	3	4	4.5	3	2	1	0.9
Hs (m)	2	2	2	2	2	2	2	2	2	2	2	2	2
Result	1	0	0	1	1	1	0	0	0	0	1	1	1

Figure 3-7 Visual representation of Vessel operation limit - made by the author

The weather window is the available temporal space in which the repair time can be conducted. It is identified by running the results obtain comparing Hs with Wh, shown in Figure 3-7 and identifying the minimum window of 1 of length of repair time. The below Figure 3-8 provides a visual representation of the beforementioned process.

<table>
<tr><td colspan="10"></td><td colspan="4">Weather window</td><td colspan="13"></td><td colspan="4">Weather window</td><td colspan="2"></td></tr>
<tr><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>1</td><td>0</td><td>0</td><td>1</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>0</td><td>1</td><td>1</td><td>1</td><td>1</td><td>0</td><td>0</td></tr>
</table>

Figure 3-8 Visual representation of a weather window (e.g. repair time = 4) - made by the author

Following the weather window, the waiting time is calculated summing the distance from the last available weather window. An example is reproduced to facilitate the understanding of the concept in Figure 3-9 below.

<table>
<tr><td colspan="10">Waiting time</td><td colspan="4">Weather window</td><td colspan="13">Waiting time</td><td colspan="4">Weather window</td><td colspan="2"></td></tr>
<tr><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>1</td><td>0</td><td>0</td><td>1</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>0</td><td>1</td><td>1</td><td>1</td><td>1</td><td>0</td><td>0</td></tr>
</table>

Figure 3-9 Visual representation of waiting time - made by the author

After having identified the waiting time it is then possible to summarize mean and standard deviation and later use it to perform the lognormal Montecarlo simulation of the waiting time to access the substation.

3.2.5 Waiting time modelling

To accurately represent the waiting time and use it as input for the Montecarlo simulation, it is necessary to identify how the data can be described as a distribution, to then summarize the whole data with measure of location and dispersion, such as the mean and the standard deviation. By looking at the plot of the collection of data it is possible to understand the variability in the results and to start making the hypothesis on the structure of the data, and thereafter of the phenomenon. The below Figure 3-10 represents an example of a set of data for waiting time, obtained following the procedure explained in Availability assessment model algorithm chapter.

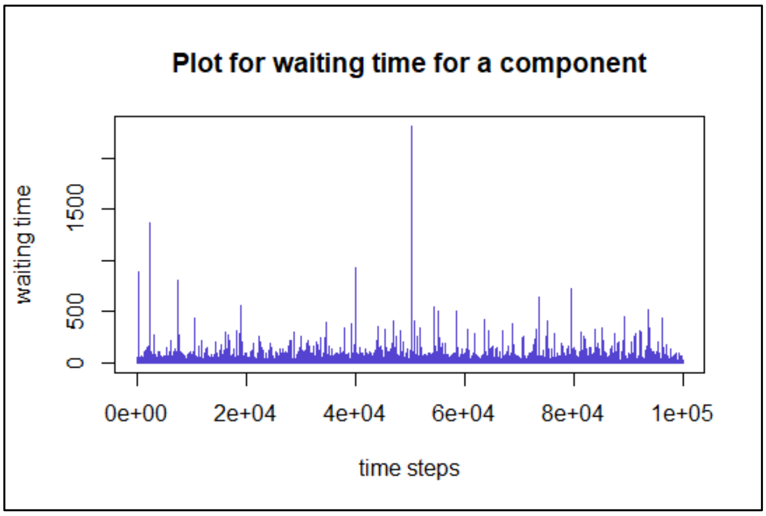


Figure 3-10 Waiting time plot – made by the author

The variation in the values displayed in Figure 3-10 provide insight on the possible nature of the data and their distribution. To gain more knowledge a histogram representing the frequency of the data is provided in Figure 3-11

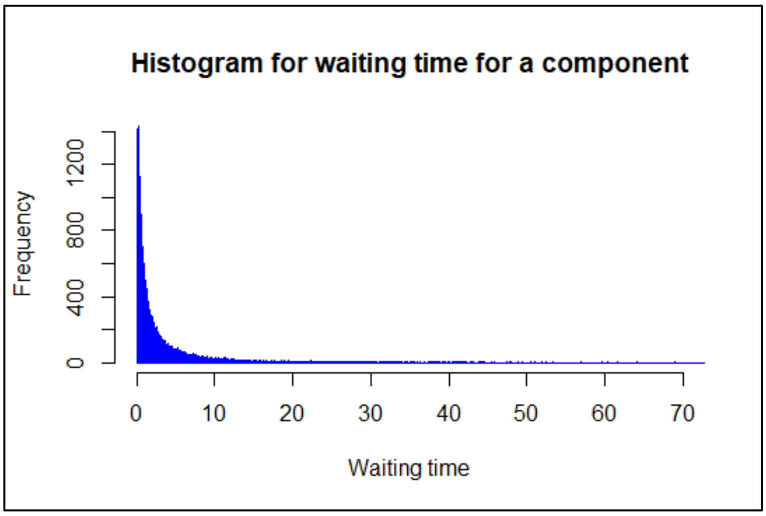


Figure 3-11 Waiting time frequency histogram – made by the author

The information provided from the histogram can help to identify a possible family of distribution to apply to the data. In this specific example, provided to facilitate the comprehension of the modelling technique, it is possible to identify at least two candidates for a distribution, an exponential and a lognormal distribution. However, by the nature itself of the working data the lognormal distribution seems to be the best candidate. The following Figure 3-12 shows the fit of a lognormal distribution on the data

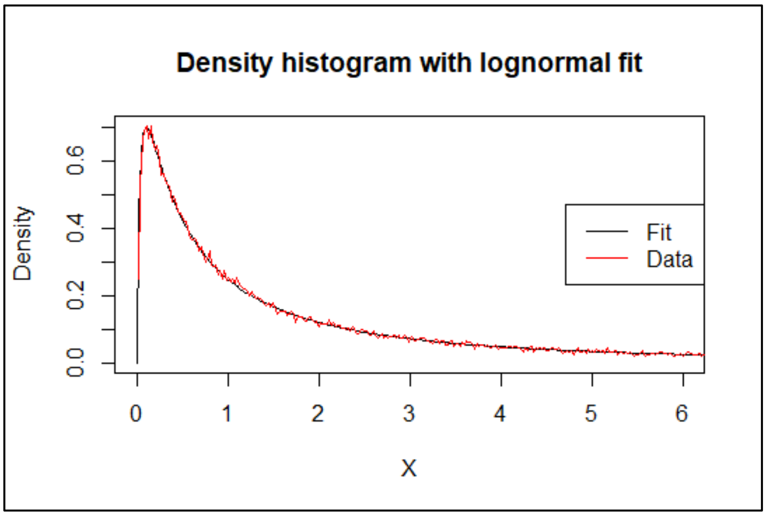


Figure 3-12 Waiting time lognormal fit – made by the author

Once the distribution is identified and it is decided that it will be the right one to describe the data it is possible to summarize the results obtained previously. The mean and the standard deviation of the waiting time are obtained and then transformed in lognormal mean and lognormal standard deviation. To summarize the data with the mean of a lognormal and the standard deviation of a lognormal it is required to retrieve the mean and the standard deviation from the data and later transform them as shows in Equation 3.1 and 3.2

$$\text{Lognormal Mean}=\log\frac{\mu^2}{\sqrt{\mu^2+\sigma^2)}}$$ 3.1

$$\text{Lognormal Standard deviation}=\sqrt{\log(1+\frac{\mu^2}{\sigma^2})}$$ 3.2

3.2.6 Failure modelling

To perform the steps explained and model the failure of the selected component it is necessary to apply a failure mode modelling technique. For the aim of this thesis work the selected components are modelled to fail following a Poisson distribution and are categorized as repairable components with repaired condition as new. Therefore, its mean time between failure won't decrease as it would in a repair "as old" but it will remain the same This assumption is made for the purpose of simplicity in the model construction and calculation. To perform the above, mean time between failure (MTBF) data are collected and used as input for the components. The MTBF are used together with the wanted time frame to calculate the lambda for each component and then simulate the number of failures in the time frame. An example of a Poisson failure distribution of a component in a certain time reference is shown in a Figure 3-13 below.

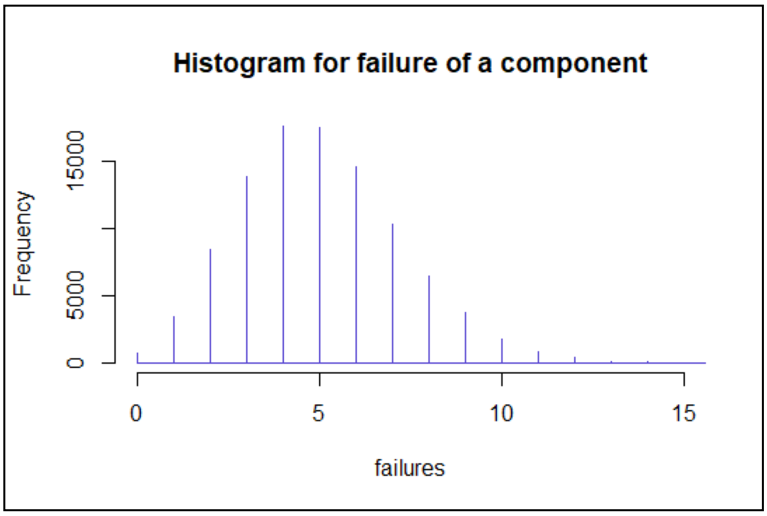


Figure 3-13 Poisson failure distribution for component - made by the author

The MTBF of a component is the sum of the time between failure (TBF) of that component and it is the results of a manufacturer studies or collection of data from the user. The formula for the MTBF can be seen in Equation 3.3

$$\text{MTBF}=\frac{1}{n}\sum_{i=1}^{i=n}TBF_i$$ 3.3

The average failure rate, or lambda, for a component is:

$$\lambda = 1/MTBF$$ 3.4

The component in the thesis work are modelled following a Poisson distribution. The variability in the failure of the component is represented by the probability mass function seen below

$$f(\lambda) = \frac{e^{\lambda t}(\lambda t)^x}{x!}$$ 3.5

With *t* being the time reference for which the failures want to be calculate for and *x* the variable of interest.

3.3 Expert opinion modelling

The vessel time, the spare part time and the repair time represent three important variables of the model. The vessel time, as mentioned in 1.7 is the expected time required to retrieve an appropriate vessel that can transport the spare parts to the substation and later perform a repair. It is a crucial part of the calculation since without a vessel the components cannot be transported to the substation, therefore the total waiting time increases and the availability decreases. The spare part time apply almost the same logic. The spare part time is the time required to retrieve a spare part from the warehouse or from a supplier. The repair time is the window of time expected to perform the entire repairment on the substation. It comprehends the transportation time from and to the substation as well.

Due to the lack of data and to better represent the uncertainty in the real context, where these types of information are hard to retrieve, the above three variables are modelled from the expert opinion. This means that a minimum value for the time, a maximum value for the time and a most likely (often call mode) value for the time are used to model a triangular distribution that is used to perform the Montecarlo simulation for these variables. The Figure 3-14 below shows two examples of two different triangular distributions, one centred one skewed on the right.

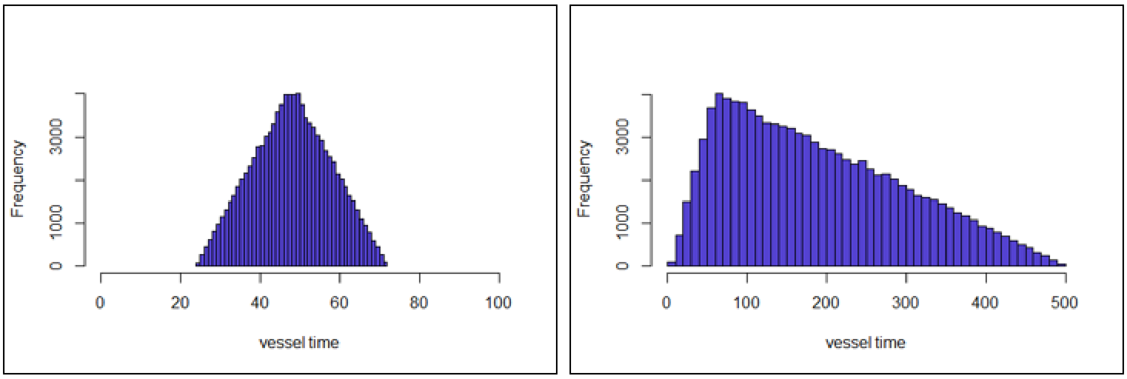


Figure 3-14 - Example of two triangular distribution representing the vessel time – made by the author

The triangular probability density function is described by the following equation 3.6:

$$f(x) = \frac{2(x - min)}{(mode - min)(max - mode)} \qquad 3.6$$

4 Case study

In this chapter an application of the above illustrated model is given by mean of a simplified case study. The number of components is reduced, the presence of redundancy over components is not accounted and the interconnection between components is oversimplified.

To perform a more comprehensive study, taking in account all the components and the interactions among components a fault tree analysis (FTA) is required. By mean of a FTA all the relations between the components, their priority, their failure modes, their connections and so on, would have been investigated and reproduced fully. However, to perform a full FTA on a substation the focus of the thesis should have been only on that matter, therefore the fault tree analysis has not been executed. Studies and literature on the matter however has been consulted as reported in the State of the art – literature chapter and visible in the Bibliography.

For the purpose of the case study some main assumptions, in addition to the ones already stated in the previous chapters, are made. The substation is considered to be well designed, manufactured and installed. For these reasons no deviations from what is to be considered ”the norm” is taken in account. The substation is in a steady power state condition. Human errors are not taken in account. Extreme environmental condition not considered in the design phase are not taken in account. The preventive maintenance is followed as planned. The maintenance is performed by qualified personnel and without delay on what considered.

For the purpose of the case study only three of the components represented in Figure 1-8 are used. Those are the high voltage cables, components and terminations, the main transformer and the medium voltage gas insulated switch gear component. The three components are represented as single linear components in Figure 4-1 and single values for their failures are considered. In the following chapters a brief but more detailed description for each component is provided and their specification for the purpose of the case study are revealed.

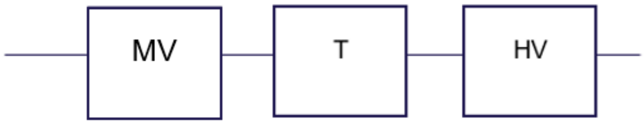


Figure 4-1 Component representation for the case study - made by the author

Medium voltage component

According to the Guidelines for the Design and Construction of AC Offshore Substations for Wind Power Plants Cigre 483 [30] the medium voltage switchgear are made up of metal enclosed, SF6 (Sulphur Hexafluoride) insulated modules, which is often referred to as GIS (Gas Insulated Switchgear). SF6 is the standard insulating solution in these applications as it is a very good electrical insulator, which means that electrical distances can be minimized, and the switchgear can be as compact as possible. A medium voltage gas insulated switchgear is an apparatus used for switching, controlling and protecting the electrical circuits and equipment on the substation. What essentially a switchgear is used for is to ensure reliability, carry quick operation and provide manual control over the various parts of the substations. There can be different type of switchgear, defined by their voltage level, a medium voltage switchgear is rated from 3.3 kV to 33 kV. A medium voltage switchgear for a production plant is represented in Figure 4-2 below.

Figure 4-2 Medium voltage Switchgear of the Biomass power Plant Steyr [31]

For the purpose of the case study some specification has been gathered from experts opinion [7] and from literature and are now presented in the below Table 4-1, Table 4-2and Table 4-3.

Component MV	Specification	Value	Unit	Source
	MTBF	1752000	hours	Expert
	MTTR	6570	Hours	Expert
repair time	min	720	Hours	Expert
	max	6570	Hours	Expert
	mode	4380	Hours	Expert
vessel time	min	24	Hours	Assumption
	max	48	Hours	Assumption
	mode	24	Hours	Assumption
spare part	min	168	Hours	Assumption
	max	720	Hours	Assumption
	mode	336	Hours	Assumption

Table 4-1 MV component specification- made by the author

Main transformer

According to Cigre 483 [30] the transformers are the main components of the offshore substation due to their function of stepping-up the voltage for power transmission and due to their size and weight. The objective of the main transformer is to increase the output voltage to reduce the loss and increase the transmission capacity when sending energy on-shore. Transformers can be divided in two categories on their application:

- Power transformer, used to transmit power over long distances at high voltages
- Distribution transformer, used to distribute power to consumers at medium and low voltage levels

The transformer the case study refers to can be categorized as a power transformer, specifically as a step-up transformer [32]. According to the definition found in to the Guidelines for the Design and Construction of AC Offshore Substations for Wind Power Plants Cigre 483 [30] the main transformers (in the case-study, only one transformer) are the largest single piece of equipment installed on the platform. The transformers drive the main overall electrical and physical design. For an indirect connection to the shore, such as in the example provided in Figure 1-4, there is the need to ramp up the voltage to deliver to shore. This is done by means of a step-up transformer (for example 132/400 kV) [30]. For the purpose of the case study some specification has been gathered from expert opinion [7] and from literature and are now presented in Table 4-2.

Component T	Specification	Value	Unit	Source
	MTBF	1752000	Hours	Expert [10]
	MTTR	6570	Hours	Assumption
repair time	min	720	Hours	Expert [10]
	max	6570	Hours	Expert [10]
	mode	4380	Hours	Expert [10]
vessel time	min	744	Hours	Assumption
	max	1488	Hours	Assumption
	mode	1488	Hours	Assumption
spare part	min	744	Hours	Assumption
	max	1488	Hours	Assumption
	mode	1488	Hours	Assumption

Table 4-2 Transformer component specification- made by the author

HV components

The high voltage components are those components of the substation located at the ”high end” of the plant that allow the transmission of the electricity onshore after that the transformer has ramped up the current. They are as well gas insulated as the MV component. For the purpose of the case study some specification has been gathered from expert opinion [7] and from literature and are now presented in Table 4-3

Component HV	Specification	Value	Unit	Source
	MTBF	1752000	Hours	Expert [10]
	MTTR	6570	Hours	Assumption
repair time	min	720	Hours	Expert [10]
	max	6570	Hours	Expert [10]
	mode	4380	Hours	Expert [10]
vessel time	min	24	Hours	Assumption
	max	48	Hours	Assumption
	mode	24	Hours	Assumption
spare part	min	168	Hours	Assumption
	max	1488	Hours	Assumption
	mode	336	Hours	Assumption

Table 4-3 HV component specification- made by the author

4.1 Case study model results

Now the result from the case study are presented. The following are the results of assuming a life time reference of 25 years for the platform, with one scheduled preventive maintenance intervention per year with an estimated triangular window time of intervention of 24 hours as minimum and mode and 48 as maximum. The inputs to the model are the data presented in the above sections. The oceanographic conditions are the one obtained in the course of the education in risk and safety management during the lectures in maintenance management and refers to the condition around the FINO2 platform in the Baltic sea [33]. For the two components MV and HV the critical height waves are to be considered of 2 meters. For a fault in the transformer it is assumed the intervention of a jack-up vessel, therefore no critical wave height is to be considered.

Waiting time

As explained in chapter 3 the waiting time is the time to be waited before sailing for the substation due to meteorological condition. In this section the result of the waiting times for the components on the case study are reported.

Significant results for waiting time due to meteorological condition for the MV component and for the HV with a critical wave height of 2 meters are: minimum waiting time of 302.1 hours, a maximum of 45447.6 hours, a median of 3793.4 hours, a mean of 4382 hours with a standard deviation of 2537.37 hours. A plot and histogram resulting of the Montecarlo simulation for the waiting time are reported below in Figure 4-4 and Figure 4-4.

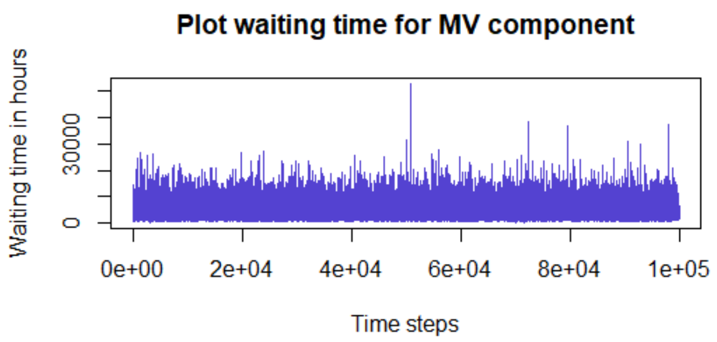


Figure 4-3 Plot for waiting time for MV component- made by the author

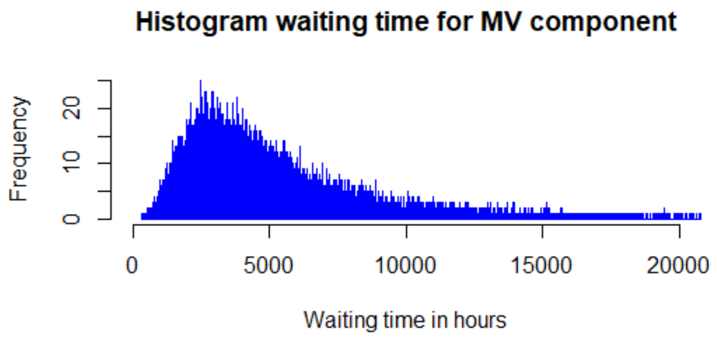


Figure 4-4 Histogram for waiting time for MV component- made by the author

The waiting time for MV component resulted in a skewed distribution with a strong disperse distribution represented by a very important standard deviation. Extreme values diverge significatively from the mean.

Because of the assumption of the utilization of a jack-up vessel the critical wave height for the transportation of the transformer is not relevant. Therefore the transformer waiting time is zero.

Vessel time

As discussed in chapter 3 the vessel time is the time to be waited before a suitable vessel to carry on with the operation can be retrieve and use. In this section the result of the vessel times for the components on the case study are reported.

The vessel time is the realization of the input provided in the previous part of the Case study chapter. Figures to help to visualize the time windows are provided below. The MV component and the HV component have been assigned the same vessel time due to the same utilization of vessel, therefore only the result from MV is reported below The plots with the realization of all the iteration from the Montecarlo for all the components can be visualized in the appendix at 9.2.

The vessel time results for MV and HV component are,

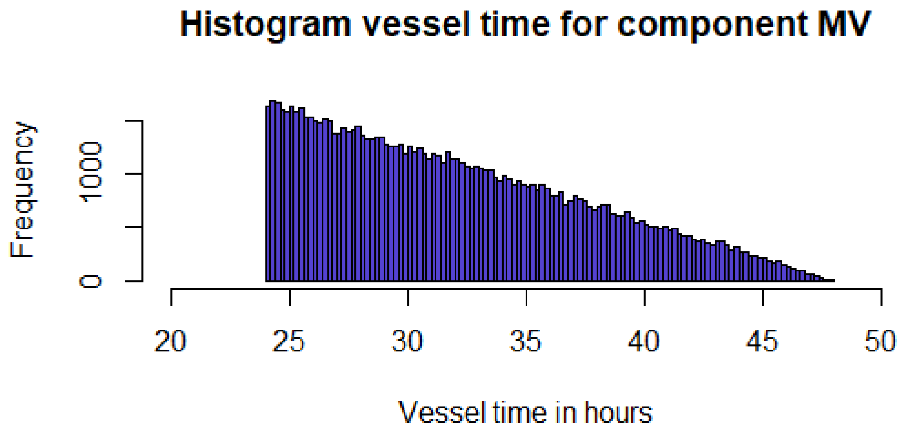


Figure 4-5 Histogram for vessel time for MV component- made by the author

For the transformer component,

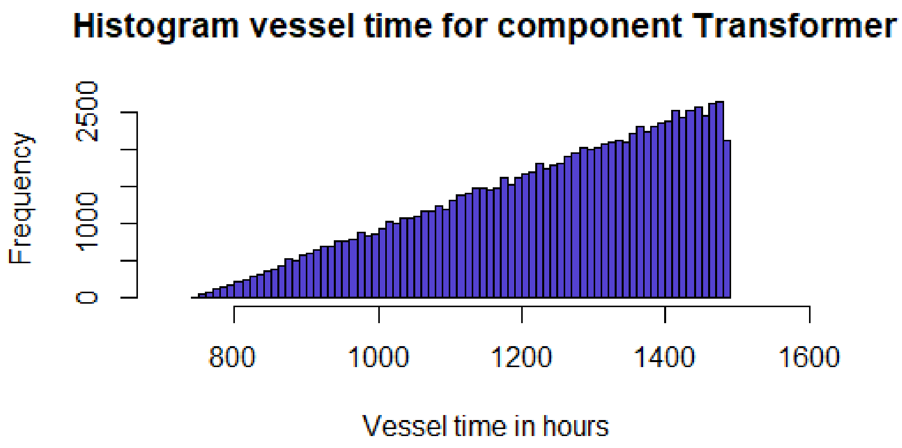


Figure 4-6 Histogram for waiting time for Transformer component- made by the author

The summary measure for the vessel time in the MV and HV components are :a min of 24 hours, a median of 31 hours, a mean of 32 hours with a standard deviation of 5 and a max of 48 hours. For what concern the transformer vessel time the summary measures are min vessel time of 747.8 hours, median of 1270, mean of 12340 with a standard deviation of 175 and a max of 1488 hours.

Spare Part time

As introduced in chapter 3 the spare part time is the time needed to find at the warehouse suitable spare part to perform the repair (or substitution) of a component. In this section the result of the repair times for the components on the case study are reported.

Spare part time are also simple reflection of the triangular distribution inputs. Following the summary results for all the components and their histogram to help visualize the results.

For the MV the minimum time to be waited to retrieve the spare part is of 168.4 hours, the median is of 320, the mean of 394 with a standard deviation of 5.66 hours and a maximum of 718 hours. The histogram is represented in Figure 4-7 below.

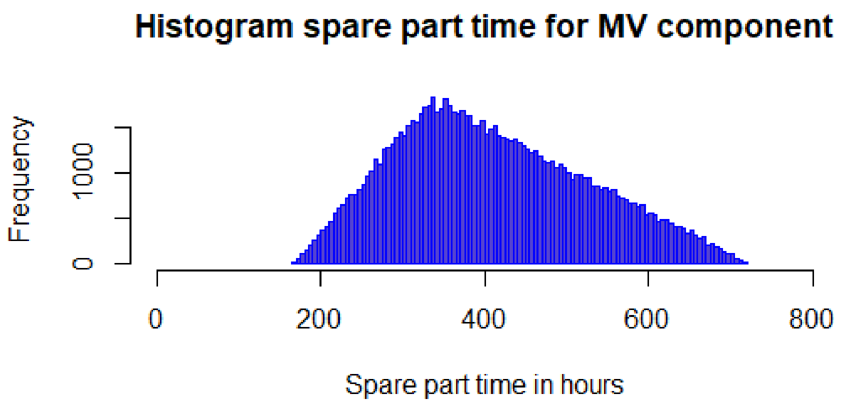


Figure 4-7 Histogram for spare part time for MV component- made by the author

For the Transformer component the minimum time to be waited to retrieve the spare part is significantly higher, 746 hours, with a median of 1116 hours and a mean of 1239 hours with standard deviation

of 175 hours and a maximum of 1488 hours. The histogram is represented in Figure 4-8 below.

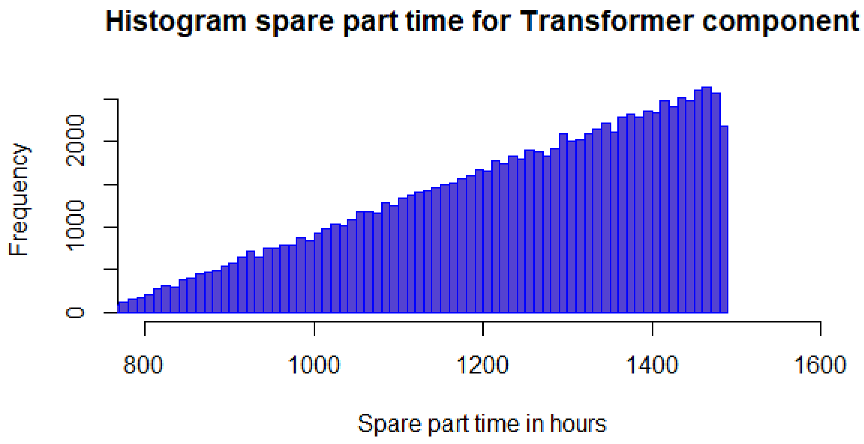


Figure 4-8 Histogram for spare part time for Transformer component- made by the author

The High Voltage component has a minimum time to retrieve the spare part of 169.7 hours, a median of 418.5 hours, with a mean of 1239 and a variation of 294 hours with a maximum of 1485 hours, very close to the precedent datum. The histogram is represented in Figure 4-9 below.

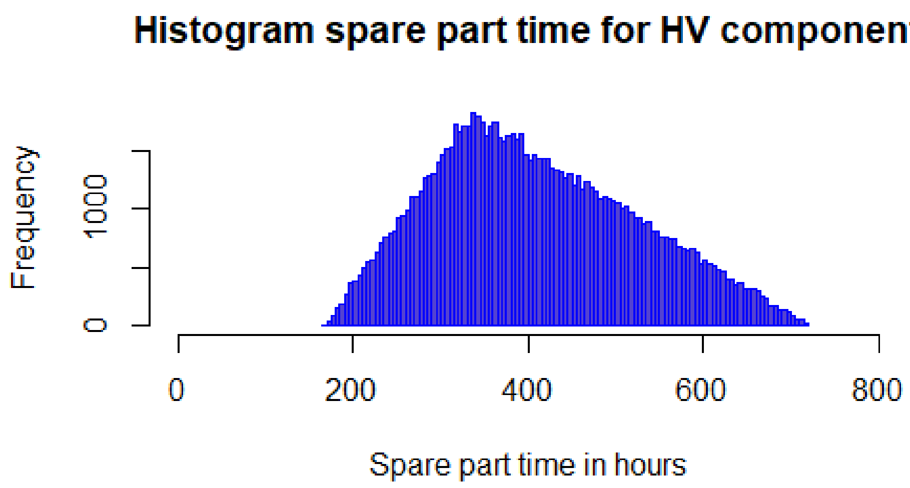


Figure 4-9 Figure 4-10 Histogram for spare part time for HV component- made by the author

Repair time

As showed in chapter 3 the repair time is the time needed to perform a repair (or substitution). in this section the result of the repair times for the components on the case study are reported.

Repair part time are also the reflection of the inputs given by triangular distribution. For this reason is not of direct interest to report or visualize all the results from this data as well. The whole collection of it, however, can be found in the appendix at Collection of plots.

Preparation time

As illustrated in chapter 3 the preparation time is the resulting time of the longest between the two component, spare part and vessel time and represent the time in which the crew is ready to sail before assessing the sea condition and afterward sail. In this section the result of the preparation times for the components on the case study is reported.

For the MV component the total preparation time resulted in a mean of 407.9 hours, with a min of 169, a max of 717 and a standard deviation of 115 hours. The shape of the distribution of the preparation time preserved the triangular form and can be seen in Figure 4-11. Of interest how the other two components present a different shape following the combination of all the elements that represent the preparation time.

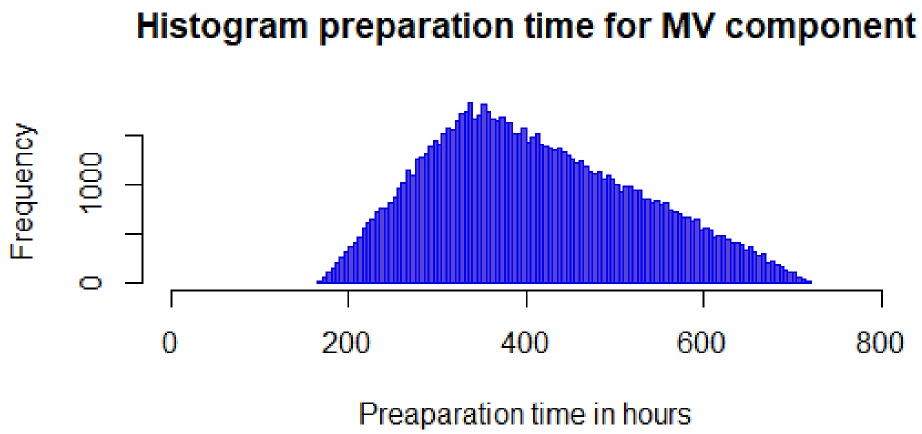


Figure 4-11 Histogram for preparation time for MV component- made by the author

For the Transformer component the preparation time is of 1338 hours on average, with a standard deviation of 121, min of 786 and max of 1488 hours. As anticipated the shape of the distribution is slightly skewed on the right.

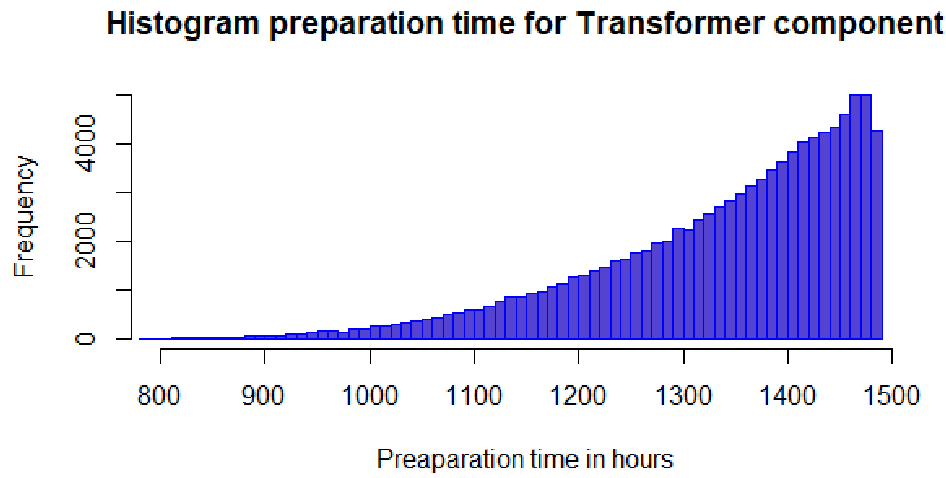


Figure 4-12 Histogram for preparation time for Transformer component- made by the author

For the HV component the preparation time is 663 hours on average, with a standard deviation of 293.71, a minimum of 169 and max of 1483 hours. Also here the shape of the distribution is skewed on the right.

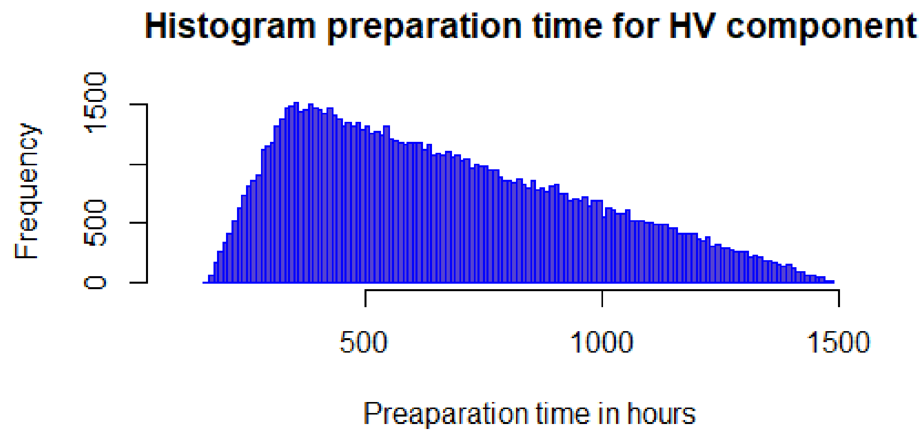


Figure 4-13 Histogram for preparation time for HV component- made by the author

Downtime due to failure

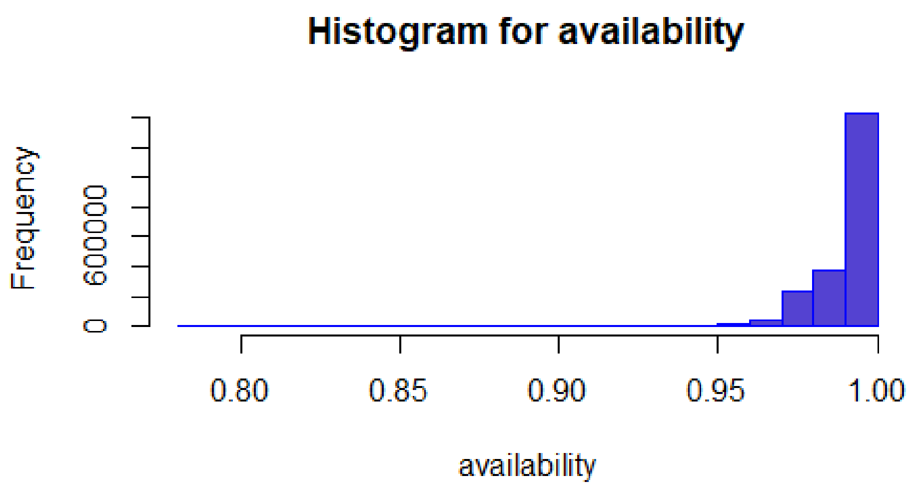
Due to the very high values of mean time between failures the downtime due to failures are not significant for the case study. It is however of interest report the maximum value that the Montecarlo simulation reports as possible to experience, however with probability to be disregarded.

For the MV component the maximum downtime possible is of 7492 hours (312 days). For the Transformer of 2842 hours (118 days). The HV component has a maximum downtime value of 11164 hours (465 days). It is interesting to notice this result. The lower value of the transformer must be due to the absence of meteorological constriction due to the assumption of the utilization of the jack-up vessel.

Availability

The result of all the above calculations is the availability. Taking in consideration the preventive maintenance and the downtime on the components, together with the required time to mobilities vessels and spare parts the result from the above data is the following.

The availability over 25 years of life time is on average 99,02%, with min value of 81,09% and max value of 99,69%. A visualization of the distribution of the availability is provided in Figure 4-14 below.



It appears clear how the dispersion of the measure is limited on a very short range. Most of the simulation falls inside the 0.95-1.00 range with very unlikely scenario under those.

Figure 4-14 Histogram of life time availability - made by the author

5 Sensitivity analysis

On one component

If in the previous chapter it was said the downtime due to failure was not relevant, since very high reliable mean time to failure specification were in place. It is however worth and interesting to verify possible changes in the availability results when components of less quality are used and therefore lower reliability is in place. In this case, for the sensitivity analysis one of the 3 components is assumed to have a much lower MTBF (from 200 years to 1) and the result in availability is explored.

The component selected is the medium voltage gas insulated switchgear (MV). The number of failures in the lifetime can vary from a minimum of 7 to a maximum of 48 with a mean of 25. The failures are illustrated in the plot of the Montecarlo simulation in Figure 5-1.

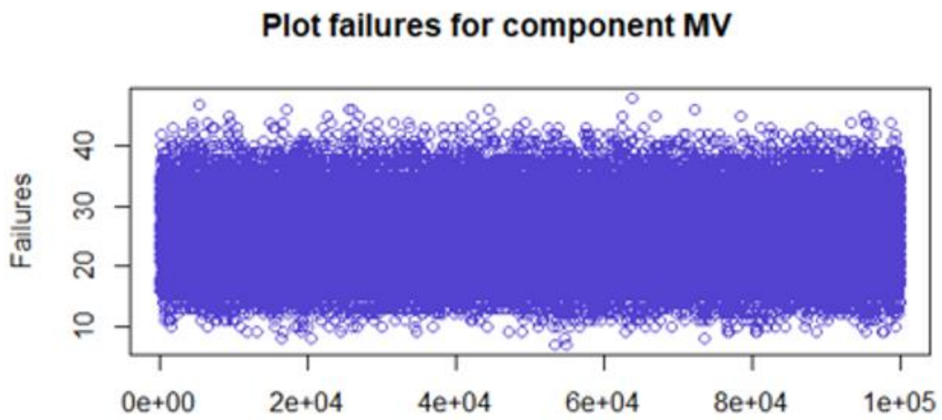


Figure 5-1 Montecarlo simulation sensitivity analysis for failures of component MV- made by the author

The variation in the result is visible also in the result of the availability. The resulting availability for three components in which one of them has significant reduced reliability has a mean of 93% with a possible minimum of 0% availability over the 25 years of activity even though very much unlikely as visible in Figure 5-2.

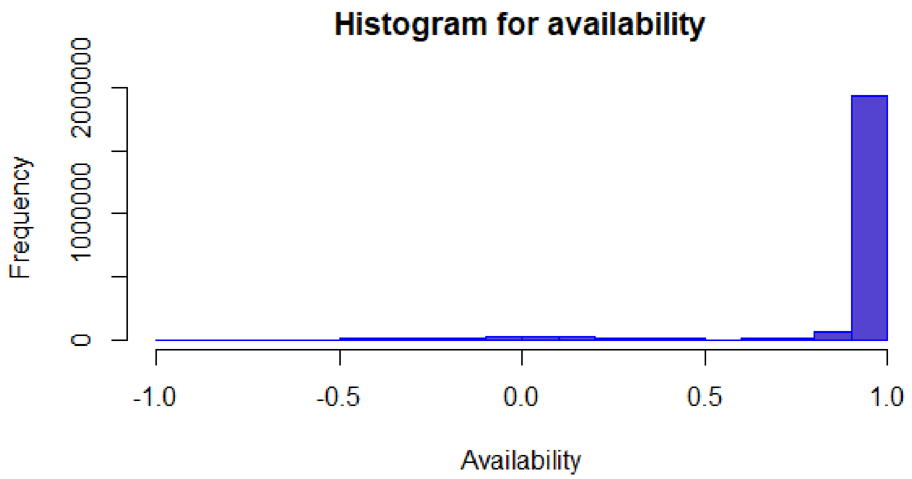


Figure 5-2 Sensitivity analysis, availability result- made by the author

On multiple components

It is of certain interest to verify the variation of the availability at the change of the various parameters. Varying progressively all the components that form the final result in the availability it provides the possibility to explore trends and influences on the final number. Performing a complete exploration of all the components with an adequate and progressive modifications of the parameters it would however require a significant amount of time and energy. Therefore for the purpose of investigate the matter the following strategy has been applied. All the parameters used in the case study will be progressively modified of a 10% and the summary results of the availability will be presented. In order to provide some valuable insight, as first only the reliability of the three components will be reduce from the initial value progressively to a 50%. Then another case will be performed where the reliability will remain the same but the various time for intervention (spare part and vessel time) will be increase up to the double of themselves. The resulting numbers in case of the modification in the reliability are shown in Table 5-1. No significant variation can be appreciated.

Reliability decrement	100%	90%	80%	70%	60%	50%
Mean availability	0.984	0.984	0.984	0.984	0.984	0.984
Median availability	0.991	0.991	0.991	0.991	0.991	0.991
Min availability	0.420	0.456	0.416	0.440	0.454	0.419
Max availability	0.996	0.996	0.996	0.996	0.996	0.996

Table 5-1 Availability results due to decrement of reliability- made by the author

In case of the increment of the mobilization time the same trend is shown. Even by double the amount the mean availability remains of 0.981, with a min of 0.406 and a max of 0.996. No significant variation can be seen.

Economic calculation

As explained in chapter Offshore wind energy costs the AEP is the annual energy production and is the calculation of the potential energy produce by a plant over a period of time, taking in account also the unavailability due to failures or others situations. It is interesting to produce a result in regards with this value by means of the model to visualize a risk-based approach result and taking account the distribution shape of the result, represented not anymore as one-point estimation.

As stated in chapter 1.6 the AEP can be calculated as:

$$AEP = MW * \ Lifetime(h) * \ Cf \tag{5.1}$$

By taking the same example the AEP for a lifetime production the formula become:

$$AEP = 50 \ MW * \ 8760 * 25 * 8760 \ * \ 0.25 \tag{5.2}$$

Where 25 are the years of expected lifetime of the platform and 8760 are the hours in a year. The result from the afore calculation when unavailability from the model is taken in consideration and uncertainty is taken in is presented in formula 5.3 and below in Figure 5-3:

$$AEP = 50 \ MW * \ 8760 * 25 * 8760 \ * \ 0.25 * Availability \tag{5.3}$$

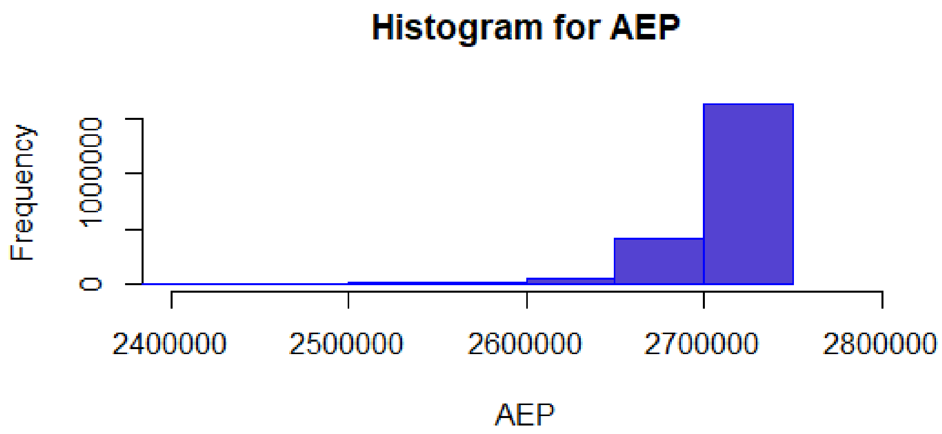


Figure 5-3 Histogram for AEP calculation from case study- made by the author

The AEP summary measures are a mean of 2710515 MW, with a possible minimum of 1941319 MW, a maximum of 2730529 and a standard deviation of 26285.54MW, placing the 60% of the data around the mean in an interval between 2684230 and 2736800 if the empirical rule is applied.

The same evaluation can be done for the LCoE. As illustrated in chapter 1.6 the levelized cost is calculated following the formula

$$LCoE = \frac{(CAPEX * \ CRF + OPEX)}{AEP} \tag{5.4}$$

Where the AEP is the above Annual Energy Production calculated for the lifetime using the lifetime availability retrieved from the model results. By assuming the CAPEX, the OPEX and the discounting value the LCoE the value can be presented as following:

- CAPEX <- 24000000 Euro
- OPEX <- 1000000 Euro
- CRF <- 0.10

The summary measure for the LCoE are an identical mean and a minimum value of 1.2 €/MW with a maximum of 1.7 €/MW and a standard deviation of 0.01 €/MW. A refiguration of the distribution of the LCoE is found in Figure 5-4 below.

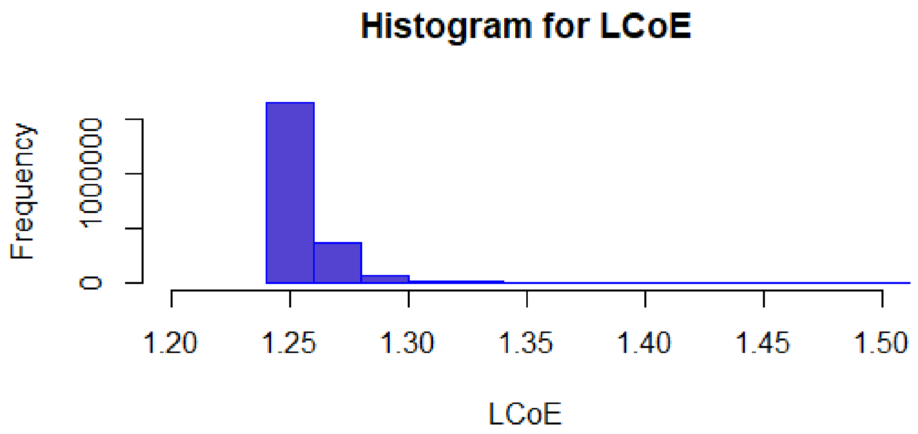


Figure 5-4 Histogram for LCoE calculation from case study- made by the author

All the above economic figures are only for educational purpose only and aim to show the possibility of the model in terms of calculations and presentation of results. The above presented figures do not represent in any way a real calculation for AEP or LCoE form an actual wind farm.

6 Discussion

Developing a model is a challenge. The analyst, the person who is in charge to work on the model, to build it and produce useful information from it not always has all the information that he might need, nor always has the knowledge of the system like the one an expert might have. It is then a very complex task the one to achieve a satisfying result. A tool that could reproduce the world as close as possible and provide correct answers when interrogated. If one doesn't fully understand the world how can he think of model it? It is for this reason that it is common to say that all models are wrong and only a few are useful. And even more, it is for this reason that the scope of this work was the one of provide a basis for investigate the availability of a substation using a non-dedicated software, to explore the possibilities of the tool and verify the capability of the analyst itself and not the one of really reproduce a full model able to represent the lifetime availability of an operational offshore substation plant. The capability of the model at the current stage is limited to a proof of concept level. Moreover, developing a model is usually a complicated process that involves many aspects and disciplines. It follows an idea, it develops with design and try and fail tests and ends with testing the model work. This discussion and conclusion discuss the findings from this thesis work and provide an overview of the achievements of the objectives for this project.

The thesis aimed to develop a model for assessing the lifetime availability of an offshore substation in a Danish wind farm to improve the risk-based approach of the industry to the quantification of availability and the economic figures useful to the develop an offshore project. An introduction to the offshore industry is provided and a generic model of an offshore wind farm substation is presented. From it, a simplify case-study is built to prove the use of the model. Using the non-dedicated software environment R a model to assess the accessibility of the platform by mean of vessel access based on oceanographic condition, together with quantification of the required time to mobilize the O&M resources and the repair time in case of failures of components are used to assess the lifetime availability of an offshore substation. The use of the lognormal distribution is made to fit the wave conditions. The triangular distribution is used to model the expert opinion. Results for all the components of the case study are presented and the availability is discussed. The main economic figure such as AEP and LCoE are presented.

The model uses a set of assumptions and has been built following a set of rules and decisions that might not be the best choices or that might be argued to be, at least, not perfect. When addressing reality and trying to describe in a small version of itself it can be hard to make the right decision to let the model represents the world appropriately. These limitations can be present for many reasons: ignorance of the analysts, lack of resources, lack of time, errors, etc. The model presented in the thesis work uses a Poisson method to estimate the occurrence of failures. This solution can be replaced using a Weibull failure analysis method or by other failures technique analysis with more complex behaviour that aim to estimate the failures with more precisions and or variability. The accessibility to the platform is calculated only employing vessels, the use of a helicopter is disregarded. This choice can be criticized and the insertion of the helicopter as a mean of transportation could have been indeed a valuable addition. The use of the expert opinion as the basis for the input of the data for the O&M resource and the repairing time was meant to fill the gap with the lack of data from the industry. A more thorough research could have achieved a better data collection and the model could have relied on fit of data collection rather than on expert inputs. However, the choice of the expert opinion as input comes also from the analyst experience that on the job often data are lacking and time is an issue, therefore often estimations are done by means of experts opinion rather than on more time-consuming fit of data. In this way the model represents more closely reality when estimating the conditions for assessing the availability. The model calculates the repair time as a unique set of time with no possibility to split the repairments in more missions and therefore underestimate the interferences from the meteorological conditions. This aspect could be improved and implemented for a more realistic representation of the accessibility conditions. The preventive maintenance allowed in the model is only of one type and it cannot be change if not only in the length and frequency. The implementation of the opportunity to select different preventive maintenance schedule technique could be an improvement in the representation of the model. Another aspect, probably the biggest of all the previous considerations, is the rather simplistic model for the case study. It has been already said that the aim of the work was to produce a model that could prove the utility of the utilization of Montecarlo technique for the assessment of the availability of a substation for an offshore plant and therefore there was no aim to fully and really represent a whole plant. However many aspects could have been implemented to scale up the model and provide a better representation, even for a simplify case-study. Some of these aspects are, among others: the recreation of parallel components and serial components to address more complexity and to consider the possibility of multiple components failure without a total outage. The redundancy of components could have been integrated and represented to provide a fairer representation of how an actual outage would hit the substation in case of failure of main components. A fault tree analysis could have been carried out. Even a simplified one. Common factor failures and common repair missions could have been taken into consideration. Other conditions for failures such as fire outbreak or other environmental and or human conditions could have been taken in consideration. The use of R as tool for the development of the model was a choice made for different reasons. R is a widely spread and commonly used programming language with a very large set of libraries and strong support of the community. The easiness of use is high if compare with other programming languages and the flexibility in the construction of the model is higher if compare with other non-dedicated program such as Excel. Moreover, the calculation capacity is higher. However, the starting curve, as it is for all the coding languages, is rather steep and led to some difficulties in the construction of the model and led to some limitations in the ability to build the desired product. It should be clear, that further efforts within the topic can be justified, as this project only demonstrates the technique as a proof of concept.

Last words for the representation of the data. Uncertainty, risk and variability are the base of this work. The use of Montecarlo analysis aimed to provide a better risk picture when assessing the availability and making decisions for offshore wind project. Sometimes showing a distribution of data together with the summary of the main results is more appropriate than providing one-point estimate results which can be misleading in the way it holds all the meaning of a result in only one value hiding how that same values vary around a mean. Retaining uncertainty in all the part of the model is very useful in estimation and decision making because allow to have a complete picture of all the possible variations and scenarios. The thesis work aimed to do so by applying distribution to all the components of the model without leaving any components as a single one-point estimation or results. The wave height, the vessel time, the spare part time, the repair time and the failures are all modelled taking in consideration their distributions and therefore uncertainty. It can be argued that a different representation of the likelihood of some data could have been propose. However that is a choice and only a matter of representation of the results.

Results discussions and considerations

The results obtained with the utilization of the case-study are of little or non-interest for a discussion regarding the real availability of an offshore substation. The case-study model is to small and to simplified to provide real insights and allow a productive discussion around it. The availability was calculated and resulted in optimal margins. The results of it were presented in a distribution which allowed to better understand how confident the result was around the mean. The AEP was calculated and represented with a distribution visualizing the variation in the results. Same for the LCoE which has been represented as a range and not as a single one-point estimation. However, it can be of interest to analyse the results from the point of view of the risk communication. The utilization of a risk approached allow the reader to understand more easily the distribution of the results and to visualize better the real meaning of the calculations. A single point estimation in the case of the assessment of a lifetime availability it can retain extreme variation and therefore can cause misleading decisions. The use of uncertainty on the other hand, allow to comprehend multiple aspects and many possible scenarios that eventually are describe by a distribution which is a better tool to visualize the risk and to understand where the values are truly at allowing a better decision-making process.

Further work

Results of availability and its distribution have been presented in the report. Main economic figures such as LCoE and AEP have been discussed and presented. A small study of how the variation of the components could affect the final results in the availability has been conducted and the results have been presented. However, for future works, it would be of real interest to perform a deeper and more profound examination of how the quality of the components and the length of the O&M times can influence the availability and in which measure every parts contributes the most so that cost-effective decision could be thought to impact on the OPEX of an offshore wind farm project and help the industry to be more competitive. Analysing different combination of different levels of reliability in the components and analysing different behaviour in the length of the O&M resources he final availability could be investigated and exploited in its values so that consideration regarding cost allocation could be improved the cost-effectiveness of the investment in the industry. In order to do so a further study should take in account not only measures of reliability and time but also costs of components and costs of O&M mobilization. It would be of certain interest for suppliers to be able to investigate what is the lower bound they could reach in terms of investment in components reliability and O&M costs without compromising the overall objective for their availability.

7 Conclusion

This study presents a feasible concept for the assessment of the availability of a substation for offshore wind farm which utilizes MC simulation to improve the basis for decision-making based on a risk-based approach. The study uses the non-dedicated software environment R for the development of a program. A generic model for an offshore substation is represented and a case study is built on it. The accessibility to the substation is modelled based on the oceanographic collection of data and the O&M resources are modelled based on the knowledge of experts. An improvement in confidence within the results for the availability is obtained using a probabilistic framework for improved modelling of expert opinions and uncertainty of data. The model represents distribution of availability results instead of only one-point estimate assessment, so that a risk picture based on distribution of results increase the confidence in the figures and help the industry to make better decisions. The case study successfully proved the model functioning and able to provides results that can calculate realistic risk results in proportion to the model's stage of development in regards with the availability and with the main relevant economic figures.

8 Bibliography

[1] Eurostat, »Europe 2020 - Overview,« Eurostat, [Online]. Available: https://ec.europa.eu/eurostat/web/europe-2020-indicators. [Senest hentet eller vist den 04 December 2019].

[2] Eurostat, »Energy statistics - an overview,« Eurostat, June 2019. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview. [Senest hentet eller vist den 04 December 2019].

[3] Eurostat, »Renewable energy statistics,« Eurostat, January 2019. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics#Renewable_energy_produced_in_the_EU_increased_by_two_thirds_in_2007-2017. [Senest hentet eller vist den 04 December 2019].

[4] W. Energy, »Wind energy in Europe, trend and statistics,« Wind Energy, 2019.

[5] M. Asgarpour, »Risk and Reliability based O&M Planning of Offshore Wind Farms,« *Aalborg University Publishers,* p. 146, 2018.

[6] W. Europe, »Offshore Wind in Europe Key trends and statistics 2018,« 2019.

[7] J. S. N. a. J. D. Sørensen, »Methods for Risk-Based Planning of O&M ofWind Turbines,« pp. 6645-6664, 2014.

[8] J.-S. S. a. J.-O. Kim, »Optimal design for offshore wind farm considering inner grid layout and offshore substation location,« *IEEE transaction on power systems,* 2017.

[9] W. Power, »Wind Power,« [Online]. Available: https://www.thewindpower.net/scripts/fpdf181/turbine.php?id=1476. [Senest hentet eller vist den 05 December 2019].

[10] P. R. D. S. K. G. Michael Korshøj Dalstrup, Interviewee, *Expert Opinion.* [Interview]. 2019.

[11] B. Associates, »Guide to an offshore wind farm,« 2019.

[12] S. R. a. R. Raczkowski, »Substations for offshore wind farms: a review from the perspective of the needs of the Polish wind energy sector,« *technical science,* Årg. %1 af %2Vol. 66, No. 4, 2018.

[13] WIkipedia, »Wikipedia,« [Online]. Available: https://commons.wikimedia.org/wiki/File:Offshore-132kv-Substation.jpg. [Senest hentet eller vist den 12 2019].

[14] J. S. Nielsen, »Risk-Based Operation and Maintenance of Offshore Wind Turbines,« p. 161, 2013.

[15] D. Hillman, »Flickr,« 23 October 2018. [Online]. Available: https://www.flickr.com/photos/dazzy1960/44347909231. [Senest hentet eller vist den 08 December 2019].

[16] K. Torn, »Flickr,« 06 September 2017. [Online]. Available: https://www.flickr.com/photos/68359921@N08/36876114366/. [Senest hentet eller vist den 08 December 2019].

[17] K. E. Vinding, »Pixabay,« November 2019. [Online]. Available: https://pixabay.com/photos/ship-offshore-supply-ship-port-4576407/. [Senest hentet eller vist den 08 December 2019].

[18] M. I. Blanco, »The economics of wind energy,« *Elsevier,* pp. 1372-1382, 2009.

[19] E. U. e. i. a. administration, »Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2019,« 2019.

[20] GOV.UK, »Electricity Generation Costs,« 2012.

[21] Siemens, »Preliminary RAM (Reliability, Availability and Maintainability) Study,« 2018.

[22] T. R. R. A. Walling, »Economic Optimization of Offshore Windfarm Substaiton and Collection System,« *GE Energy,* p. 7.

[23] M. M. R. J. S.-A. P. Luca Emanuele Seresina, »Virtual simulation of evacuation of Viking Life-Saving Equipment premises in case of a fire scenario,« 2019.

[24] »On risk-based operation and maintenance of offshore wind turbine components,« *Elsevier,* nr. Reliability Engineering and System Safety, pp. 218-229, 2010.

[25] D. M. A. M. James Carroll, »Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines,« *Wind Energy,* August 2015.

[26] C. D. W. L. Fanny Douard, »A PROBABILISTIC APPROACH TO INTRODUCE RISK MEASUREMENT INDICATORS TO AN OFFSHORE WIND PROJECT EVALUATION – IMPROVEMENT TO AN EXISTING TOOL ECUME,« *Elsevier,* årg. Energy Procedia 24, p. 255 – 262, (2012).

[27] J. P. L. N. K. Ole-Erik V. Endrerud, »MARINE LOGISTICS DECISION SUPPORT FOR OPERATION AND MAINTENANCE OF OFFSHORE WIND PARKS WITH A MULTI METHOD SIMULATION MODEL,« i *Winter Simulation Conference*, 2014.

[28] I. B. S. Matthias Hofmanna, »NOWIcob – A tool for reducing the maintenance costs of offshore windfarms,« *Elsevier,* årg. 35 (2013) 177 – 186, p. 177 – 186, 2013.

[29] O.-E. V. E. M. H. R. M. a. I. B. S. Iain Dinwoodie, »Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Windfarm,« *Wind Engineering,* årg. 39, nr. 1, p. 1–14, 2015.

[30] C. G. 3.26, »Guidelines for the Design and Construction of AC Offshore Substations for Wind Power Plants,« CIGRE publication, 2011.

[31] Sensenschmied, »Wikipedia,« 2013. [Online]. Available: https://commons.wikimedia.org/wiki/File:Schaltanlage_Hochspannung_3.jpg. [Senest hentet eller vist den 2019].

[32] K. Das og N. Antonios Cutululis, »Offshore Wind Power Plant Technology Catalogue - Components of wind power plants, AC collection systems and HVDC systems,« *DTU Orbit,* p. 67, 2017.

[33] O.-E. V. E. M. H. R. M. I. B. S. Iain Dinwoodie, »Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms,« *WIND ENGINEERING,* årg. Volume 39, p. 14, 2015.

9 Appendix)

9.1 R code

```
#

#this code wants to assess the availability for a substation located offshore based on:

#weather condition at the time of failures of component

#mean time between failures of component

#window time to assess the availability parameter (contract time of 5 yrs, or full life time, or etc)

#mean time to repair of components

#vessel availability at the time of failures of component

#critic height for vessel ability to sail (some vessels can sail in some weather condition some cannot)

#spare part for replacement availability at the time of failure of component

#in the code some assumptions are used.

#main assumptions are:

#the components are considered independent to each other

#the calculations do not take in consideration parallel or linear construction model

#not all the possible components of a substation are represented in the code. it is assumed that only critical component are represented in the calculation number of component can be added

#the estimation for the various times are retrive from expert opinion

#along with the code several comments will try to explain the calculations and the decisions

#the code is the result of the thesis work period and it has been written by Luca Seresina in the period of October-November-December 2019 together with the thesis report

#keep clean

rm(list = ls())

#set your own directory

getwd()
```

```
#set your own directory or it will not work

setwd("C:/Users/bsaso/OneDrive/Desktop/upload")

#adding needed library

library(magicfor)

library(triangle)

library(plyr)

library(zoo)

library(base)

library(datasets)

library(graphics)

library(grDevices)

library(grid)

library(methods)

library(stats)

library(utils)

library(caTools)

library(MASS)


################################################################################


#set options


################################################################################

sim <- 100000 #number of iteration,  the more iterations  the more difficult would be the computation
```

```
################################################################################

#name lifetime

#setting the life time of the substation we want to estimate the availability for

lt <- 25 #years we want to estimate availability for

lth <- lt*8765 #we transform years in hours


################################################################################


#n of preventive repair set per year

#the number of services set up as preventive check every year on the substation

service <- 1

#n of service in the time selected to estimate availability

ltserv <- lt*service


################################################################################


#calling functions


source("LucaSeresina_preventivetimefunction_Risk4_montecarloavailability.R") #will provide us with the estimate of time use for preventive maintenance

source("LucaSeresina_downtimefunction_Risk4_montecarloavailability.R") #will provide us with the estimate of time use for corrective maintenance

source("LucaSeresina_availabilityfunction_Risk4_montecarloavailability.R") #will provide us with the estimate of the availability


################################################################################
```

```
preventive <- preventivetime(ltserv,24,48,24) #insert expert opinion for preventive maintenance intervantion. min, max, mode. the result is a vector with the preventive time

#example of use of variables for HV-GIS component

#timerepair
a <- 6570 #max time to repair
# hs
b <- 2
# mtbf
c <- 200
# minvessel
d <- 24
# maxvessel
e <- 48
# modevessel
f <- 24
# minspare
g <- 168
# maxspare
h <- 720
# modespare
i <- 336
# minrepair
l <- 720
# maxrepair
```

```
m <- 6570

#moderepair

n <- 4380


componenta <- componentsetting(a,b,c,d,e,f,g,h,i,l,m,n) #the results is a vector containing the downtimes for failures


#using the dollar sign is possible to extract more information from each components

#here an example


#mv-gis component


waitingtimecomponenta <- componenta$`vector of waitingtime`

plot(waitingtimecomponenta, type="l",col=rgb(0.33, 0.26, 0.82),

     xlab="Time steps",

     ylab="Waiting time in hours",

     main="Plot waiting time for MV component")

hist(waitingtimecomponenta,

     main="Histogram waiting time for MV component",

     xlab="Waiting time in hours",

     border="blue",

     xlim=c(0,20000),

     col=rgb(0.33, 0.26, 0.82),

     breaks=100000)

meanwaitingtimemvgis <- mean(waitingtimecomponenta)

stdwaitingtimemvgis<-sd(waitingtimecomponenta)
```

```
meanwaitingtimemvgis

stdwaitingtimemvgis

summary(waitingtimecomponenta)


failurescomponenta <- componenta$`vector of failures`

failurescomponenta

plot(failurescomponenta, type="l",col=rgb(0.33, 0.26, 0.82),

    xlab="Time steps",

    ylab="Failures",

    main="Plot failures for component MV")


plot(failurescomponenta,col=rgb(0.33, 0.26, 0.82),

    xlab="Time steps",

    ylab="Failures",

    main="Plot failures for component MV")


hist(failurescomponenta,

    main="Histogram failures for component MV",

    xlab="Failures",

    xlim=c(0,1),

    col=rgb(0.33, 0.26, 0.82),

    breaks=100000)


meanfailuremvgis <-mean(failurescomponenta)

stdfailuremvgis<-sd(waitingtimecomponenta)

meanfailuremvgis
```

```
stdfailuremvgis

summary(failurescomponenta)

# hist(failurescomponenta)

#

# plot(failurescomponenta, type="l",col=rgb(0.33, 0.26, 0.82),

#      xlab="time steps",

#      ylab="failures",

#      main="Plot for failures for a component")

#

# hist(failurescomponenta,

#      main="Histogram for failure of a component",

#      xlab="failures",

#

#      xlim=c(0,5),

#      col=rgb(0.33, 0.26, 0.82),

#      breaks=100000)

# max(waitingtimecomponenta)


vesseltimecomponenta <- componenta$`vector of vesseltime`

plot(vesseltimecomponenta, type="l",col=rgb(0.33, 0.26, 0.82),

    xlab="Time steps",

    ylab="Vessel time in hours",

    main="Plot vessel time for component MV")


hist(vesseltimecomponenta,

    main="Histogram vessel time for component MV",
```

```
    xlab="Vessel time in hours",
    xlim=c(20,50),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)
meanvesseltimemgvis <-mean(vesseltimecomponenta)
stdvesseltimemvgis<-sd(vesseltimecomponenta)
meanvesseltimemgvis
stdvesseltimemvgis
summary(vesseltimecomponenta)

sparepartcompnenta <- componenta$`vector of sparetime`
plot(sparepartcompnenta, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="Time steps",
    ylab="Spare part time in hours",
    main="Plot spare part time for MV component")

hist(sparepartcompnenta,
    main="Histogram spare part time for MV component",
    xlab="Spare part time in hours",
    border="blue",
    xlim=c(0,800),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)
meansparepartmvgis <- mean(sparepartcompnenta)
stdsparepartmvgis<-sd(vesseltimecomponenta)
meansparepartmvgis
```

```
stdsparepartmvgis

summary(sparepartcompnenta)

`

repurariontimecomponenta <- componenta$`vector of reparation time`

plot(repurariontimecomponenta, type="l",col=rgb(0.33, 0.26, 0.82),
     xlab="time steps",
     ylab="Repair time in hours",
     main="Plot repair time for MV component")

hist(repurariontimecomponenta,
     main="Histogram repair time for MV component",
     xlab="Repair time in hours",
     border="blue",
     xlim=c(0,7000),
     col=rgb(0.33, 0.26, 0.82),
     breaks=1000)

meanrepairtimemvgis <- mean(repurariontimecomponenta)


preparationtimecomponenta <- componenta$`vector of preparationtime`

plot(preparationtimecomponenta, type="l",col=rgb(0.33, 0.26, 0.82),
     xlab="time steps",
     ylab="preparation time in hours",
     main="Plot preparation time for MV component")

hist(preparationtimecomponenta,
     main="Histogram preparation time for MV component",
     xlab="Preaparation time in hours",
     border="blue",
```

```
    xlim=c(0,800),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)
meanpreparationtimemvgis <- mean(preparationtimecomponenta)
stdpreparationtimemvgis <- sd(preparationtimecomponenta)
summary(preparationtimecomponenta)

downtimecorrectivefailcomponenta <- componenta$`vector of downtimecorrectivefail`
plot(downtimecorrectivefailcomponenta, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="Time steps",
    ylab="Waiting time in hours",
    main="Plot downtime due to corrective fail for MV component")
hist(downtimecorrectivefailcomponenta,
    main="Histogram downtime due to corrective time for MV component",
    xlab="Downtime time in hours",
    border="blue",
    xlim=c(0,1000),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100000)
meandowntimecorrectivemvgis <- mean(downtimecorrectivefailcomponenta)
stddowntimecorrectivemvgis <- sd(downtimecorrectivefailcomponenta)
summary(downtimecorrectivefailcomponenta)



#####################################################################
```

```
#TRANSFORMER

#timerepair

o <- 6570 #max time to repair

# hs

p <- 1000 #no problem in access sea

# mtbf

q <- 200

# minvessel

r <- 744

# maxvessel

s <- 1488

# modevessel

t <- 1488

# minspare

u <- 744

# maxspare

v <- 1488

# modespare

z <- 1488

# minrepair

ab <- 720

# maxrepair

bc<- 6570

#moderepair

cd<- 4380
```

```
componentb <- componentsetting(o,p,q,r,s,t,u,v,z,ab,bc,cd) #the results is a vector containing the downtimes for failures


waitingtimecomponentb <- componentb$`vector of waitingtime`
plot(waitingtimecomponentb, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="Time steps",
    ylab="Waiting time in hours",
    main="Plot waiting time for Transformer component")
hist(waitingtimecomponentb,
    main="Histogram waiting time for Transformer component",
    xlab="Waiting time in hours",
    border="blue",
    xlim=c(0,20000),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100000)
meanwaitingtimetrafo <- mean(waitingtimecomponentb)
stdwaitingtimetrafo<-sd(waitingtimecomponentb)
meanwaitingtimetrafo
stdwaitingtimetrafo
summary(waitingtimecomponentb)



failurescomponentb <- componentb$`vector of failures`
plot(failurescomponentb, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="Time steps",
    ylab="Failures",
```

```
    main="Plot failures for component Transformer")
hist(failurescomponentb,
    main="Histogram failures for component Transformer",
    xlab="Failures",
    xlim=c(20,50),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100000)
meanfailuretrafo <-mean(failurescomponentb)
# hist(failurescomponenta)
#
# plot(failurescomponenta, type="l",col=rgb(0.33, 0.26, 0.82),
#     xlab="time steps",
#     ylab="failures",
#     main="Plot for failures for a component")
#
# hist(failurescomponenta,
#     main="Histogram for failure of a component",
#     xlab="failures",
#
#     xlim=c(0,5),
#     col=rgb(0.33, 0.26, 0.82),
#     breaks=100000)
# max(waitingtimecomponenta)


vesseltimecomponentb <- componentb$`vector of vesseltime`
```

```
plot(vesseltimecomponentb, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="Time steps",
    ylab="Vessel time in hours",
    main="Plot vessel time for component Transformer")

hist(vesseltimecomponentb,
    main="Histogram vessel time for component Transformer",
    xlab="Vessel time in hours",
    xlim=c(700,1600),
    col=rgb(0.33, 0.26, 0.82),
    breaks=1000)
meanvesseltimetrafo <-mean(vesseltimecomponentb)
stdvesseltimetrafo<-sd(vesseltimecomponentb)
meanvesseltimetrafo
stdvesseltimetrafo
summary(vesseltimecomponentb)

sparepartcompnentb <- componentb$`vector of sparetime`
plot(sparepartcompnentb, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="Time steps",
    ylab="Spare part time in hours",
    main="Plot spare part time for Transformer component")

hist(sparepartcompnentb,
    main="Histogram spare part time for Transformer component",
    xlab="Spare part time in hours",
```

```
    border="blue",
    xlim=c(500,1600),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)
meansparparttrafo <- mean(sparepartcompnentb)
stdsparparttrafo<-sd(sparepartcompnentb)
meansparparttrafo
stdsparparttrafo
summary(vesseltimecomponentb)

#print this pic below with  "Plot repair time for Transformer component#

repara riontimecomponentb <- componentb$`vector of reparation time`
plot(repara riontimecomponentb, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="time steps",
    ylab="Repair time in hours",
    main="Plot repair time for Transformer component")
hist(repara riontimecomponenta,
    main="Histogram repair time for Transformer component",
    xlab="Repair time in hours",
    border="blue",
    xlim=c(0,7000),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)
meanrepairtimetrafo <- mean(repara riontimecomponentb)
```

```
preparationtimecomponentb <- componentb$`vector of preparationtime`
plot(preparationtimecomponentb, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="time steps",
    ylab="preparation time in hours",
    main="Plot preparation time for Transformer component")
hist(preparationtimecomponentb,
    main="Histogram preparation time for Transformer component",
    xlab="Preaparation time in hours",
    border="blue",
    xlim=c(800,1500),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)
meanpreparationtimetrafo <- mean(preparationtimecomponentb)
stdpreparationtimetrafo <- sd(preparationtimecomponentb)
summary(preparationtimecomponentb)

downtimecorrectivefailcomponentb<- componentb$`vector of downtimecorrectivefail`
plot(downtimecorrectivefailcomponentb, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="Time steps",
    ylab="Waiting time in hours",
    main="Plot downtime due to corrective fail for Transformer component")
hist(downtimecorrectivefailcomponentb,
    main="Histogram downtime due to corrective time for Transformer component",
    xlab="Downtime time in hours",
    border="blue",
    xlim=c(0,1000),
```

```
    col=rgb(0.33, 0.26, 0.82),
    breaks=100000)
meandowntimecorrectivetrafo <- mean(downtimecorrectivefailcomponentb)
stddowntimecorrectivetrafo <- sd(downtimecorrectivefailcomponentb)
summary(downtimecorrectivefailcomponentb)




############################################################
#HV
#timerepair
de <- 6570 #max time to repair
# hs
ef <- 2 #no problem in access sea
# mtbf
fg <- 200
# minvessel
gh <- 24
# maxvessel
hi <- 48
# modevessel
il <- 24
# minspare
lm <- 168
# maxspare
```

```
mn <- 1488

# modespare

no <- 336

# minrepair

op <- 720

# maxrepair

pq<- 6570

#moderepair

qr<- 4380


componentc <- componentsetting(de,ef,fg,gh,hi,il,lm,mn,no,op,pq,qr) #the results is a vector containing the downtimes for failures


waitingtimecomponentc<- componentc$`vector of waitingtime`

plot(waitingtimecomponentc, type="l",col=rgb(0.33, 0.26, 0.82),

    xlab="Time steps",

    ylab="Waiting time in hours",

    main="Plot waiting time for HV component")

hist(waitingtimecomponentc,

    main="Histogram waiting time for HV component",

    xlab="Waiting time in hours",

    border="blue",

    xlim=c(0,20000),

    col=rgb(0.33, 0.26, 0.82),

    breaks=100000)
```

```
meanwaitingtimehv <- mean(waitingtimecomponentc)

stdwaitingtimehv<-sd(waitingtimecomponentc)

meanwaitingtimehv

stdwaitingtimehv

summary(waitingtimecomponentc)


failurescomponentc <- componentc$`vector of failures`

plot(failurescomponentc, type="l",col=rgb(0.33, 0.26, 0.82),

     xlab="Time steps",

     ylab="Failures",

     main="Plot failures for component HV")


hist(failurescomponentc,

     main="Histogram failures for component HV",

     xlab="Failures",

     xlim=c(20,50),

     col=rgb(0.33, 0.26, 0.82),

     breaks=100000)

meanfailurehv <-mean(failurescomponentc)

# hist(failurescomponenta)

#

# plot(failurescomponenta, type="l",col=rgb(0.33, 0.26, 0.82),

#      xlab="time steps",

#      ylab="failures",

#      main="Plot for failures for a component")

#
```

```
# hist(failurescomponenta,
#      main="Histogram for failure of a component",
#      xlab="failures",
#
#      xlim=c(0,5),
#      col=rgb(0.33, 0.26, 0.82),
#      breaks=100000)
# max(waitingtimecomponenta)



vesseltimecomponentc <- componentc$`vector of vesseltime`
plot(vesseltimecomponentc, type="l",col=rgb(0.33, 0.26, 0.82),
     xlab="Time steps",
     ylab="Vessel time in hours",
     main="Plot vessel time for component HV")

hist(vesseltimecomponenta,
     main="Histogram vessel time for component HV",
     xlab="Vessel time in hours",
     xlim=c(20,50),
     col=rgb(0.33, 0.26, 0.82),
     breaks=100)
meanvesseltimehv <-mean(vesseltimecomponentc)

sparepartcompnentc <- componentc$`vector of sparetime`
plot(sparepartcompnentc, type="l",col=rgb(0.33, 0.26, 0.82),
```

```
    xlab="Time steps",
    ylab="Spare part time in hours",
    main="Plot spare part time for HV component")

hist(sparepartcompnenta,
    main="Histogram spare part time for HV component",
    xlab="Spare part time in hours",
    border="blue",
    xlim=c(0,800),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)
meanspareparthv<- mean(sparepartcompnentc)
stdspareparthv<-sd(sparepartcompnentc)
meanspareparthv
stdspareparthv
summary(sparepartcompnentc)

`

repárariontimecomponentc <- componentc$`vector of reparation time`
plot(repárariontimecomponentc, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="time steps",
    ylab="Repair time in hours",
    main="Plot repair time for HV component")
hist(repárariontimecomponentc,
    main="Histogram repair time for HV component",
    xlab="Repair time in hours",
```

```
    border="blue",
    xlim=c(0,7000),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)
meanrepairtimehv<- mean(reparariontimecomponentc)

preparationtimecomponentc<- componentc$`vector of preparationtime`
plot(preparationtimecomponentc, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="Time steps",
    ylab="Preparation time in hours",
    main="Plot preparation time for HV component")
hist(preparationtimecomponentc,
    main="Histogram preparation time for HV component",
    xlab="Preaparation time in hours",
    border="blue",
    xlim=c(100,1600),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)
meanpreparationtimehv <- mean(preparationtimecomponentc)
stdpreparationtimehv <- sd(preparationtimecomponentc)
summary(preparationtimecomponentc)

downtimecorrectivefailcomponentc <- componentc$`vector of downtimecorrectivefail`
plot(downtimecorrectivefailcomponentc, type="l",col=rgb(0.33, 0.26, 0.82),
    xlab="Time steps",
    ylab="Waiting time in hours",
```

```
    main="Plot downtime due to corrective fail for HV component")


hist(downtimecorrectivefailcomponenta,
    main="Histogram downtime due to corrective time for HV component",
    xlab="Downtime time in hours",
    border="blue",
    xlim=c(0,10000),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)
meandowntimecorrectivehv <- mean(downtimecorrectivefailcomponentc)
sddowntimecorrectivehv <- sd(downtimecorrectivefailcomponentc)
summary(downtimecorrectivefailcomponentc)
###############################################################


availability <- availability(preventive,componenta,componentb,componentc)#the result is a vector containing the availability. it is possible to plug as many as components ones want to investigate


hist(availability,
main="Histogram for availability",
xlab="Availability",
border="blue",
col=rgb(0.33, 0.26, 0.82))


hist(availability,
    main="Histogram for availability",
```

```
    xlab="Availability",
    border="blue",
    xlim=c(0.98,1.00),
    col=rgb(0.33, 0.26, 0.82),
    breaks=100)

hist(availability,
    main="Histogram for availability",
    xlab="Availability",
    border="blue",
    xlim=c(0.98,1.00),
    col=rgb(0.33, 0.26, 0.82),
    breaks=1000)

result <- summary(availability)
result
mean(availability)
sd(availability)

AEP <- 50*lth*0.25*availability
summary(AEP)
sd(AEP)
hist(AEP,
    main="Histogram for AEP",
    xlab="AEP",
    border="blue",
```

```
    col=rgb(0.33, 0.26, 0.82))


hist(AEP,
    main="Histogram for AEP",
    xlab="AEP",
    border="blue",
    xlim=c(2400000,2800000),
    col=rgb(0.33, 0.26, 0.82))



hist(AEP,
    main="Histogram for AEP",
    xlab="AEP",
    border="blue",
    xlim=c(2400000,2800000),
    col=rgb(0.33, 0.26, 0.82),
    breaks=1000)


CAP <- 24000000
OP <- 1000000
CRF <- 0.10
LCoE <- ((CAP*CRF+OP))/(AEP)
summary(LCoE)
sd(LCoE)


hist(LCoE,
```

```
    main="Histogram for LCoE",
    xlab="LCoE",
    border="blue",
    col=rgb(0.33, 0.26, 0.82))

hist(LCoE,
    main="Histogram for LCoE",
    xlab="LCoE",
    border="blue",
    xlim=c(1.2,1.5),
    col=rgb(0.33, 0.26, 0.82))

hist(LCoE,
    main="Histogram for LCoE",
    xlab="LCoE",
    border="blue",
    xlim=c(1.245,1.255),
    col=rgb(0.33, 0.26, 0.82),
    breaks=1000)
```

9.1.1 R code, Downtime function

#function for estimate the waiting time in case of failure of component to go out to the offshore substation

#this function allow to calculate the time that the vessel crew will need to wait on average before neing allowed to sail and performed the repair. the calculation are based on the required time to performed the repairment and the ability of the choosen vessel to sail

#the function will require to insert the repair time for the component in analysis and the critical height of waves for the vessel with which the crew will carry the component

```
# d <- function(...){
#   x <- list(...) # THIS WILL BE A LIST STORING EVERYTHING:
#   sum(...)       # Example of inbuilt function
# }


componentsetting <- function(timerepair, hs, mtbf, minvessel, maxvessel, modevessel, minspare, maxspare, modespare, minrepair, maxrepair, moderepair){


  repairtime <-  timerepair*2
  timestamp <- read.table(file="timestampwave.txt", header=TRUE)
  height <- timestamp$Hs
  svr <- ifelse(height<hs,1,0)
  wwva <- runmin(svr,repairtime)
  twaita <- wwva
  k <- 0
  for(i in seq_along(wwva)){
    if((wwva[i]==1)){
      twaita[i] <- 0
      k <- 0
    }else {
      k <- k+0.5
      twaita[i] <- twaita[i] + k
    }
  }
```

```
mawt <- mean(twaita)
sawt <- sd(twaita)
m <- mawt
s <- sawt
lA <- log(m^2 / sqrt(s^2 + m^2))
sA <- sqrt(log(1 + (s^2 / m^2)))
waitingtime <-rlnorm(sim, lA, sA)
waitingtime[is.nan(waitingtime)] = 0


hmtbf <- mtbf*8765 #we transform it in hours

lambda <- (1/hmtbf)*lth #parameter for the poisson distribution

failures <- replicate(sim,rpois(1,lambda))


vesstime <-replicate(sim,rtriangle(1, minvessel,maxvessel,modevessel))


sparetime <-replicate(sim,rtriangle(1, minspare,maxspare,modespare))


reptime <-replicate(sim,rtriangle(1, minrepair, maxrepair, moderepair))


preptime <- pmax(sparetime,vesstime)


downtimecorrective <- preptime+waitingtime+reptime
```

```
  downtimecorrectivefail=( sapply(failures, function(failures) sum(sample(downtimecorrective, size = failures, replace = TRUE))))



  downtimeresults <- list("vector of waitingtime"=waitingtime,"vector of failures"= failures,"vector of vesseltime"=vesstime, "vector of sparetime"=sparetime, "vector of reparation time"=reptime, "vector of preparationtime"=preptime, "vector of downtimecorrectivefail"=downtimecorrectivefail)


  return(downtimeresults)
}
}
```

9.1.2 R code, Availability function

```
#function for estimate the availability in the lifetime


availability <-function(prevtime, ...){
  x <- list(...) # THIS WILL BE A LIST STORING EVERYTHING:
  x <- unlist(x)
  mymatrix=matrix(x,ncol=seq_along(x),byrow=T)
  sum <-  rowSums(mymatrix)
  totcorrdown <- sum
  totdowntime <- totcorrdown+prevtime
  avafail <- rep(lth,sim)
  failavailability <- (avafail-totdowntime)/avafail
  mava <- mean(failavailability) #mean availability in 5 years
  return(failavailability)
}
```

9.2 Collection of plots

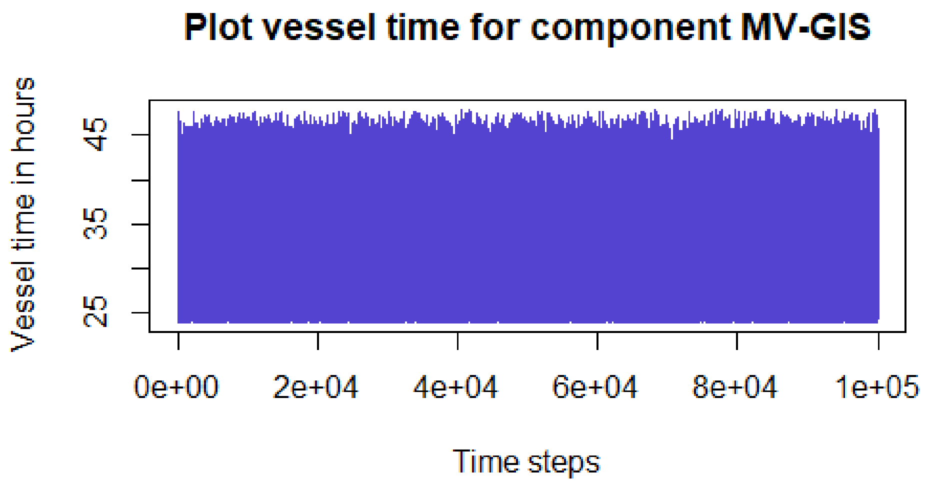


Figure 9-1 Plot for vessel time for MV component - made by the author

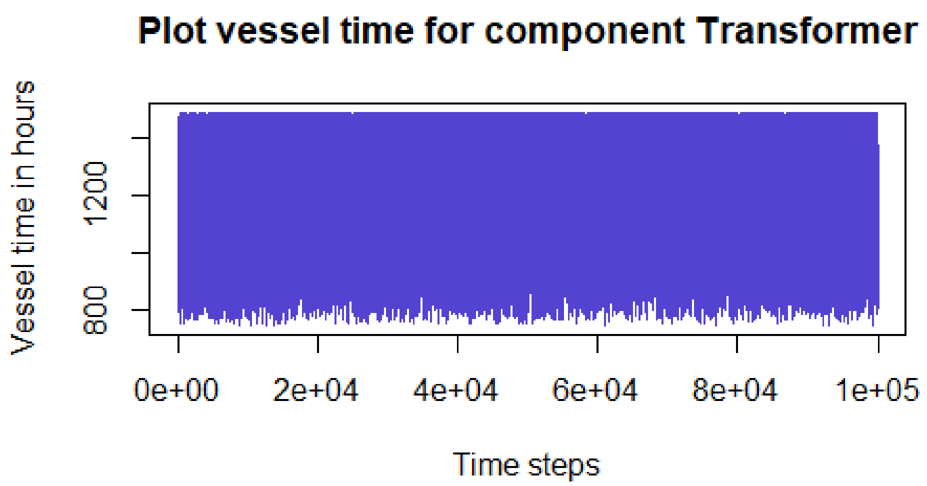


Figure 9-2 Plot for vessel time for Transformer component - made by the author

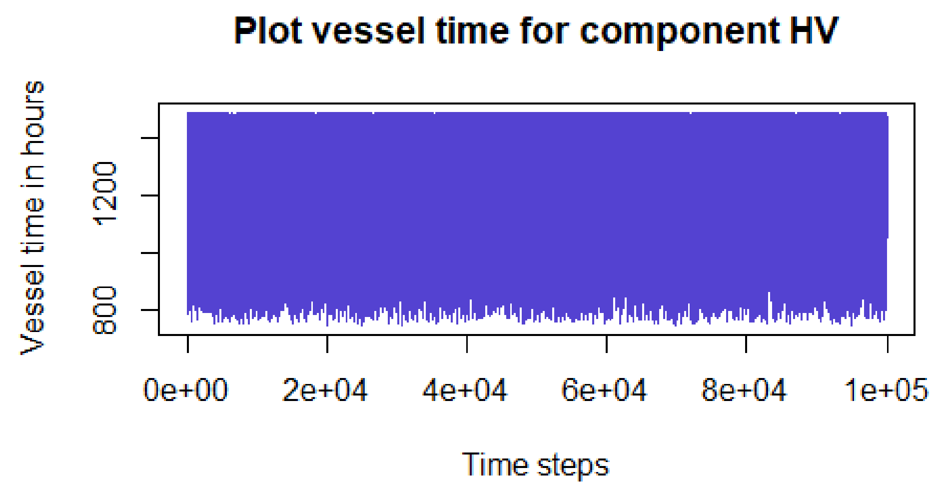


Figure 9-3 Plot for vessel time for HV component - made by the author

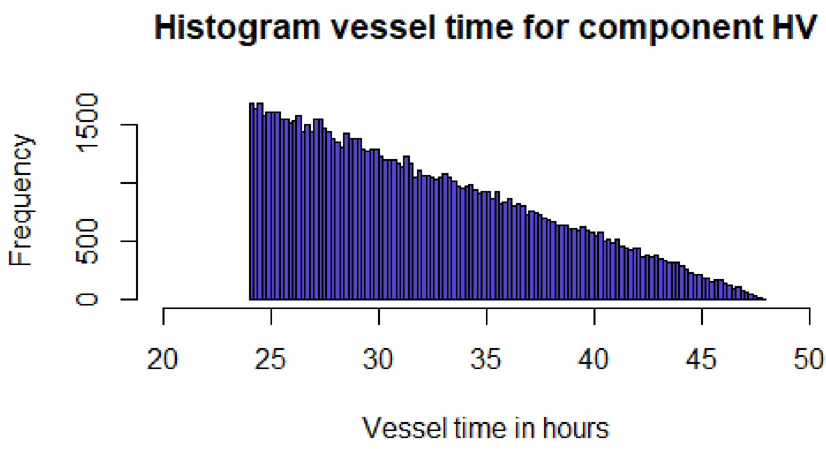


Figure 9-4 Histogram for vessel time for HV component - made by the author

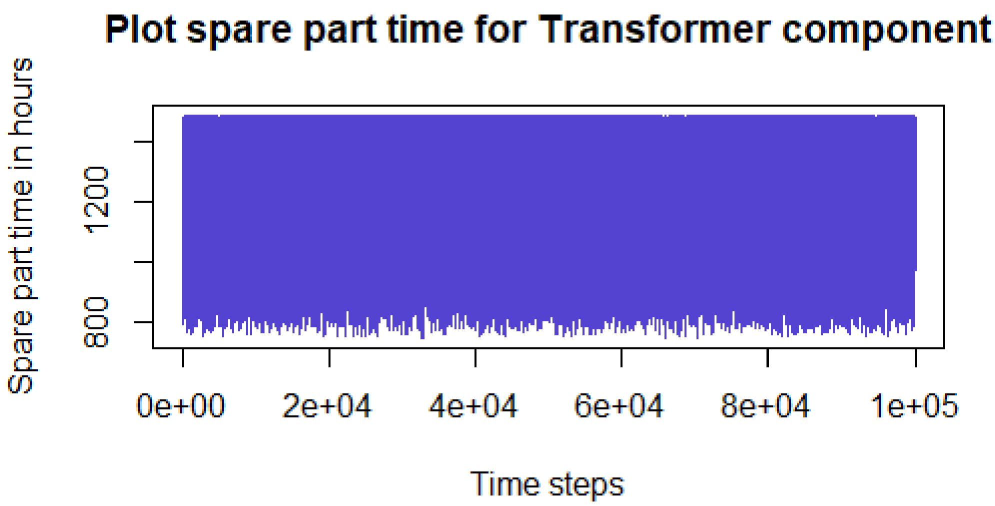


Figure 9-5 Plot for vessel time for Transformer component - made by the author

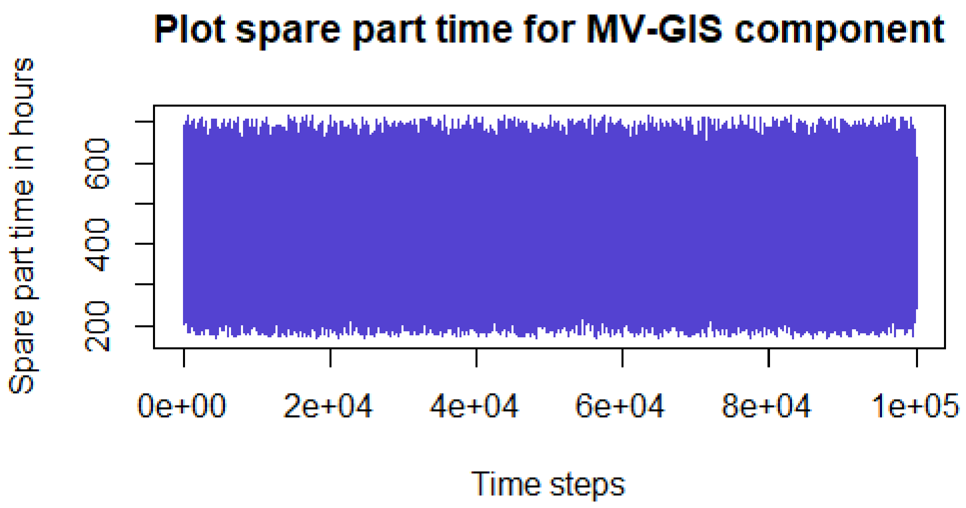


Figure 9-6 Plot for spare part time for MV component - made by the author

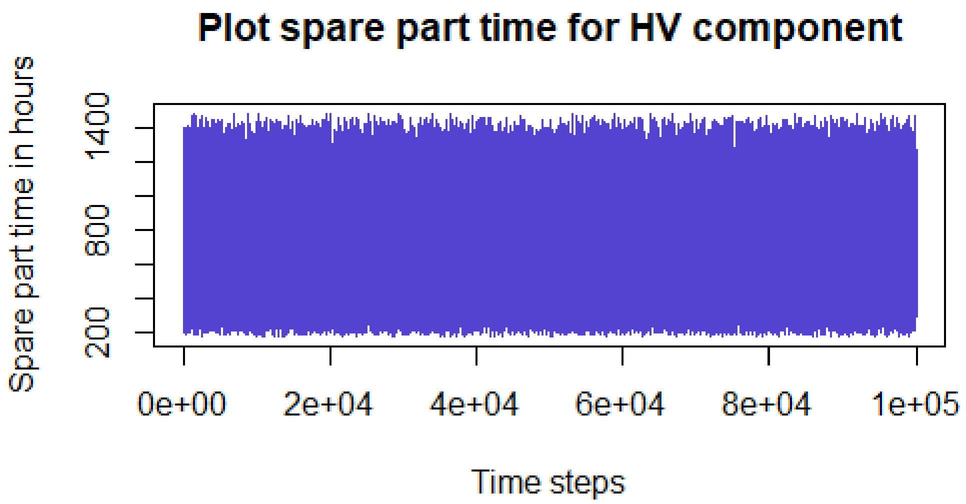


Figure 9-7 Plot for spare part time for HV component - made by the author

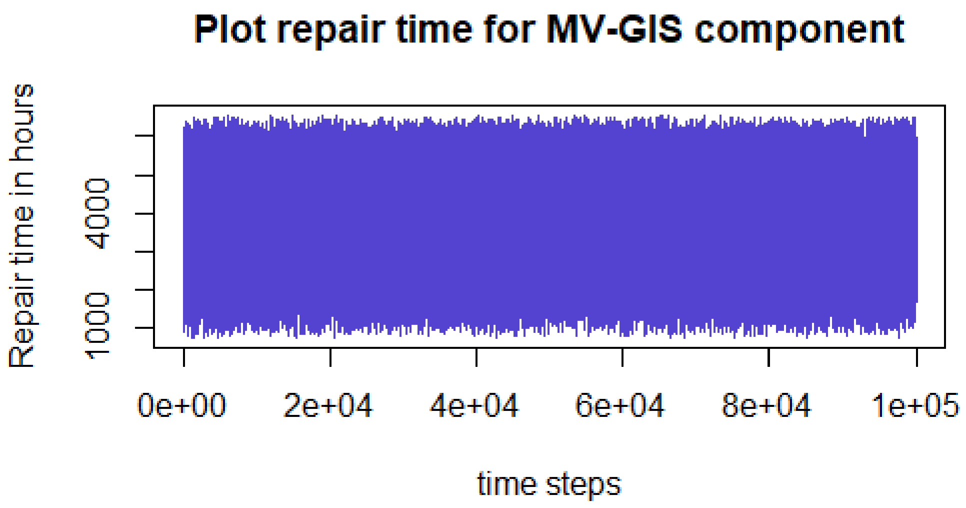


Figure 9-8 Plot for repair time for MV component - made by the author

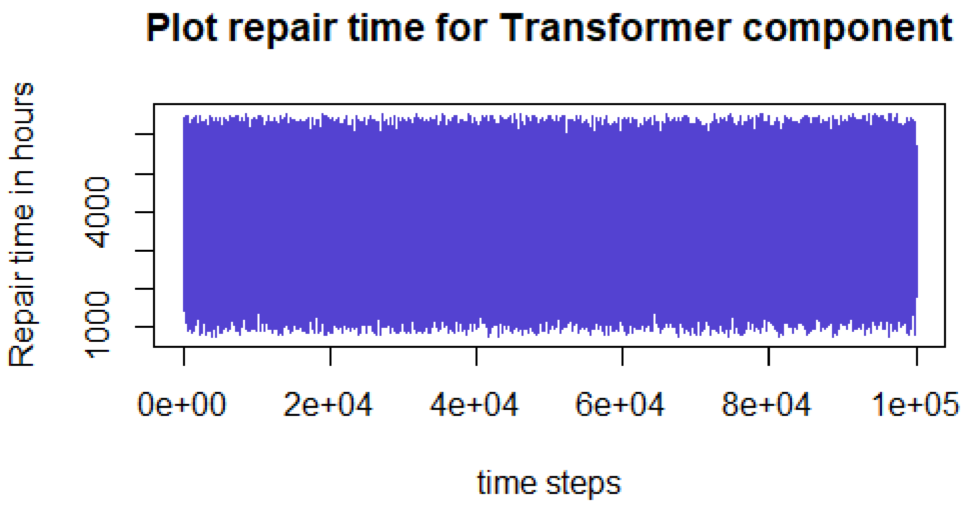
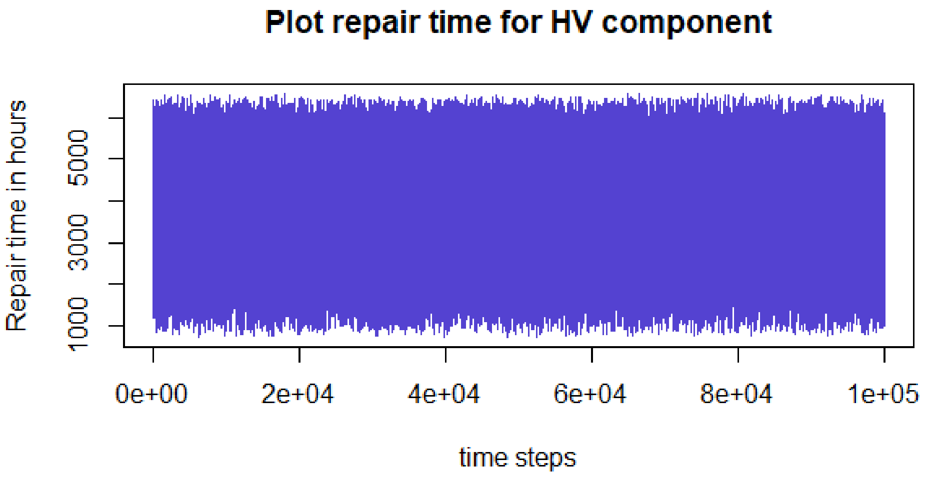


Figure 9-9 Plot for repair time for Transformer component - made by the author



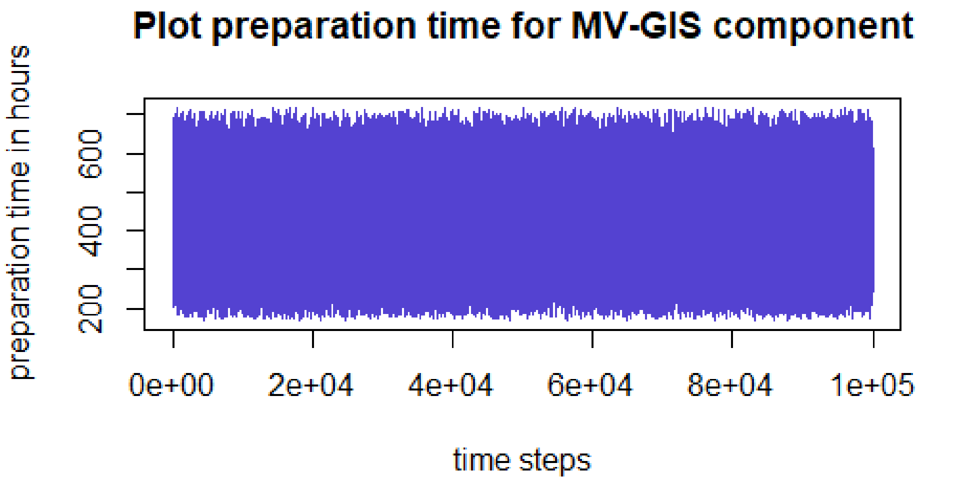


Figure 9-10 Plot for preparation time for MV component - made by the author

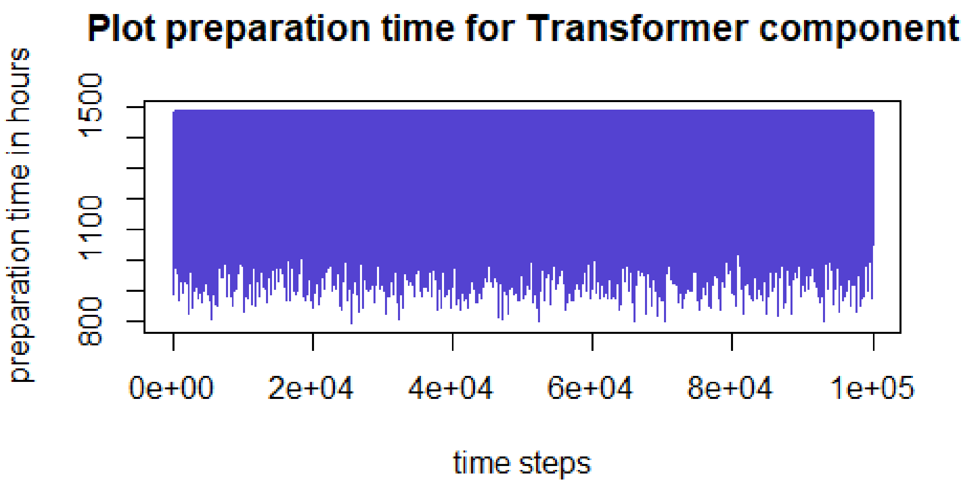


Figure 9-11 Plot for preparation time for Transformer component - made by the author

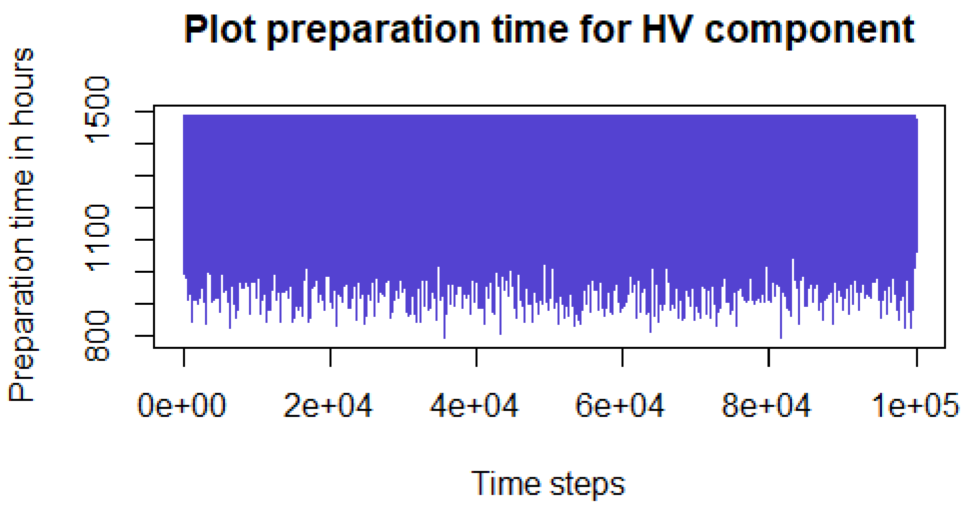


Figure 9-12 Plot for preparation time for HV component - made by the author

9.3 Thesis contract

Application for Thesis Contract

AALBORG UNIVERSITY

13/09/2019

Type of thesis
Master's Thesis (kandidatspeciale / afgangsprojekt)

Student(s)

Name	CPR no.	Email
Luca Emanuele Seresina	100693-4575	lseres18@student.aau.dk

Signature

Department and Study Board
Byggeri og AnlÃ¦g
Studienævn for Byggeri og anlæg

Programme
Risk and Safety Management (Master of Science and Technology)

Project Supervisor(s)
Jannie Sønderkær Nielsen <jjn@civil.aau.dk>

Signature

Project Title
Assessment of the uncertainty on the availability of an offshore substation

Starting	Deadline	ECTS Credits
01/09	10/01/2020	30

Project Description
The project aims to develop a model for assessing the lifetime availability of an offshore substation in a Danish wind farm. The work combines failure components modelling, incidents modelling, sea condition modelling, platform accessibility assessment and repairing time, and uncertainties related to these are propagated to estimate the resulting uncertainty on the availability. Based on the model, studies are made to find measures to increase the availability and to decrease the probability of low availability.
The result of the study strives to provide a risk-based point of view on availability over the lifetime of a substation providing possible useful insight over feasibility of projects and potentials for reduction of cost in the operation and maintenance part of the project.

Plan for Thesis Supervision and Lab Work

The thesis supervisor meets with the student approximately every one or two weeks to discuss progress, time schedule, resources, lab work, ideas, issues, etc. The meetings are held via Skype. The meetings are planned every time for the time ahead, based on the development of the project, the tasks and other relevant matters.

Approved by Head of Studies

19/9-19

Date

Signature