

# Optimization of Offshore Wind Farm Installation Procedure With a Targeted Finish Date

Vigney Kumar

Delft University of Technology





# Optimization of Offshore Wind Farm Installation Procedure With a Targeted Finish Date

by

**Vigney Kumar**

in partial fulfillment of the requirements for the degree of

**Master of Science**

in Sustainable Energy Technology

at the Delft University of Technology,

to be defended publicly on Friday November 24, 2017.

Thesis committee: Prof. dr. S. J. Watson, TU Delft, Chair of the thesis committee  
Dr. ir. M. B. Zaayer, TU Delft, Supervisor  
ir. Ashish Dewan, ECN, Supervisor  
Dr. ir. O. M. Napoles, TU Delft, External

An electronic version of this thesis is available at <http://repository.tudelft.nl/>.



# Abstract

Offshore Wind Farm (OWF) installation procedure is a complicated phase requiring excellent management of resources for timely completion of tasks. As installation cost is an important aspect of the building phase of the OWF, the graduation project looks into the optimization of offshore wind farm installation procedure with a targeted completion date as a priority. In this thesis, an optimization approach is built around an ECN in-house software, specially developed for simulating various OWF installation strategies. Ultimately, the result of the dissertation is to have a method that provides added flexibility to simulate different OWF installation planning, yet obtaining optimal installation cost. A concise literature review describes the significance of the current research and the potential that metaheuristic approaches bring to solve installation scheduling problems. Within the metaheuristic approach, the genetic algorithm is chosen as the optimization procedure to use in current work. The objective of the optimization procedure throughout the research is minimizing the total installation cost. The target end date in this study is implemented in the form of a constraint to steer the optimizer solution within the specified limit. A new methodology is proposed to generate an automated planning for the different installation procedures to facilitate the link between the optimizer and ECN tool. The project also considers uncertainty introduced due to weather and describes the considerations made to account for the same. The different case-studies illustrate the potential of introducing a metaheuristic optimizer in solving OWF installation scheduling problems. While, the new procedure leads to obtaining reduced installation costs for a given planning, analyzing with real OWF projects will further substantiate the chosen approach.



# Acknowledgement

I wish to thank some important people who helped me bring this thesis work to a good end. Firstly, I would like to express thanks to Prof. *Michiel Zaaijer* for helping me find a topic that suited my curiosity. I consider myself fortunate to have you as my supervisor, without your attention, enthusiasm and guidance, my work would not have been productive.

To *Georgios Katsouris* and *Ashish Dewan*, I am grateful for allowing me to work on a challenging and relevant topic as an intern at ECN. A special appreciation for Ashish for his selfless support and assistance during the complete project period. I am very thankful to *Clym Stock-Williams* for his support and assistance with helping me understand and implementing the optimization procedure. Furthermore, I am grateful to *Piet Warnaar* from ECN for his valuable inputs and suggestions during the modeling process of the project. Moreover, a big thanks to all my friends and colleagues at ECN for making my stay even more special.

I am thankful towards the complete examination committee for the time spent on evaluating this document. Last but not least, I would like to thank my family and friends for supporting me in this last stage of my study.

*Vigney Kumar*  
*Delft, November 2017*





# Contents

<b>List of Figures</b>	<b>ix</b>
<b>List of Tables</b>	<b>xi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Research Motivation . . . . .	2
1.2 Objective . . . . .	4
1.3 Report Outline . . . . .	4
<b>2 Offshore Installation Scheduling Problem</b>	<b>5</b>
2.1 Offshore Wind Installation Challenges . . . . .	5
2.1.1 Foundations . . . . .	5
2.1.2 Wind Turbines . . . . .	6
2.1.3 Cables . . . . .	6
2.1.4 Conclusion . . . . .	6
2.2 ECN Install . . . . .	7
2.3 Optimization of Installation Planning . . . . .	7
2.3.1 Need for Optimization . . . . .	8
2.3.2 Existing Studies on OWF Installation and Planning . . . . .	8
2.3.3 Optimization Choices . . . . .	9
2.4 Optimizer Addition to ECN Install . . . . .	10
<b>3 Automated Planning</b>	<b>13</b>
3.1 Automated Planning Requirement . . . . .	13
3.2 Automated Planning Blocks . . . . .	13
3.3 AP Block Inputs . . . . .	14
3.3.1 Vessel Type Library . . . . .	15
3.3.2 Harbor Library . . . . .	16
3.3.3 Equipment Library . . . . .	17
3.3.4 Default Database Template . . . . .	17
3.4 AP block implementation . . . . .	17
3.5 Interdependency between Sequences . . . . .	21
3.6 Automated Planning Integration with Optimizer . . . . .	23
3.7 AP Block Verification . . . . .	24
<b>4 Optimizer Modelling</b>	<b>27</b>
4.1 Optimization Model Setup . . . . .	27
4.1.1 Installation Problem Design Variables . . . . .	28
4.1.2 Objective Function . . . . .	28
4.1.3 Constraints . . . . .	29
4.2 Uncertainty Consideration . . . . .	30
4.2.1 Weather Simulation Requirements . . . . .	30
4.2.2 ECN Install Output Analysis . . . . .	31
4.3 Genetic Algorithm . . . . .	32
4.3.1 Genetic Algorithm Terminology . . . . .	32
4.3.2 Genetic Algorithm Operation . . . . .	34
4.3.3 MATLAB GA Integer Solver . . . . .	36
4.4 GA Parameter Tuning . . . . .	37
4.4.1 Abstract Problem . . . . .	37
4.4.2 Control Parameter Testing . . . . .	39
4.4.3 Conclusion . . . . .	40

<b>5</b>	<b>Case Study</b>	<b>43</b>
5.1	OWF location	43
5.2	Market Overview	44
5.3	Case Study 1	44
5.3.1	Description	44
5.3.2	CASE 1A	45
5.3.3	CASE 1B	46
5.3.4	CASE 1C	47
5.3.5	Discussion	49
5.4	Case Study 2	49
5.4.1	Description	49
5.4.2	Discussion	53
<b>6</b>	<b>Conclusions and Future Work</b>	<b>55</b>
6.1	Conclusions	55
6.2	Future work	56
<b>A</b>	<b>Appendix A</b>	<b>59</b>
A.1	Wind Turbine components and Resources	59
A.1.1	Substructure	59
A.1.2	Wind Turbine Components	60
A.1.3	Electrical Infrastructure	61
A.1.4	Substation	61
A.1.5	Vessels	62
A.1.6	Equipment	62
A.1.7	Port	64
A.1.8	Working Technicians	64
<b>B</b>	<b>Appendix B</b>	<b>65</b>
B.0.1	Inputs and Planning	65
B.0.2	Pre-Processor	66
B.0.3	Simulator	66
B.0.4	Post-Processor	67
B.0.5	Install Model	67
<b>C</b>	<b>Appendix C</b>	<b>69</b>
C.1	Data handling in ECN INSTALL	69
C.2	Simulation settings for ECN Install	70
	<b>Bibliography</b>	<b>73</b>

# List of Figures

1.1	Offshore wind Energy Statistics [1]	1
1.2	ECN Install User Interface	2
1.3	Capital cost breakup of an offshore wind turbine [2]	3
2.1	ECN Install tool architecture	8
2.2	New project architecture	11
3.1	Automated planning flow diagram	14
3.2	Sequence limitations	15
3.3	Vessel Library	16
3.4	Foundation transport methods	18
3.5	Pre-assembly combinations [3]	20
3.6	Pre-assembly Concepts applied in the industry	22
3.7	Interdependency between different sequences	23
3.8	Interdependency with multiple vessels	23
3.9	AP block in Project architecture	24
3.10	Installation planning simulated in ECN Install old (v2.1)	25
3.11	Automated planning testing blocks	25
4.1	Different end date exceeding penalty functions	29
4.2	ECN Install output uncertainty handling	31
4.3	GA terminology	32
4.4	single point crossover operation	33
4.5	Mutation operation	34
4.6	Different offspring for new population [4]	34
4.7	GA work flow diagram	35
4.8	Design variable (DV) representation in GA population	36
4.9	Knapsack problem representation in GA	38
4.10	Influence of crossover fraction	40
4.11	Influence of elite count	41
5.1	Borssele wind farm zone [5]	43
5.2	start date vs total installation cost	46
5.3	Vessel types vs total installation cost	46
5.4	start date vs total installation cost	47
5.5	Target end date comparison	48
5.6	Division 1 vs Division 2 Jack-up vessels	48
5.7	GA convergence plot	49
5.8	Sequence of installation activities	50
5.9	Sub-case start date ranges vs Installation costs	54
A.1	Types of substructures [3]	59
A.2	Wind turbine components:(a) Nacelle & Hub, (b) Blades, (c) Tower, (d) Tower section	61
A.3	Electrical infrastructure	62
A.4	Offshore substation	62
A.5	(a) Rock dumping vessel,(b) Heavy lift vessel,(c) Multi-purpose vessel,(d) Cable lay vessel	63
A.6	(a) ROV ,(b) Pile hammer,(c) Crane	63
A.7	Harbour use for OWWF installation	64
B.1	Foundations installation planning	66

---

B.2	Pre-Processor planning gantt chart . . . . .	66
B.3	Post-Process gantt chart . . . . .	67
B.4	Average delays breakdown per step and delay type. . . . .	67
C.1	Database template structure . . . . .	69
C.2	Activity levels defined in ECN Install . . . . .	70
C.3	Planning data flow diagram to ECN Install . . . . .	70
C.4	Settings file in ECN Install . . . . .	71

# List of Tables

3.1	Project inputs	15
3.2	Vessel Library	16
3.3	Verification sequence inputs	24
3.4	ECN Install old (v2.1) vs ECN Install (2.2) results	26
3.5	Final verification	26
4.1	Design variable bounds	28
4.2	Optimization time vs Number of weather simulations	31
4.3	Tuning parameters for GA	37
4.4	Problem similarity	39
4.5	Parameter tuning results	39
5.1	New projects in Europe region [6]	44
5.2	Sub-cases for foundation installation	45
5.3	Optimization parameter specifications	45
5.4	Optimal solution for sub-case 1A	45
5.5	Optimal solution for sub-case 1B	46
5.6	Optimal solution for sub-case 1C	49
5.7	Optimization parameters	50
5.8	Number of vessels and Pre-assembly combination design variable study	51
5.9	Number of foundation vessel evaluation	51
5.10	Wind turbine preassembly combination evaluation	52
B.1	ECN Install Input parameters	65



# Nomenclature

## Latin Symbols

$C$	Total installation cost (€)
$c$	Cost (€)
$d$	Installation duration (days)
$f$	Finish date
$j$	Number of object types
$k$	Object type
$nsim$	Total number of weather realizations
$nvars$	Number of variables
$O_{obj}$	Example objective function
$p()$	Penalty function
$v_j$	Option cost per object (€)
$W$	Knapsack weight limit
$w_j$	Option weight per object (kg)
$x$	Design variable
$y$	Mean installation cost (€)
$y_{knapsack}$	Knapsack objective value
$Y_{xopt}$	Objective value (€)

## Abbreviations

$ABC$	Artificial Bee Colony
$AP$	Automated Planning
$BWFZ$	Borssele Wind Farm Zone
$CAPEX$	Capital Expenditure
$CE$	Constraint Evaluation
$DES$	Discrete Event Simulation
$ECN$	Energy Research Centre of the Netherlands
$EEZ$	Exclusive Economic Zone

<i>ES</i>	Evolutionary Strategy
<i>GA</i>	Genetic Algorithm
<i>GUI</i>	Graphical User Interface
<i>IP</i>	Initial Planning
<i>MILP</i>	Mixed Integer Linear Programming
<i>O</i>	Optimizer
<i>OHVS</i>	Offshore High Voltage Station
<i>OWF</i>	Offshore Wind Farm
<i>PSO</i>	Particle Swarm Optimization
<i>ROV</i>	Remotely Operated Underwater Vehicle
<i>SA</i>	Simulated Annealing
<i>SD</i>	Start Date
<i>TED</i>	Target End Date
<i>TSO</i>	Transmission System Operator
<i>UC</i>	Uncertainty Consideration
<i>WT</i>	Wind Turbine



# 1

## Introduction

In this rapidly expanding 'circular energy society' that we live in, the world's population is looking intently for innovations to promote sustainability. Energy providers are increasingly trying to look at ways to meet the demand using green energy and replace conventional sources [7]. Wind power shares a large part of the renewable energy market around the globe. In 2016 the wind energy sector saw an addition of more than 54 GW, taking the global installed capacity to almost 487 GW [8]. Onshore wind power prominently stands out as one of the most cost-effective and mature technologies in the renewable space. While offshore wind is a promising technology, it is still one of the more expensive energy technologies available commercially. Offshore sites show a higher potential of electricity generation with minimal noise and visual impacts to concerned communities over the onshore wind sites. Hence, last decade has seen a significant interest in offshore wind technology, where it is drawing substantial research initiatives to develop into a more competitive energy source [9]. Global offshore wind is expected to have close to 34 GW of installed capacity by 2020 [10]. A total of 2.2 GW of offshore wind power was added in 2016 globally among seven markets. The overall installed capacity of offshore wind at present stands at 14.3 GW spread across fourteen markets around the globe.

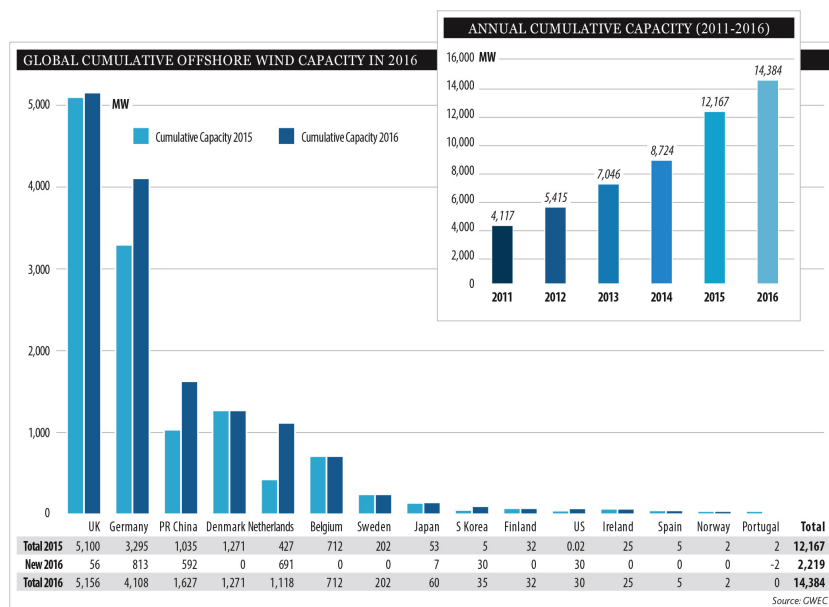


Figure 1.1: Offshore wind Energy Statistics [1]

By 2016, close to 88% (12 GW) of the offshore wind farms were located in European coastal waters. The other 12% is based in China, Japan, South Korea and the United States as seen in figure 1.1.

On the European level, UK accounts for the largest offshore wind energy market with around 35% of installed capacity. Germany closely follows it with 29% of the market share [1]. It is expected that offshore wind will contribute to large portions of the 20% renewable energy target set by the European Union for the year 2020 [11]. As the proliferation of offshore wind industry continues, one can notice the steady increase in the size of individual turbine rated powers and wind farms. With experience, the industry is becoming more favorable for installing larger farms in much more remote and appealing locations. Thus, it is essential to obtain a good understanding of the different aspects of the technology. Eventually, it will facilitate the industry to mature faster and instil confidence among the investors. Among the various drivers in the Offshore Wind Farm (OWF) value chain, the installation process is one of the critical cost and time-sensitive steps during the wind farm building phase. Specifically this project looks into optimization in installation scheduling problem as the topic of research. It is important to introduce the different actors involved in the study and the platform utilized for implementing the optimization procedure for the dissertation. The project is jointly done with Energy research Center of the Netherlands (ECN) and TU Delft. The former is a research organization working actively in the renewable energy domain. Looking at the vast opportunity for improvement in the OWF installation market, ECN has developed a tool by the name of ECN Install v2.2 (from now on referred as ECN Install in rest of the report) with the aim of calculating the total costs and overall duration by facilitating the simulation of various installation schemes. It is a planning and logistics tool to simulate realistic offshore wind farm installation schedules that the decision maker desires. The tool allows the user to visualize the installation plans taking into account the various delays in the different activities. This project aims to test the optimization concept on ECN Install tool. Chapter 2 will elaborate more about the software in detail. Figure 1.2 shows a screenshot of the tool to the reader for gaining a basic idea about ECN Install. This research dives deeper into solving some of the pressing issues faced in the tool and introduces an optimizer in the offshore wind farm installation modelling process.

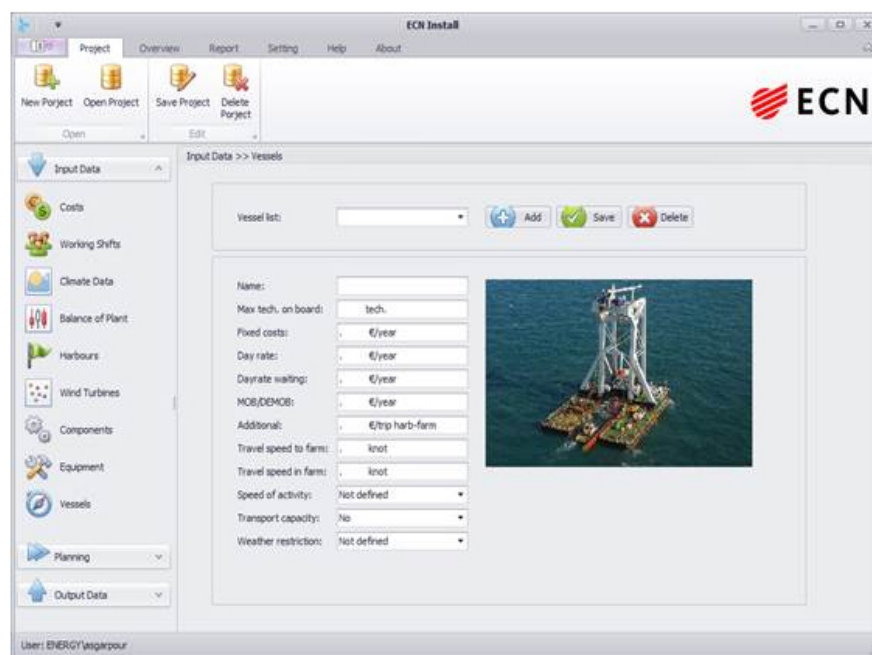


Figure 1.2: ECN Install User Interface

## 1.1. Research Motivation

In the past few years, offshore wind energy has continued its steady growth in Europe and simultaneously making efforts in entering new markets around the globe like the US and Asia [9]. Offshore wind power is steadily seeing a shift from the niche to mainstream market space. The fact that offshore sites hold enormous wind potentials does not guarantee complete harnessing of wind into a useful form of

energy. Given that it encompasses many challenges like high cost of installing foundations, installing wind turbines and connecting the wind farm to the grid which is decidedly dependent on weather, wind and sea conditions [12]. For Offshore wind to become competitive with other renewables, a substantial study is required in manufacturing, installation, operations and maintenance procedures in the immediate future [13]. In the case of onshore wind where the capital costs are driven mainly by wind turbines, the offshore wind sector comprises of multiple parameters contributing to the project costs. The figure 1.3 below shows a value distribution for a generic offshore wind farm.

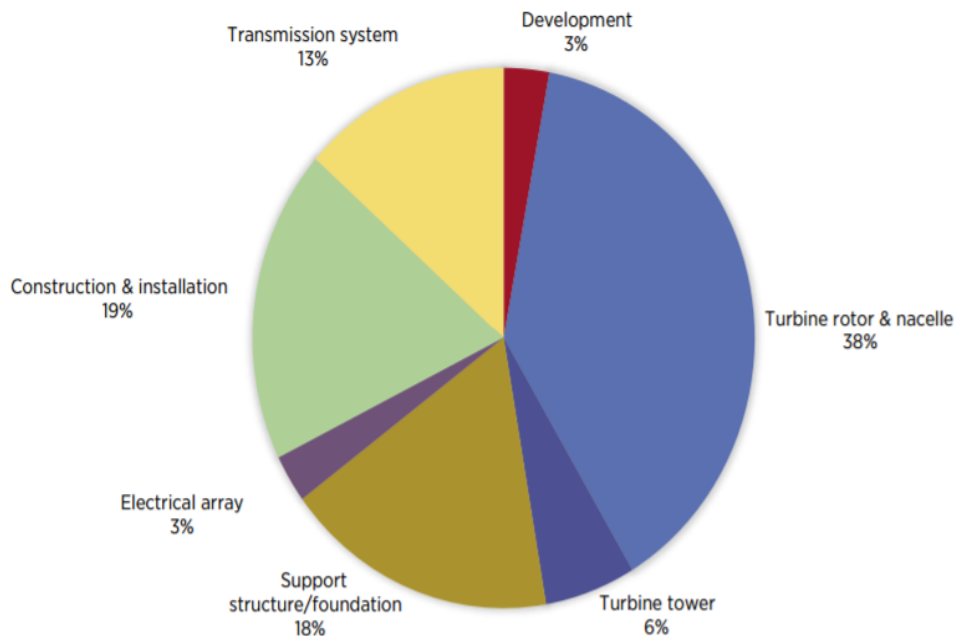


Figure 1.3: Capital cost breakup of an offshore wind turbine [2]

Based on the wind energy growth statistics the installation procedure still accounts approximately 15 to 20% of the total project capital costs. The growing interest in OWF's moving to deeper waters and further away from the shores is resulting in the installation process becoming a prominent topic of research [14]. The installation phase of OWF project has multiple complications which needs to be taken into consideration [15]. The wind farm installation period involves critical stages like the assembly of different turbine components, transportation of parts in vessels, construction of foundations and cable laying in deep waters to name a few. Moreover, the investment costs in OWF projects are in the range of 1.5 to 3.5 M€/MW [16]. Hence, even a slight process improvement can lead to savings of millions in total project costs.

With turbine sizes increasing annually for offshore conditions the complexity of the installation procedure is also intensifying correspondingly. The different installation activities experience uncertainty due to harsh weather conditions, possible equipment failures and component delivery delays during the build. Usually, the resources like vessels and equipment used in the installation phase are needed for the next subsequent projects and tolerate limited flexibility with dates. The uncertain conditions mentioned above also introduce considerable ambiguity on project end date. The OWF installation phase involves numerous actors, where exceeding a project target end date will account to heavy penalties. Therefore, every player participating in the installation stage of the wind farm intends to complete the work within the target end date while accounting for the uncertainties along the way. Additionally, the delays in the installation phase can also have large-scale repercussions on the preceding steps in the OWF project and add to unnecessary cost escalation. Hence, the optimal planning for OWF installation procedure is key for maintaining a balance in the complete value chain.

The current research effort will develop a method for the user to assess the optimal installation procedure for the OWF project quantitatively. In the following sections, the goals of the research, as well as the report structure, is briefly explained.

## 1.2. Objective

The objective of the thesis study is outlined as:

“To have an approach supporting the decision maker to obtain minimized costs for OWF installation procedure with a targeted completion date as a priority.”

Ultimately, the result of the project is to have a method that provides added flexibility to OWF installation planning and estimates the most optimal solution in reasonable time frames. The points below summarize the different steps required to achieve the goal as mentioned above:

- Identify the key challenges to address in the ECN tool.
- Formulate the design problem and prepare installation tool for optimization analysis.
- Selection of suitable optimization model for the project.
- Provide flexibility to house a range of installation situations.
- Validate the necessary modules for the new approach.
- Run cases studies to reflect on the new approach towards solving installation scheduling problem.

## 1.3. Report Outline

**Chapter 1** through **2** provide introductory information with some background idea about the installation planning problem. In **Chapter 2** the different installation challenges are outlined, and the OWF installation problem is formulated. This chapter also includes existing literature work done in installation scheduling problems. **Chapter 3** introduces the automated planning approach to the reader and describes the methodology proposed for integrating the optimizer with the ECN Install. **Chapter 4** zooms into the optimizer and covers the topic of uncertainty quantification method implemented in the project. **Chapter 5** includes the various validations and verification done in the project. This chapter also contains the optimizer parameter tuning results. Later, **Chapter 6** presents the case studies done in the project. Finally, **Chapter 7** includes the conclusion of the thesis work and includes the recommendations for future research.

# 2

## Offshore Installation Scheduling Problem

Installation scheduling is one of the critical steps demanding a high level of planning for the timely completion of a wind farm to go operational. The challenges with OWF logistics and installation process are associated with several factors. Distinguishing the issues relating to the installation procedure is a demanding activity, but on the other hand highly essential to identify the means to improve the existing installation process. The reader who is not familiar with OWF field is suggested to refer the Appendix A section to get a basic understanding of the different resources and components used in the installation process. In the first section, the various challenges faced during the offshore wind farm installation procedure are given. This is followed by a section dedicated to defining the optimization problem for OWF installation procedure. Finally, the chapter concludes with the proposed method to integrate the optimization approach with ECN Install.

### 2.1. Offshore Wind Installation Challenges

Offshore wind farm installation is not a straightforward procedure and has many uncertainties to overcome. As explained in the introductory chapter the basis of optimizing installation process of OWF's is linked to understanding the different challenges associated with it. Any installation phase is strictly bound by time, and total cost sustained during the building process. The various resources used during the installation period are expensive and have substantial contributions in the CAPEX of the project. The different vessels and labor chartering costs are the largest influencers for escalating the total expenses in a project. The subsections below recapitulates the key challenges encountered in the OWF installation industry depending on the activity under consideration.

#### 2.1.1. Foundations

The options for different foundation types are numerous with each one impacting the installation time and cost differently. When comparing jackets and tripods with monopiles, the latter takes less time to install as they are lighter, less complex structures and require fewer pile driving operations per component. Next, the water depth and soil type are critical parameters deciding the component outlay and installation period. The addition of scour protection increases the different vessel requirements and add to the expenditure and duration of the project.

The installation vessels are the most important variable accounting for the maximum installation expenses. Thus, the selection of the right vessel for the installation activity is an essential task. Important parameters like the vessel workability, crane specifications, speed and deck space determine not only the per foundation installation time but also impact on the total build time. Similarly, the choice of the port has significant repercussions on the project expenses and time duration. The harbor loca-

tion determines the fluidity of onshore logistics and the distance to farm. The offshore site distance regulates vessel travel time and eventually effects the project CAPEX. When considering the weather restrictions for the foundation activities, they are less susceptible to wind conditions when comparing with the turbine installation procedure. Nonetheless, weather delays can be expected due to severe weather conditions; again stressing the point about precise resource selection and planning.

### 2.1.2. Wind Turbines

The wind turbine installation activities over and above the reasons listed in section 2.1.1 are influenced by the total number of turbines to install, vessel selection, technicians experience and installation concept adopted for the project [3]. Unlike the foundations, the weather plays a central role while planning the installation steps. This is due to the height of lift activities undertaken during turbine installation. These high lifts for crane mandate greater workability restrictions hence reducing the available weather windows for operation. Importantly, the turbine size and level of onshore assembly influence the total installation time and eventually the cost sustained during the project. Finally, the sensitive dimensions of wind turbine components augment the challenges in the wind turbine installation process.

### 2.1.3. Cables

The offshore wind farm consists of two different cable installation activities (Inter-array cables and export cables). The bottlenecks in the installation are also dependent on the complexity of the project. To begin with, the cost and time for installing infield array cables are dependent on the number of turbines, the layout of the farm, soil type, burial depth, scour protection requirements and so forth. While considering export cable installation the soil type, burial depth and location of the onshore station are some of the critical parameters controlling the installation time. In both types of activities, the weight and length of the cables have a large impact on the total costs involved in the project. The dimensions of the cables influence the vessel selection and eventually the installation time of the activities. The cable laying installation ultimately is a trade-off between the vessel and the burial method implemented in the project.

### 2.1.4. Conclusion

There are other difficulties like the limited availability of purpose-built vessels for OWF installation market. Likewise, setting up the best possible loading sets on the vessels based on the weather windows is a big challenge. The possibility of component or equipment damage during the installation activity can severely impact the project expenditures. Hence, it is important for a contractor or project developer to consider numerous uncertainties in a project and design the most optimal installation strategy to minimize the overall cost and duration. This study will look into some important factors affecting the OWF installation procedure and propose suitable solutions. It is an apt moment to define the scope of the thesis work to the reader. Although the optimization study in OWF installation scheduling is a large domain, this thesis assumes the decision maker already knows the turbine, foundation type and the cable specifications utilized in the wind farm. Similarly, the study does not look into the onshore logistics and availability of resources during a project. It is assumed there are no delays in the onshore value chain and all the required vessels or equipment are available during the installation planning stage. The scope of work is restricted towards optimizing the offshore installation scheduling problem with the continued availability of resources predefined by the user. Before we dive deeper into the optimization problem, it is essential to introduce the ECN Install tool for the reader to understand the key aspects to address in the new approach. The optimization topic is introduced in section 2.3 subsequently after the reader gets an overview about ECN Install in section 2.2.

## 2.2. ECN Install

This section takes forward the different wind farm components and resources and demonstrates the modeling approach followed in the software space. Chapter 1 gave a small introduction to the tool. This segment further covers the incentive for building ECN Install, with an outline of the user interface and the logic followed in the modeling. The Install package is based on MATLAB platform to support the back-end code and C program for the front end GUI (Graphical User Interface). The significance of installation activity in the offshore wind industry is already outlined in section 1.1. Hence, a robust OWF installation planning tool can benefit multiple users like installation contractors, wind farm developers, institutions, etc. The tool aims to provide precise time and cost indications for various installation procedures. It highlights the barriers during the installation activities and supports in eliminating project risks. ECN Install is designed to test various conceptual installation strategies for accelerating the knowledge transfer between different actors involved. It leads towards efficient resource management to minimize the possible delays and overall costs for simulated schedules. The ECN Install simulation tool is in existence from early 2014, where over the years it has seen systematic improvements and got assigned a particular version at every point. The final commercial tool is based on version 2.1 (starting now referred to as ECN Install old). On the other hand, there are additions made in the back-end code and an internal version is provided for this research study. The distinct differences between the versions will be highlighted when obligated in the report. In the version of the tool utilized for this project, a general simulation of the complete value chain of the OWF installation procedure can be represented. ECN tool is a time driven simulation software which primarily facilitates in estimating a tentative project completion time and the various costs involved during the installation procedure. The tool provides excellent flexibility in the hands of the user to model the desired planning and export the cost and time outputs for any project. Due to the high reliance on the user-defined inputs, the outputs are profoundly dependent on the quality of input data. The following section breaks the ECN install into blocks and explains the installation scheduling approach followed in the software.

### Tool Architecture

This section covers the modeling logic applied in the ECN Install tool. It should be clear to the reader from the figure 2.1 that the tool houses four key modules (Input Data, Planning, Processing, and Results). Starting with the input block which stockpiles all the parameters required for the following blocks to run the simulation. This includes library of resources (Vessel, equipment, technicians, components), wind farm specifications (Wind turbine data, weather data, port) and other relevant cost parameters required for the planning process. The Planning block shown in the figure below is where the user prepares the actual schedule for the installation activities to evaluate in the tool. The planning comprises of a group of 'Steps' which further results in a collection of 'Sequences' (Refer figure B.1 in Appendix B). The Processing module holds two blocks called the Pre-processor and the Simulator respectively. Pre-Processor tab aids to process the planning and inputs by the user without considering the various types of delays. The Simulator block as the name suggests simulates the planning based on the weather data and outputs the new planning accounting for effects of delay. Lastly, the Results (Post-Processor) module contains the tabs to post-process the simulation solutions in a presentable manner to facilitate decoding of the planning created initially. Each of the modules introduced above is explained more elaborately for more insight into the tool in appendix B. The reader is recommended to refer to appendix B for better understanding about the working of ECN Install.

## 2.3. Optimization of Installation Planning

In the field of technical analysis, optimization is the process of adjusting an existing procedure to make it more efficient. These adjustments include selecting certain design variables and trying different combinations to move towards an optimal solution while eliminating the bad results along the way. Installation planning problems being very dynamic and difficulty in forecasting specific weather realizations pose extra challenges in finding effective solutions. This section will justify the need for optimizer with the ECN Install tool and the advantages which follow this decision.



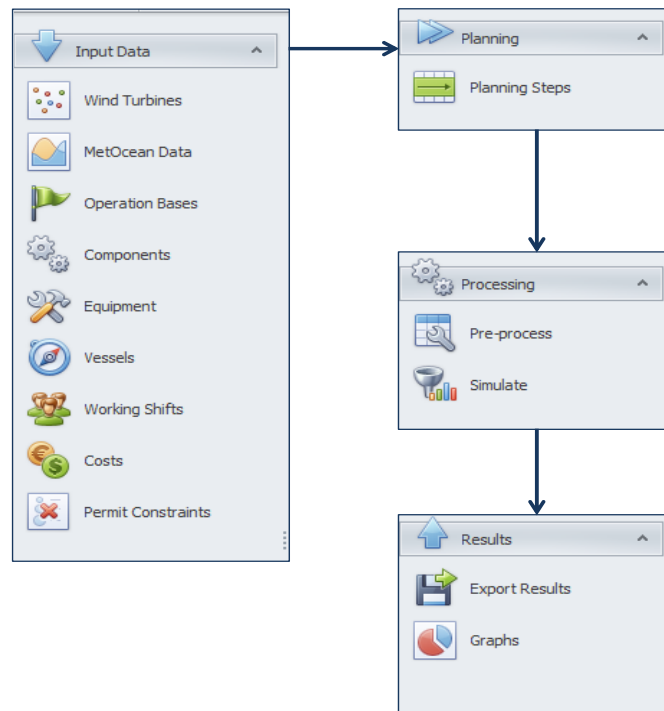


Figure 2.1: ECN Install tool architecture

### 2.3.1. Need for Optimization

The Install tool in the current state has limited capabilities when it relates to replicating industry scenarios without extensive assistance from the user. As stated before, the quality of inputs define the accuracy of the simulation results in the tool. With the Offshore wind sector developing at a fast pace it is necessary for the tool to improve analogs with the industry too. The addition of an optimizer for the tool is aimed at searching a larger solution space and present best possible outcomes under given constraints for the decision makers utilizing the tool. There are numerous permutations and combinations possible to process before finally obtaining the optimal or close to optimal solution. A manual calculation is impractical and time intensive. Hence, ideally an optimizer is desired to do these heavy duty calculations. Now that it is established that an optimization approach is interesting to incorporate with the ECN Install, key-value additions are listed below:

- Capture more of the reality by evaluating different design variable combinations in the tool.
- Simulate different strategies and compare the best choice. Eventually, cost saving for contractors and project developers.
- Avoid very conservative schedules for the installation phase. Allow the user to make better decisions for the project.
- Providing suitable results with reduced inputs from the user, reducing the dependency of final output with the quality of input data (Wind farm, installation activity specific inputs and weather data required).

### 2.3.2. Existing Studies on OWF Installation and Planning

This section gives a summary of the previous work done on offshore wind farm installation planning. OWF Installation scheduling problems are comparatively new domain of research compared to other topics like layout optimization or aerodynamics for offshore wind farms. There were only limited papers found directly relevant to installation scheduling. The different approaches followed in literature for



OWF installation procedure are highlighted here.

Scholz-Reiter et al. [17] introduce a mathematical model making use of mixed integer linear programming (MILP) with the goal of minimizing the total time for building the wind farm. Their model studied three different scenarios and examined the vessel requirements. The model calculated optimized loading sets, resource demands and optimal installation sequence for the different cases. A major drawback of the model was its ability to run only for short time horizons. To overcome these limitations, Scholz-Reiter et al. [12] proposed a heuristic approach to solve a similar installation planning problem. The new approach was able to solve for longer time horizons with more complexity in installation activities for varying weather states.

Next, Lutjen and Karimi [18] proposed a simulation approach for port inventory control system. They also followed a heuristic approach based on the one developed in [12] to simulate the installation planning process. They finally present the two-level approach of scheduling and inventory management (material restock) for offshore wind farms.

Ait-Alla et al. [19] introduce a model to deal with aggregated installation planning problem. The paper considers operational constraints like weather and vessel availability. Weather windows are split into categories from good to bad conditions in the problem. The model generates an estimated medium planning horizon schedule which minimizes the total costs of the given project. The model takes into consideration the costs and weather restrictions per vessel type selected for installation.

Y.T. Muhabie et al. [20] shows a new approach to tackle the offshore wind farm installation problem. The help of Discrete Event Simulation (DES) is applied to model weather, vessel characteristics and turbine assembly scenarios. The simulation is carried out with both historical weather realizations and probabilistic approach. In the probabilistic approach, various distributions are prepared in the simulation depending on the weather window required and the resource weather restrictions. The DES method considers only points in time (events) and instances in between are not of interest. It is a popular approach used in transportation management, flow management and management of failures. The findings provide a new framework to address risks and uncertainties in OWF installations.

The C.A. Irawan et al. [21] work addresses the optimization work in the offshore wind farm installation planning. A bi-objective optimization for minimizing the costs and completion period of the installation scheduling problem is presented. The authors suggest two different approaches to solve the multi-objective problem. One using compromise programming with the exact method and the other with metaheuristic techniques. The paper makes an interesting conclusion on the different approaches, where the exact method attains optimality for all cases. However, the increase in the size of the problem resulted in an exponential growth in computation time for the exact method when compared to metaheuristic approach. The metaheuristic approach ran much faster and produced well overall.

Therefore, based on the learning from the existing literature work the next section will focus on selecting an appropriate optimizer and integrating it with ECN Install tool.

### 2.3.3. Optimization Choices

Every problem has certain select optimization compatibility based on the problem setup. The optimal solution for a problem can be found either by exhaustive search or using an optimal finding algorithm for any planning problem. A big drawback of the exhaustive search is the time taken to obtain an optimal solution. On the other hand, algorithms dedicated to finding local or global optimum solutions are much faster at converging to the desired solution.

When the optimization choice for ECN Install is under consideration, it is important to evaluate the problem setup and the possible design space for the optimizer. Any optimizer linked to the Install tool will need to input a combination of design variables and allow the ECN tool to work as a black box to evaluate the combination and deliver the results. These results would be later passed through the optimizer to select the most optimal solution. Thus, it is essential to pick a derivative-free optimization algorithm to satisfy the needs as mentioned earlier. This project includes a large design space for the optimizer to look for an optimal solution and hence to avoid any sub-optimal solutions a global search optimizer is preferred.

Due to the high complexity of optimization problems under uncertainty, time and again traditional approaches which assure optimal solutions tend to be reasonable only for small problem sizes. They require a great deal of computational power to function for large instances. Stochastic optimization is the general class of techniques which use some degree of randomness to find good (or sometimes optimal) solutions to hard problems [22]. Metaheuristics are the most general of these kinds of algorithms and are applied to an extensive range of problems [23]. There are different metaheuristic approaches, but this report only considers search algorithms. It is mainly due to their popularity and flexibility to adapt to different problems easily.

By listing the above requirements, a global search and gradient free algorithm are desired for this project. It is preferred to develop a custom-made algorithm for the design problem, nonetheless is a very time-consuming and complex proposition. Considering the effort required for development and time limitations for the project the MATLAB optimization toolbox is chosen for carrying out the study with ECN Install tool. MATLAB platform provides three global search algorithms in the toolkit. The Genetic algorithm (GA), Particle swarm optimization (PSO) and Simulated annealing (SA) [4]. The problem representation differs for every algorithm mentioned above and testing each one is not a pragmatic approach. It is later found that the problem representation of GA and PSO methods are more comparable [24][25]. The GA is selected for the project as it is a very popular algorithm with large literature base for assistance. The GA toolbox is easy to adapt to different design challenges, and the problem representation could be altered for PSO method in future with little effort if necessary. Moreover, it is the only algorithm providing a ready option for evaluating integer constrained design variables. The GA is a population-based approach which means it would evaluate multiple parameter combinations in one iteration. This feature would be beneficial while dealing with large installation problems with a high count of design variable evaluations. Lastly, the toolbox also provides the multi-objective capabilities which could be used in the future. Ultimately, it should be clarified that the specific optimizer selected for the project is one of the ways to solve the installation problem and not the only choice suggested by the author.

## 2.4. Optimizer Addition to ECN Install

The introduction of optimizer calls for certain modifications to the existing architecture of ECN Install. The block diagram below shows the methodology to integrate the Genetic algorithm optimizer with ECN Install together. The introduction of an optimizer with the ECN Install tool requires the development of supporting blocks for the optimization approach to function appropriately. Referring to the figure 2.2, starting with the first block in black which has the primary purpose of collecting all the wind farm and project data for any installation planning in study. The existing blocks from the old architecture of ECN Install are highlighted in grey shades. These comprise of the weather simulator introduced in B.0.5 and the ECN Install tool itself. The two primary additions are the automated planning (in chapter 3) and optimizer blocks (covered in chapter 4). The initial planning block as the name suggests works on the same principals of the automated planning block, although its functionality is restricted to initializing the project before proceeding into optimization phase. In this project weather is the only uncertain variable considered throughout the study. Based on the overview given about the new weather simulator, the uncertainty consideration for the results from ECN Install is carried out in the UC block (in chapter 4). Reviewing the objective defined in section 1.2, there is a requirement to evaluate the project end date in this study which is achieved in CV block (in chapter 4). The optimization analysis with ECN Install is a repetitive process where different design variable combinations are tried till the optimal result is achieved. Once the best combination is obtained, this is represented by the optimal solution block in green. To indicate the repetitive process of the optimizer the loop is highlighted with a dashed block and red arrows for the reader.

The block diagram above represents the problem approach adopted for this research work. The following chapters will elaborate the various blocks in detail and provide more insight to the reader about the integration process with ECN Install.

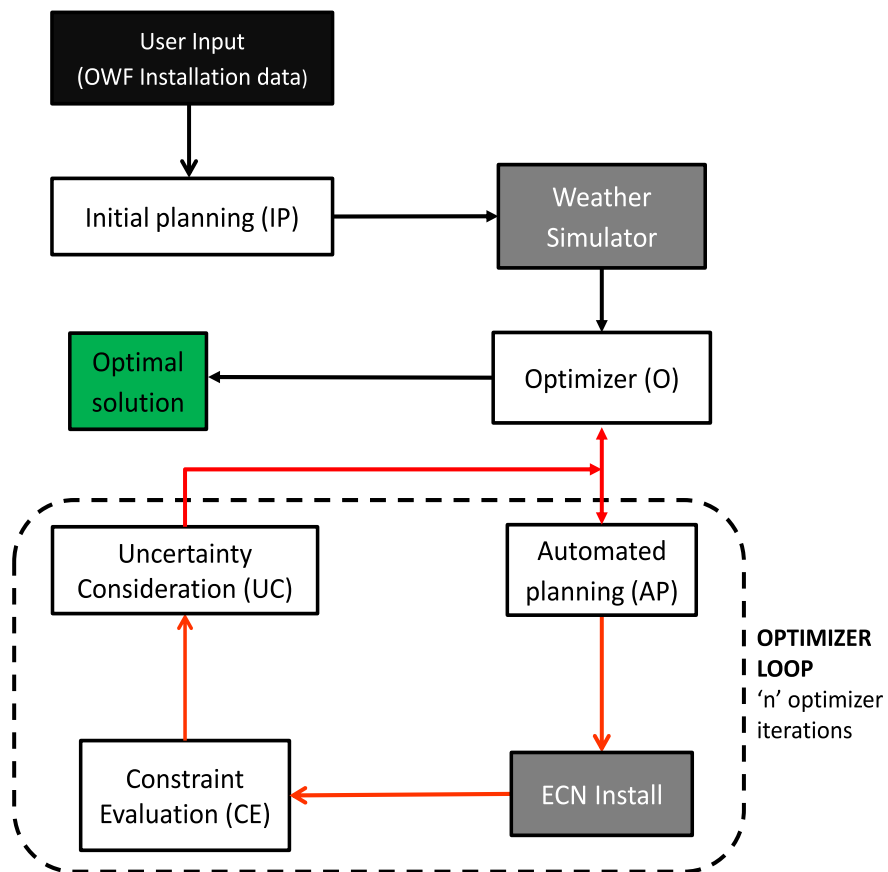


Figure 2.2: New project architecture



# 3

## Automated Planning

This chapter covers the methodology applied for generating the Automated Planning (AP) based on the initial inputs for the project. The following sections explain the primary requirement of this block in the project. This is followed by a summary of the limitations and benefits of using this approach and the various assumptions made in the modeling process. Next, a section is dedicated for a deeper understanding into the course of translating the inputs from the user into installation planning for ECN Install tool. Finally, the last part explains how the automated planning is integrated into the optimizer loop as shown in figure 2.2 (chapter 2).

### 3.1. Automated Planning Requirement

The current commercial version of ECN Install requests the user to create the complete time and resource planning for any project. This approach was sufficient as all the resources remained fixed and the ECN Install accounted for uncertainty due to weather and translated the delays in the form of costs and time values. The addition of an optimizer with ECN Install software entails certain changes to the old architecture as introduced in section 2.4. Unlike the old approach where fixed user inputs are used for simulations the new method iterates various combination of different resources to find the optimal solution. Hence, there is a need to automate the planning processes to allow the optimizer to make such changes dynamically during the GA optimization. In the new methodology, the user provides certain fixed parameters for the project that do not alter during the complete installation schedule evaluation. The rest of the process is automated based on the particular choice of resource in the planning (done by the optimizer). While the requirement of AP block is unavoidable it brings certain advantages and some limitations to take into consideration. The new approach reduces the project planning time to few minutes compared to hour or more depending on the complexity of schedule. Additionally, the user is no longer required to calculate the precise number of repetitions of activities which was previously mandatory. On the contrary, AP block approach operates with pre-defined templates for different installation procedures. Hence, limiting the flexibility to make changes in the sequence of installation activities. The different inputs and logic behind the planning process will be explained in the sections to follow.

### 3.2. Automated Planning Blocks

Automated planning in the software platform is created using a standardized approach for different installation components. The specific blocks vary based on the installation activity, but the logic behind the building process remains the same. The block diagram below shows the basic approach used in the planning process. The block diagram explains the process during the initialization process where the user inputs are stored first. *Installation Type* block is where the scope of the project is decided (refer table 3.1). The *Selection and Build* block constructs the planning based on the inputs from the previous

blocks. This block retrieves the required information from the different libraries explained in the next section. The planning and the inputs are stored in the mandatory Database format to simulate the planning in ECN Install software. The installation sequence module shows a typical sequence created in the automated planning block. The specific steps change based on the installation activity, but the logic behind the formulation of the planning is very similar. Three types of blocks namely Loading, Traveling and Installation are used as the backbone structure for any installation sequence planning. The section 3.4 of this chapter explains the use of these three blocks in different installation scenarios.

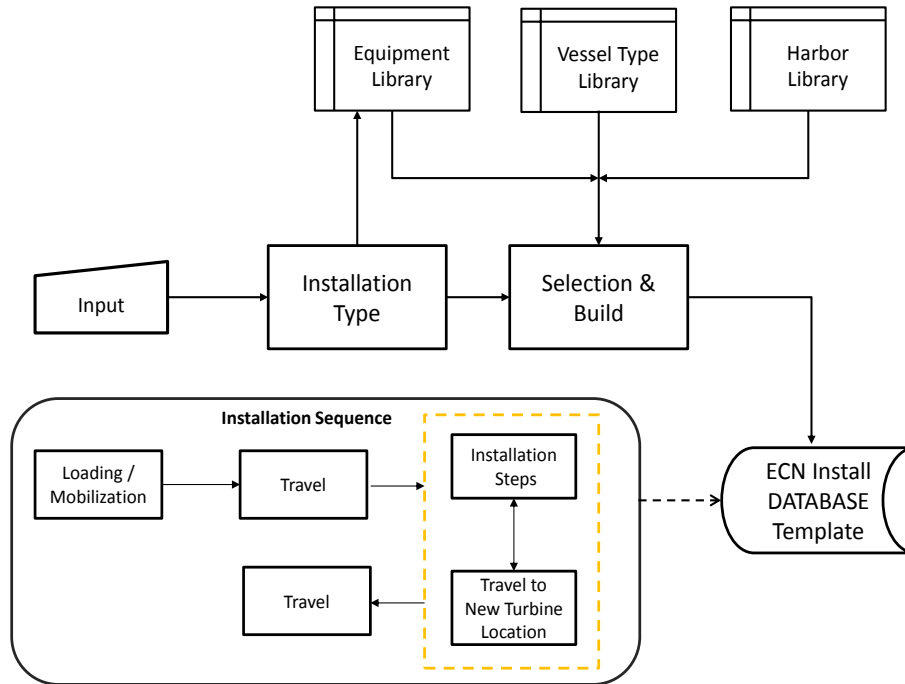


Figure 3.1: Automated planning flow diagram

### 3.3. AP Block Inputs

The inputs from the user need to be passed in a predefined format that is accepted by ECN Install. As the automated planning is finally aimed to feed the schedule into ECN simulator, the same format is required to be followed for the automated planning to work with ECN Install. The data handling process in the ECN Install is explained in appendix C for interested readers.

The following section explains the various inputs given by the user to generate the automated planning for each installation process. First, the necessary resources involved in the OWF installation scheduling problem are identified. The engineering choice of resources like the vessel, equipment, and port is found to be most important to look into [26] in the current work. Once this aspect is established the resource classification is necessary for the software implementation. Specific resource Libraries are created inside AP module to access common information for every planning. The following subsections will look into the classifications and cover the reasons behind creating the classifications inside each library. The library serves as a common point for the AP block to select a suitable resource for the planning. The next subsections explain the different libraries in more detail.

Building on the introduction from section 3.1, the automated planning block still requires specified inputs from the user to create the necessary planning. Table 3.1 summarizes the general inputs needed for simulating a typical project in ECN Install running with automated planning approach. The specific inputs for installation activities like foundations and wind turbines are covered in section 3.4 with more details.

Input Parameter	Remarks
Project complexity	1. Only foundation installation 2. Foundations + wind turbines installation 3. Foundations + wind turbines+ infield cable installation Note: Scour protection option available for all 3 options
Wind farm location	GPS coordinates of the OWF location (In degrees)
Wind farm	1. Total number of wind turbines 2. Number of turbines, wind turbine power curve(optional) and hub height. 3. Number of turbines, wind turbine power curve(optional) and hub height.
Weather data	Wind and wave height data for wind farm location and ports (optional)
Fixed costs (optional)	Miscellaneous fixed costs and project management costs

Table 3.1: Project inputs

It is important to note in the current version of ECN Install, an installation planning can only be defined with one particular vessel or equipment for every step. Refer to figure 3.2 to understand the above limitation. E.g. In reality a sequence where a non-self-propelled vessel is used for installing a wind turbine component will require multiple tug boats to drive the vessel to a particular location. However, as mentioned before, ECN Install limits entering these multiple vessel and/or equipment. To compensate for the same, extreme weather workability and cost of both the vessels are accounted for.

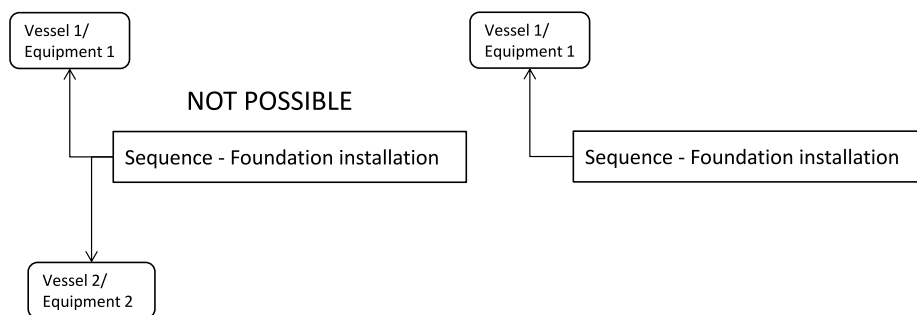


Figure 3.2: Sequence limitations

### 3.3.1. Vessel Type Library

Vessels in the offshore wind industry have varied chartering costs based on their size, purpose and workability. To model close to reality, suitable divisions are required based on which the vessels can be grouped. Grouping vessels into divisions help address the size and workability parameters to a large extent. Storing these divisions in different sub-libraries help differentiate based on the type of installation activity.

All the purpose-built vessels for the OWF installation industry house a primary crane to do the lifting operations necessary. As the installation vessels have varied capabilities, the maximum crane lift capacity becomes a common parameter to group the vessels. An internal vessel database (provided by ECN) is studied, and the necessary vessels per installation activity are collected in the beginning. Similarly, the classification for rock dumping vessel is done based on the cargo capacity, and the cable lay vessel is divided depending on the carousel weight capacity. Table 3.2 summarizes the different vessel divisions depending on the type of installation activity. To get a clear idea about the structure of vessel library the reader can refer to figure 3.3.

Installation Type	Foundations and Wind turbines	Scour Protection	Infield cables
Vessel Class	Crane Lift Capacity(mT)	Loading Capacity(mT)	Carousel Weight (mT)
Division 1	Component $\geq 1200$	Capacity $>20000$	Capacity $\geq 7000$
Division 2	$800 < \text{Component} < 1200$	$15000 < \text{Capacity} \leq 20000$	$3000 < \text{Capacity} < 7000$
Division 3	Component $\leq 800$	Capacity $\leq 15000$	Capacity $\leq 3000$

Table 3.2: Vessel Library

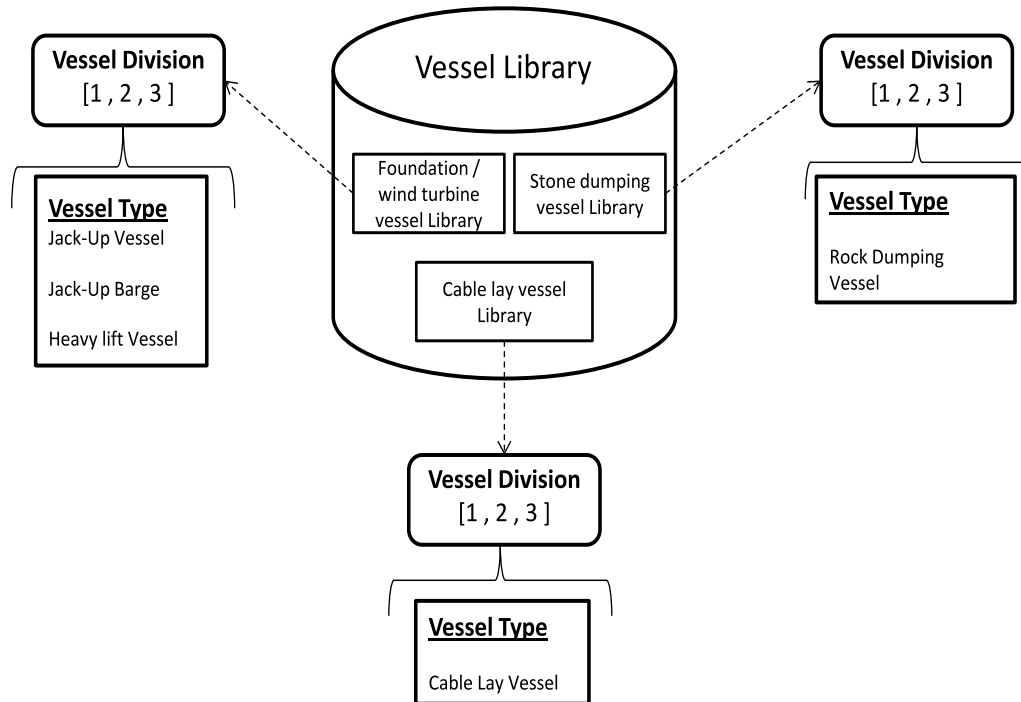


Figure 3.3: Vessel Library

The cost parameters and duration of activities for each of the above vessel types are collected from ECN sources and saved in the library. All the different cost parameters assumed for the project are long-term chartering costs and do not consider real-time market rates. Finally, the different working weather restrictions for every vessel type is updated.

### 3.3.2. Harbor Library

Harbor is an important component to carryout the complete installation procedure. It connects the onshore logistics to the offshore activities in during the OWF build. A harbor library is created for the AP block to retrieve the required port while creating the installation planning. Since, the AP block works with the optimization process where multiple port options are simulated and user intrusion for entering distance between OWF and harbor is not practical. For overcoming this limitation, the Great Circle distance algorithm is applied to calculate the distance between two locations provided that the longitude and latitude values for both points are known [27].

Firstly, a list of all installation capable ports are collected from the 4C Offshore site and categorized based on country [28]. Currently, the Database is made for ports in UK, Netherlands, Denmark, Belgium, and Germany. The harbor library has latitude and longitude coordinates saved for every new selection in the list. The user inputs the coordinates of the wind farm and the automated planning calculates the distance between the selected port and wind farm based on the exact selection. A suitable port selection also depends on the area used for onshore logistics at the site. The day rates depend on



the actual area utilized and as this falls under the onshore resource optimization domain it is excluded from current work. For simplicity a fixed day rate value is assumed for all the harbor locations in library.

### 3.3.3. Equipment Library

The Equipment Library is created based on the type of installation type selected. Currently, the equipment used is relatively standardized with limited choices. It is created for the AP block to choose the relevant equipment based on the installation activity and also planning for future situations if more number of options would be available to install the same resource.

### 3.3.4. Default Database Template

As explained in section 3.3, the MATLAB code of ECN Install accepts the user inputs and planning information in a specified manner. This requirement is adhered to and all the inputs and automated planning is reproduced in the same required format for the tool. There is a Default template file used as a starting point for storing the data in the desired format. The template block can be seen in figure 3.1 after the Selection & build module.

## 3.4. AP block implementation

This sections initially lists the different assumptions taken into consideration while modeling the AP block approach. This is followed by the description about the procedure followed in implementing automated planning for different installation procedures. As stated before, the automated planning prepares an installation planning based on a user selected installation strategy. The specific assumptions considered for the AP block modeling approach are listed below:

- The Wind turbine type and farm size for installation planning are fixed. Thus, the decision maker is required to know the number of turbines, turbine class (MW rating), and power curve(optional) before running the AP procedure.
- The installation activity templates are pre-defined. This saves considerable amount of time for user during input stage but on the contrary limits the flexibility in installation schedules.
- Number of technicians per type of activity are fixed. The required number of technicians are decided based on old wind farm projects. The user is still given the option to overwrite the default values with the ones required for the specific simulation.
- All the planning is created following a 24/7 working period (mostly followed in offshore wind industry).
- Component cost<sup>1</sup> is not considered in the automated planning process. I.e. only installation cost is the main parameter of study from the CAPEX<sup>2</sup>. This data is set to zero in the AP block.
- The different vessels and equipment are classified per type. The specifications of the resources (Vessels/equipment) under the same category are alike.
- The duration of installation activities (Step level) are fixed per type of resource. There is provision to change the values in MATLAB code if the user desires.
- Multiple vessel concepts are not modelled within particular sequence of activities.(explained in section 3.3)
- Fixed activity duration is assumed in automated planning block. The activity duration is fixed to default value which does not change during the complete simulation.

Section 3.3 gives an overview of the automated planning approach modelled in this study. The following parts describe the method followed for different installation activities.

<sup>1</sup>Cost of manufacturing foundations, wind turbine components and transmission cables etc.

<sup>2</sup>Capital expenditure (CAPEX) are the expenses incurred in building the complete value chain of the OWF. It accounts for various types of expenditures as shown in figure 1.3.

### Scour Protection

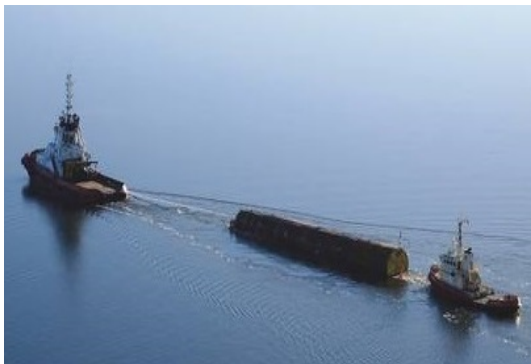
Scour is a type of erosion of soil around the structure in the seabed. This is especially significant in locations with tidal currents around the structure [29]. In such cases, it becomes beneficial to prepare a rock bed around the structure to avoid the above scenario. Scour protection is applied to foundations which are secured to the seabed. The rock dumping is performed in phases where first the small rocks are precisely dropped around the substructure location. The next step of the rock dumping is done after the foundations are installed where large stones are placed to secure the scour protection from eroding away over time [3].

### Software Implementation

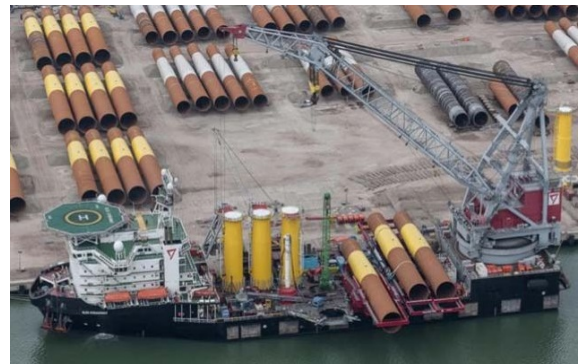
The installation procedure for scour protection case is included in the automated planning process. It is provided as an option to the user to select for the project. The scour protection follows the same building processes as seen in figure 3.1. During the installation step if the user does not input the amount of rock dumping per foundation location a default value of 2300 tons is fixed in the simulation [30]. Using the pre-defined template for scour protection installation the AP block builds the loading and traveling process for completing the sequence planning.

### Wind turbine Foundations

There are various methods available in the market to transport the foundation from the onshore location to the wind farm site. The shipping choice is dependent on the type of foundation, size of the component, distance to port, weather conditions and installation vessel used for the project [3]. When talking about monopiles, they can be transferred using one installation vessel. The other option involves implementing feeder concept where the main installation vessel is stationed at the offshore wind farm construction site, and the substructures are transported on a barge or feeder vessel continuously from the onshore location [31]. There is also the option where the monopiles are capped on either end and floated at sea. They are then towed by small boats to the offshore site while the main installation stays put at the wind farm [31]. The transition piece is generally carried on a barge in feeder concept or on the main installation vessel with the monopiles as seen in figure 3.4b.



(a) Monopile tow to installation site [32]



(b) Monopiles and transition piece on heavy lift vessel  
(Source-Seaway heavy lifting)

Figure 3.4: Foundation transport methods

The installation strategy followed for monopiles is fairly standard in the industry. First, the monopile is upended into vertical position using a special gripping device. This is followed by placing a pile driving hammer over the structure. The monopile is hammered into the seabed to a predefined depth. Usually, about 30 to 50% of the monopile is below the seafloor [33]. Next, the transition piece is installed over the monopile by grouting or direct bolting procedure. Finally, rock dumping vessels are employed to secure the seabed around the monopile against erosion if required for the project.

### Software Implementation

The automated planning approach models the foundation transport with a single vessel concept. The steps are split into four categories. The Loading step, Traveling step, installation step and finally the Traveling step again to conclude the iteration. The loading step is where the foundation components are stacked onto the vessel to be sailed to wind farm location. Next, the traveling step is executed where the vessel sails from the harbor to the wind farm site. The installation step contains the specific installation operations like the one mentioned above. Once the installation work is complete the vessel sails inside the wind farm to a new location, repeating the installation activity until all components are in place. Finally, the empty vessel travels back to the harbor which is represented by the traveling step to repeat the above process up until the necessary installations are completed.

### Infield Cabling

The array cable installation process is essential in connecting the different wind turbines in the farm to the grid. A few popular offshore cable installation methods are explained in this section. After the cables are laid on the seabed they also need to be buried a few meters below the ocean floor for safety [34]. There are two popular methods relevant for the wind industry.

*Cable lay and bury:* In this approach, the specific section of the sea floor is unearthed using a purpose-built dredging vessel. Once the process is completed, the cable is laid inside the furrow using a cable laying vessel. The furrow is later covered using a dredge. This method is utilized for both infield and export cables laying procedure.

*Simultaneous lay and bury:* The cable laying vessel has a large turntable with the cable to be installed. These vessels are equipped with a plow or supported by a different vessel to create a trench for laying the cable in the seabed. High-pressure water jets are popularly used to diffuse the seabed and simultaneously bury the cables. The other method in the same class employs a Remotely Operated Underwater Vehicle (ROV) in place of a plow. This method is popularly used in infield array cable installations where the ROV buries the cables under the seabed [30].

At the outset, the vessel positions itself close to the foundation for starting the cable lay process. Every foundation installed offshore is preserved with a messenger wire close to the cable entry point on the foundation. This messenger wire is recovered and connected with the actual array cable on board the vessel. Next, the pull-in operation is carried out, and the array cable is secured to the foundation. The vessel starts the laying process on the seabed until it reaches the next foundation site. The same pull-in operation is done at the new foundation site, and the iterative approach continues until the completion of cable laying procedure [35]. Once the cable is laid, a different vessel is deployed to bury the cable for safety reasons. A working class ROV is used to complete the cable installation activity. This project considers only inter/infield cable installation in the OWF planning and excludes the OHVS (Offshore High Voltage Station) and export cable works. It is observed that Transmission system operators (TSO) in countries like Netherlands, Germany, and Denmark are given responsibility to build offshore grid network to facilitate the linking of multiple wind farms in the North Sea [36]. Hence, this section only covers the installation strategy applied in the wind farm cable network.

### Software Implementation

The array cable installation is split into two sequences of activities. One responsible for the cable lay process and the other for the cable bury phase. The required length of the infield cables is loaded onto the cable lay carousel. The vessel thereafter travels to the wind farm location to begin the installation activity. The simultaneous lay and bury approach explained in the above subsection is modeled for installing the cables. Once the installation is complete, the vessel returns to port and prepares for new load out, if necessary. To make the process automated for the user the cable weight per meter (40 kg/m) [37] and the distance between the turbines (7 times rotor Diameter) are preset [38]. The user is given the option to change these parameters depending on the project specifications. The above assumptions allow the AP block to generate the array cable sequence with limited inputs from the user.

### Wind turbines

The installation of wind turbines is carried out after the foundations are completed. The installation of turbines is normally the last major installation works done for the wind farm project. In many cases, the same vessel utilized for foundation installation is used for turbines as it saves the hassle for the project developers to mobilize new additional type of vessels for the installation activity. However, this cannot be avoided in some situations and can result in separate vessels operating to install turbines. This section briefly explains the different installation concepts applied in the offshore wind market. The transportation methods are usually done with a single installation vessel. The feeder concept is not very popular in the case of wind turbines. It is only considered, if the main installation vessel movement needs to be reduced or the loading of the optimal number of components is not achieved with one vessel. A large number of wind turbine components allow many combinations of pre-assembly options to use in a project. In cases, the tower is split into two sections the number of elements increases to 7. Figure 3.5 below summarizes all the different pre-assembly combinations used, and the total number of crane lifts required per option. Some extent of pre-assembly is desired to reduce the number of offshore crane lifts which will minimize the size of weather windows required for the installation activity.

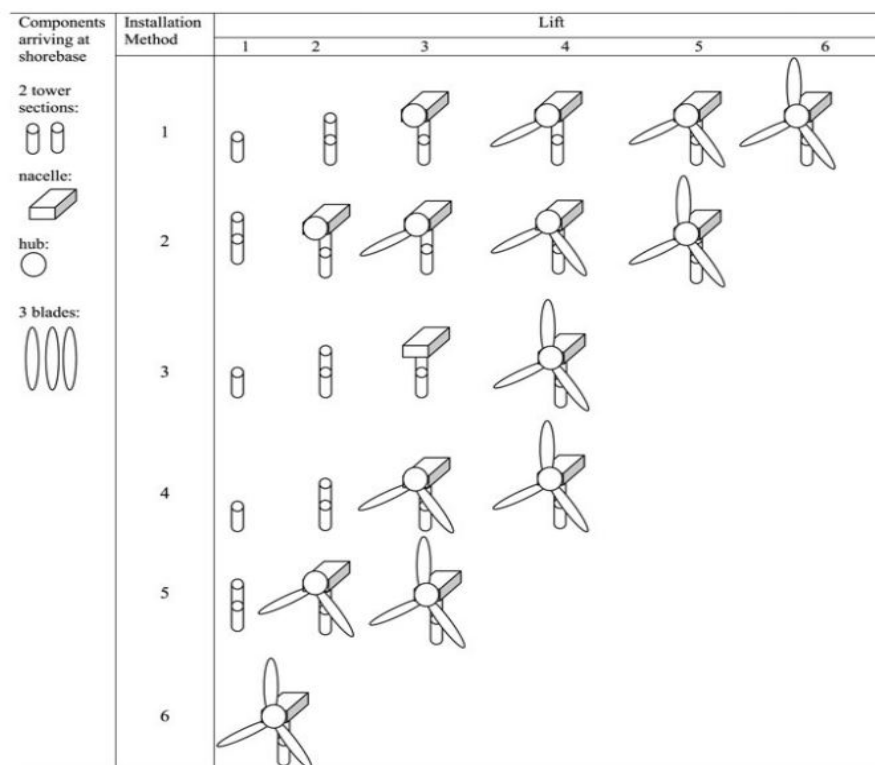


Figure 3.5: Pre-assembly combinations [3]

Installation method 1 requires the most amount of lifts where the majority of the components are assembled offshore. The only exception being the hub and nacelle assembled prior at onshore. This method is practical when the wind farm is far from the port and allows efficient utilization of the deck area. Hence, allowing more number of turbine components to be transported in one trip. The Greater Gabbard, Lynn & Inner Dowsing wind farms are few examples where this strategy was implemented [15].

The second option is similar to the first option but avoiding one lifting operation of the tower as it is pre-assembled in this case. This method like the above ones carries the disadvantage of requiring a separate lift for the blades but due to the larger number of components possible to be transported on the vessel and substantial experience with installing the components together efficiently the weather delays are less significant. This is the most popular installation method employed in the industry. Rhyl Flats, Gemini and Burbo Bank wind farms [3] are few locations this configuration was used. Example

of the installation steps are shown in figure 3.6a , 3.6b , 3.6c.

In the third method, the rotor and three blades are assembled onshore, and the tower is transported in 2 parts with the nacelle separately. Initially, the two sections of the tower are installed. It is followed by the installation of nacelle section. This method eliminates the lifts for the blades and requires just one lift to install the entire rotor(refer figure 3.6e). As a trade-off, the number of components carried on the vessel is reduced compared to the above options. The Horns Rev 2 and Nysted wind farms used this configuration [15].

The fourth and fifth option employ what is called the "bunny ear" configuration. In this method, the rotor and two blades are assembled in a bunny ear setup. Finally, one blade is installed separately at the offshore site. The only minor difference lies in the pre-assembly of the tower in the fifth method which is missing in option four. This configuration also demands different cranes to install the bunny ear configuration and is not a popular choice in the installation market shown in figure 3.6f. This option was implemented in North Hoyle, Barrow and Scroby Sands wind farms to name a few [15].

The final concept suggests the complete assembly of the turbine onshore. The assembled turbine is carried on a barge or installation vessel and installed on the foundation. This method requires a heavy lift crane vessel to carry out the installation activity. This option is not actively used in the industry yet due to the complexities of lifting a delicate turbine assembly in offshore conditions. This method was tested in the Hywind pilot park offshore project seen in figure 3.6d [39].

### Software Implementation

Wind turbine installation modeling can be done in many combinations. However, to simplify the process, the three widely used methods are identified and translated into planning templates. The option 2,3 and 5 from figure 3.5 are the selected choices to implement in the software [3]. The wind turbine installation follows the same sequence as shown in figure 3.1. At first installation vessels usually undertake a mobilization process where they are fitted with a purpose built equipment to aid during the building phase. Based on the vessel type and pre-assembly configuration the AP block decides the loadout count for the components. Next, the travel and the installation steps are executed for the desired planning. Wind turbine installation activities demand high elevation crane lift hence the tool extrapolates the wind speeds at those heights to improve modeling accuracy.

## 3.5. Interdependency between Sequences

In the current version of ECN Install while simulating multiple sequences of installation activities, for example, foundation work, array cable installation or wind turbine installation; the user can define a particular start date for every sequence exclusively. Unfortunately, while simulating a multi-sequence case in optimization analysis, the objective function demands to minimize the total project cost which is not possible until the sequences are linked together. To overcome the above limitation a basic sequence-sequence interdependency is implemented. Figure 3.7 below gives a better understanding.

In essence, the end of a step inside the first sequence provides the start date for the next sequence. The exact point of the link in the first sequence is for the decision maker to choose. The user also can decide a fixed number of days delay after the completion of the first sequence. To differentiate between the different interdependency, every sequence is represented with a unique number based on its installation activity. For instance, the foundation installation activity is given a number 1, and the wind turbine installation sequence is specified a number 2. The user is free to fix the exact gap between both the sequences depending on the reference numbers. The unique reference approach is especially advantageous when two different vessels are installing the same component (foundations or turbines). In such cases, the sequences will have the same number, and the automated planning procedure spits the installation activity between the sequences and assigns the same start date to both sequences. This is illustrated in figure 3.8.

As an illustration, two vessels are selected by the optimizer as a combination to install 100 foundations in total. The automated planning will generate two unique sequences for each vessel for installing the foundations. In cases the sequence numbers are the same, each vessel is assigned 50 foundations





(a) Tower section installation (source-Offshore technology)



(b) Single blade installation (source-EDF Energy)



(c) Nacelle installation (source-Jack-up barge)



(d) Complete turbine lift (source-Hywind)



(e) Full rotor lift (Source-Brave Tern)



(f) Bunny ear assembly installation (Source- Seajacks)

Figure 3.6: Pre-assembly Concepts applied in the industry

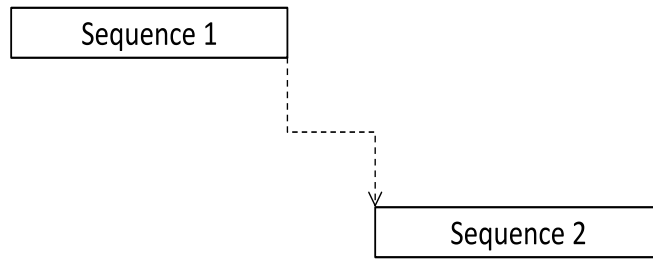


Figure 3.7: Interdependency between different sequences

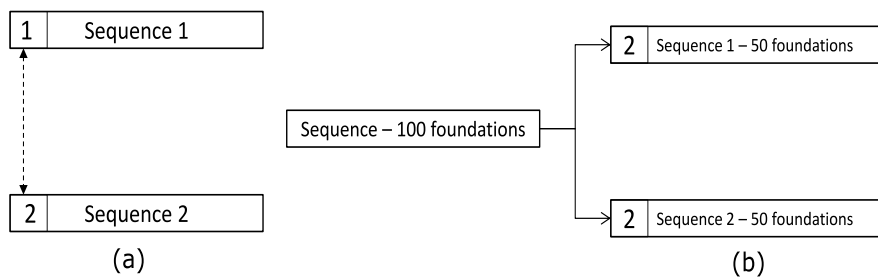


Figure 3.8: Interdependency with multiple vessels

to install separately and are allocated with the same start date for both sequences. In the current research, a simple sequence level interdependency is presented which works efficiently with the optimization approach to account for the total costs and time for the simulated schedules. If complex interdependency between different step level activities are included in later ECN Install releases, the automated planning block will require major modification to adapt to real-time changes in the order of activities.

### 3.6. Automated Planning Integration with Optimizer

The primary automated block is split into two sub-blocks. One of these blocks is dedicated to initializing the planning file called as the IP block (refer to figure 3.9). At this point, the fixed parameters for the installation scheduling case are saved. The fixed database template is subsequently passed inside the optimization loop (marked in red). There is a separate planning block named as AP to handle the changes in the optimization process. AP block automatically creates the planning based on the changes in design variables. The different design variables for the project and the related optimization parameters are discussed in next chapter in more detail. Zooming into the AP block shows the planning module containing two important sub-blocks. The Design variable processing block is developed to translate the optimizer choices into solution space variables of ECN Install tool. The following block creates the new planning based on the optimizer variable changes. Finally, before passing the data into ECN install a feasibility check of design variables is done to filter infeasible choices. For example, a jack-up barge has a 850 tonne crane lift capacity while a heavy lift vessel in the same division has a 1000 tonne crane lift capacity. Assuming the component to install is 900 tonnes the jack-up barge is not possible to use for installation and is filtered out before running in ECN Install. This block is introduced to avoid running additional runs in ECN install and save overall optimization analysis time. Now that the reader has got a grasp on the ancillary blocks for study, the next chapter will dive into the optimizer block.

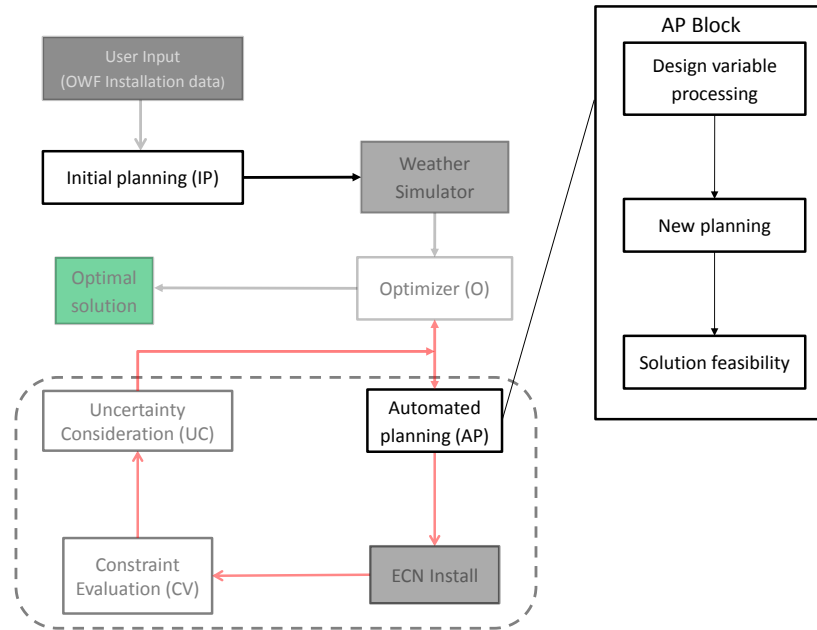


Figure 3.9: AP block in Project architecture

### 3.7. AP Block Verification

Previous sections of the chapter describe the need and the procedure behind working of the AP block in this study. To ensure proper functioning of the AP block for building correct planning, a specific test case is prepared to verify the automated planning implementation in this research. Verification is the task of establishing if the model execution is done appropriately. The verification is done by comparing duration and cost of an installation sequence that is build with AP block and later simulated in *ECN Install old* (v2.1).

Without this step, there is no guarantee about the quality of results obtained from the optimization procedure. A part of an existing wind farm installation project is recreated in *ECN Install old* for the verification process. Since ECN Install does not allow interdependency between different sequences, the verification process is carried out for a single installation sequence only. The table below summarizes the AP block inputs:

Parameter	Remarks
Weather data	5 years of wind [m/s] and significant wave height [m]
Foundation type	Monopile & Transition piece
Number of foundations	90
Vessel type	Jack-up vessel
Start date	30 <sup>th</sup> June, 2015
Harbor	Eemshaven,NL

Table 3.3: Verification sequence inputs

A two step process is followed for the verification procedure. The steps are listed below;

1. Comparison of ECN Install v2.1 and v2.2
2. Comparison of ECN Install v2.2 and AP block method

As explained, a similar planning is created in *ECN Install old* (v2.1) with necessary inputs. Figure 3.10 shows the planning created in *ECN Install old*. It is ensured that the cost parameters of the vessel, equipment, and port are the same for both cases. Even though the AP blocks work inside the



optimization loop, for the verification study, it is tested in a standalone format (see figure 3.11). The AP block inputs are specified similarly to the ones in *ECN Install old*. For example, the vessel type, port, and start dates are inputs to the AP block (in this case only). Whereas, in an optimization run, these are design variables and do not require input by the user.

The planning created in *ECN Install old* is simulated with five years of historical weather data for the wind farm location. Since *ECN Install old* does not include a separate weather simulator to generate synthetic weather data, the weather simulator for the AP block simulation is also switched off. Therefore, while running the installation sequence with the AP block, the same five years of historical weather data is used for simulation.

Foundations (Aeolus)	Sequence	30	30-6-2015	74 days	2
▼ Load monopiles	Group	3			2.1
Load MP	Step	1		3 hour	2.1.1
▼ Load transition piece	Group	3			2.2
Load TP	Step	1		2 hour	2.2.1
▼ Travel to wind farm	Group	1			2.3
Travel to wind farm	Step	1		3.3 hour	2.3.1
▼ Installation MP	Group	3			2.4
Anchor and position vessel	Step	1		1 hour	2.4.1
Jack up	Step	1		0.7 hour	2.4.2
Uplend and position MP	Step	1		1.8 hour	2.4.3
Piling MP	Step	1		4.5 hour	2.4.4
Lift and Stabilize TP	Step	1		1.3 hour	2.4.5
Grout	Step	1		2 hour	2.4.6
Jack down	Step	1		0.7 hour	2.4.7
Travel to next turbine	Step	1		1 hour	2.4.8
▼ Travel back to wind farm	Group	1			2.5
Travel back to harbour	Step	1		3.3 hour	2.5.1

Figure 3.10: Installation planning simulated in ECN Install old (v2.1)

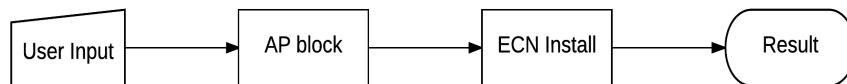


Figure 3.11: Automated planning testing blocks

STEP 1

The total cost and duration results are post-processed from both the methods that are discussed above. The author restates the different ECN install versions introduced earlier in section 2.2 to avoid any confusions while discussing the results in this section. ECN Install is available in 2 versions, *ECN Install old* (v2.1) which exists in both MATLAB platform and with GUI format. The ECN Install (v2.2) used for this research is only available on MATLAB platform. With this clarification, the installation sequence is created in *ECN Install old*. The same installation sequence is then simulated in *ECN Install old* (v2.1 GUI) and ECN Install v2.2 code. Table 3.4 shows the total cost of installing the foundations at the wind farm location. The first column signifies the five different years of historical weather data used for verification purpose. Observing the table, it is clear that there are differences in the results from both the cases. Importantly, the cost calculated from ECN Install (v2.2) is higher than the one from *ECN Install old* (v2.1). This slight discrepancy is found to be in the vessel cost calculation procedure (seen in table 3.4). The reason for this is attributed to the change in the vessel resource calculation module in ECN Install while updating from v2.1 to v2.2.

Simulation year	ECN Install total cost(K€) [v2.1 GUI]	ECN Install total cost(K€) [MATLAB v2.2]	Difference in results (K€)
1	30,884	30,934	50
2	30,809	30,909	100
3	30,670	30,770	100
4	31,425	31,425	0
5	29,461	29,511	50
Simulation year	Vessel total cost(K€) [v2.1]	Vessel total cost(K€) (v2.2)	Difference in results(K€)
1	25,050	25,100	50
2	25,000	25,100	100
3	25,000	25,100	100
4	25,600	25,600	0
5	23,900	23,950	50

Table 3.4: ECN Install old (v2.1) vs ECN Install (2.2) results

## STEP 2

As stated before, the second step followed in the comparison of v2.2 and AP block method. This is done by running the ECN Install v2.1 installation planning file in ECN Install v2.2 MATLAB code and comparing with the AP block results. Table 3.5 below shows the total project cost and duration for all the different weather realizations. The above verification process proves that the AP block is functioning as desired and can be integrated into the optimization study for this dissertation.

Simulation year	ECN Install total cost(K€) [v2.2]	AP total cost(K€) [MATLAB v2.2]	ECN Install duration v.2.2(days)	AP method duration (days)
1	30,934	30,934	95.4	95.4
2	30,909	30,909	94.5	94.5
3	30,770	30,770	94.5	94.5
4	31,425	31,425	96.5	96.5
5	29,511	29,511	88.9	88.9

Table 3.5: Final verification

# 4

## Optimizer Modelling

This chapter covers the optimization analysis for the research where the genetic algorithm (GA) selected in section 2.3.3 is studied more extensively. The chapter begins by explaining the problem which will be subject to optimization. The sub-section discusses uncertainty considerations in installation scheduling study. The chapter concludes by giving an overview of GAs and how they are implemented using the MATLAB optimization toolbox.

### 4.1. Optimization Model Setup

The previous chapters provide the basis for defining the installation problem in the optimizer. Before looking into the GA optimization solver, it is vital to define the exact problem to study. First, let us introduce some basic terms related to optimization study. Typically, any optimization procedure will have an objective function, a set of design variables, and constraints bounding the solution space. The formulation of an optimization problem in a metaheuristic framework entails the variation of select design variables for any solution which is then evaluated in the objective function. The objective function values different combinations of the design variables and the optimizer strives to provide the best solution. A general example is drawn on to differentiate the terms introduced above.

Assuming  $x_1, x_2, x_3$  are design variables; Typical objective function is represented as:

$$\text{Objective Function}(O_{obj}) = \text{Minimum}(x_1, x_2, x_3) \quad (4.1)$$

$$\text{Subject to Constraints} : [g(x) \leq \text{Value}], [h(x) \geq \text{Value}] \quad (4.2)$$

$$\text{Where } (x_1^{\min} < x_1 \leq x_1^{\max}), (x_2^{\min} \leq x_2 < x_2^{\max}), (x_3^{\min} \leq x_3 \leq x_3^{\max}) \quad (4.3)$$

Constrained optimization problems can either have *hard constraints* which require design variables to satisfy the set conditions, or as *soft constraints* which penalize specific variables in the objective function depending on the extent of exceeding the fixed conditions. Optimizer constraints can be expressed in different forms based on the problem under consideration. Referring to above example the design variables  $X_i$  have fixed bounds which influence the solution space domain for the optimizer. A feasible solution is one which satisfies all the constraints and falls inside the solution bound space. Whereas, an optimal solution is the best choice for the optimization problem, which is reached when design variables meet all the constraints and attain a maximum or minimum objective value depending on the final goal. Based on this synopsis we can learn some terms used to describe genetic algorithm in the MATLAB toolbox to follow in section 4.3. Before moving to that this section describes the design variables, objective function, and constraints for the installation scheduling problem.

### 4.1.1. Installation Problem Design Variables

Design variables like the ones discussed in section 4.1 are parameters which will be varied by the optimizer to reach an optimal solution for installation scheduling problem. Firstly, the design variables to evaluate in the installation optimization study are listed below:

- Project start date
- Vessel Division
- Vessel type (per vessel division)
- Number of vessels
- Harbor
- Wind turbine (WT) transport pre-assembly combination

Section 1.1 highlights an essential fact about the need for finishing the installation activities within the fixed time limit. Hence, it is imperative to know about the best starting time for the project. With this reasoning, the project start date is fixed as a design variable to study. The importance of the installation vessel is already reported in section 3.3. Thus, the vessel division, vessel type and the number of vessels are added as design variable choices for study. Additionally, since the port capabilities, port weather, and distance makes a considerable difference in project duration, it is interesting to analyze this fact in the optimization procedure (3.3). Finally, based on the explanation in section 3.4, the different onshore pre-assembly options result in different vessel types, installation duration and eventually translate into varying project costs. Thus, this completes the final category of design variables for this dissertation. The above list puts together the different categories of optimizer variables, where there is one start date variable and the other variables are duplicated depending on the installation activity studied. The table 4.1 reiterates the bounds for the design variables discussed above.

Design Parameter	Lower bound	Upper bound	Remarks
Start Date	1	35	Limited to 35 options due to computation time limitations
Vessel Division	1	3	Refer section 3.3.1
Vessel Type	1	2 or 3	Depends on installation activity , Refer section 3.3.1
Number of vessels	1	2	Limited to maximum 2 vessels based on industry feedback
Harbor	1	[2 to 15]	Depends on the users choice for different ports
WT transport pre-assembly	1	3	Separate components, full rotor assembly, bunny ear setup

Table 4.1: Design variable bounds

### 4.1.2. Objective Function

Once the design variables are selected, the next logical step requires defining the objective function of the optimizer to evaluate for every individual combination. The total cost incurred during any OWF installation work is one of the most critical parameters to investigate. It is also a key driver for decisions taken during wind farm installation phase [12]. Ultimately, the contractors or project developers intend to minimize the installation costs and maximize resource utilization in a project. Therefore, the optimization procedure is built to minimize the mean installation cost ( $y$ ) for given combination of design variables  $x$ , as shown in equation 4.4. The terms  $i$  and  $nsim$  are related to unique weather realizations which are explained in section 4.2.

$$Y_{xopt} = \arg \min_x (y) \quad (4.4)$$

Referring to figure 2.2 in chapter 2, the optimizer function can be compared to the objective function of this project. It includes all the important blocks to calculate an objective function value which is finally passed to the optimizer.

### 4.1.3. Constraints

Two types of constraints are used in the optimizer model for this study. The first kind is in the form of *lower* and *upper* bounds for different design variables listed in table 4.1 which are already discussed in section 4.1. Looking back at section 1.2 the thesis objective entails for minimizing the installation costs while keeping target date as a priority. This project target end date check is applied in the form of a soft constraint which influences the objective function value. The following section covers the procedure to incorporate the target end date constraint in the optimization model.

#### End Date Penalty Function

This subsection is dedicated to understanding the various types of penalty functions and the procedure applied to implement them. The primary purpose of a penalty is aimed at directing the optimizer away from poor results. Often OWF installation contracts outline distinct penalty procedures depending on the project. The figure 4.1 below shows a few penalty functions that can be implemented for OWF installation projects. The SD term indicates the start date for a project and TED represents the target end date set for the same. Based on communication with industry experts, a few different penalty methods are listed below:

*Energy production loss penalty:* This function calculates the penalty with loss of wind turbine output (per day) due to excess delay. The final computed loss is added to the total installation costs. On the other hand, this function can be advantageous if the project is completed before the target date. Contrary to the penalty case, if any project finishes before the target period, a profit value is added to the installation costs, thereby reducing the total expenditures. This type of function is shown in figure 4.1 with a green shade.

*Linearly increasing penalty:* For any dates exceeding the target time a linearly increasing penalty is computed. Example, the dates exceeding close to the target end date get a smaller penalty and dates further away from the target get a more substantial penalization which is obvious from the figure 4.1. This type of penalty is shown in orange.

*Step function penalty:* A step function applies a penalty value for any date exceeding the target value. Exceeding by a day or 10 days will have the same influence on the penalty value. This type of function is shown in red (figure 4.1).

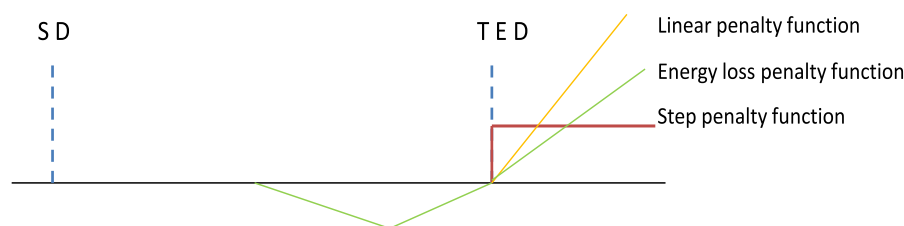


Figure 4.1: Different end date exceeding penalty functions

This research considers a step function to demonstrate the penalty function concept. The 'Constraint Evaluation block' (CE) in figure 2.2 houses this penalty function. Consequently, it is important to understand the procedure followed to set the target end date (TED) and penalty values in this study. The TED and penalty values are variable for every project and is decided by the decision maker (e.g based on the contract). Since, no specified target dates and penalty values were available for current thesis work a simple procedure is followed to set the necessary TED and penalty value for a planning before simulating the optimization procedure.

An example is shown to understand better about setting the target end date. Let us assume a project for installing monopiles is planned for simulation. The start date variable bounds are set from 1st April until end of August. Here, the last possible start date (upper bound) of August is used to check the total duration required for completing the installation activities assuming best weather conditions (no weather delays). Next, a 10% margin over this duration is added and finally translated into a target end date for given installation plan (refer eq. 4.5). The 10% margin is the usual consideration taken for weather uncertainty (inputs from industry professionals) but it is ultimately up to the decision maker to specify a different margin or override the above method and set the target value manually.

$$\text{Target End Date (TED)} = SD + [10\% * \sum d], \quad (4.5)$$

*where d represents (Installation activity duration)*

The penalty value is variable per installation project and can range from one to more than 10% of the installation contracted costs (information from industry experts). Initially, few test instances for single sequence and complete wind farm installation projects are simulated. Finally, based on observing the approximate installation costs obtained for the above test instances a penalty value of 0.5 M€ for single sequence cases and 5 M€ for simulating complete wind farm project are fixed.

## 4.2. Uncertainty Consideration

Uncertainty analysis is a technique to measure the amount of certainty of a particular result. Uncertainty propagation calculates the uncertainty on a particular derived quantity depending on the uncertainties in the input data. In most cases, an input quantity is used in some form to calculate the final derived result in the analysis. As introduced earlier in section 1.1 and 2.1, weather is a critical stochastic variable to investigate in OWF installation scheduling problems. Weather realizations present a certain level of randomness which directly affect the final planning necessary for OWF installation procedure. Imperfect estimation of uncertainties can result in severely under-budgeting installation activities. The uncertainty study is split into two sections: one part looking at the inputs; and the other to examine the output quantity.

### 4.2.1. Weather Simulation Requirements

The start of optimization analysis requires specifying the number of different weather instances to simulate in the weather simulator. Based on this, different weather realizations are fixed, and the optimization procedure is run for the generated weather scenarios (from the weather simulator). For example, if the number of weather simulations is set to 100, the weather simulator will train for a specified period of historical weather data (wind, significant wave height) and create 100 different weather realizations with the same statistical properties. These 100 cases are passed into the optimizer loop (refer to figure 2.2). For every individual planning created in AP block, ECN Install computes the deterministic results for 100 different weather cases. Ideally, the number of weather simulations required should be chosen based on the installation scenario. The influence of weather can differ depending on the sequence of installation activities as the the resources selected for OWF installation procedure have varying weather restrictions. To account for the uncertainty in weather appropriately large number of weather instances (more than 50) are necessary. Simulating more weather realizations helps account for varied weather conditions for the same project which finally minimizes any unforeseen situations due to weather. Table 4.2 below summarizes the approximate time required to run an optimization procedure for a complete wind farm installation scenario (export cable and high voltage station installation work excluded).

The reader can refer to figure 2.2 to understand the evaluation process better. In table 4.2, the first column indicates the number of weather realizations generated in the weather simulator. The next column shows the time taken to finish a single evaluation in ECN Install. For example, let us assume 50 different weather realizations are generated for a installation logistics problem. A single evaluation in ECN Install will simulate the installation schedule for 50 different weather realizations.

No. of weather simulations	Single ECN Install evaluation (s)	Total unique evaluations	Total time (hr)
200	916	1500	34.8
150	747	1500	28.8
100	490	1500	20.1
70	335	1500	14.6
50	233	1500	11.1

Table 4.2: Optimization time vs Number of weather simulations

The time taken to simulate these 50 weather scenarios in ECN Install is 233 seconds (See table). This number increases linearly with increasing number of weather simulations, as installation results need to be calculated for more weather realizations. In the new architecture ECN Install is integrated with an optimization procedure. Hence, every individual combination of design variables translate to new installation schedule which is evaluated in ECN Install (one unique evaluation). Test runs reveal that the total number of unique evaluations of ECN Install inside the optimization process never exceed 1500 counts. Hence, this value is taken as a benchmark for calculating the total optimization analysis time. The last column finally displays the total optimization time in hours assuming all optimization computations are done with 12 parallel cores on ECN cluster. In this research, the weather simulations are capped at 100 different realizations due to limited availability of ECN cluster. The next section gives a run through of the process followed for uncertainty consideration at ECN Install output.

#### 4.2.2. ECN Install Output Analysis

The previous section elucidates on an exact number of weather realizations run in ECN Install. Looking back at figure 2.2, the uncertainty consideration block indicated in the figure is covered here. Figure 4.2 below shows the process flow of output from ECN Install to the optimizer.

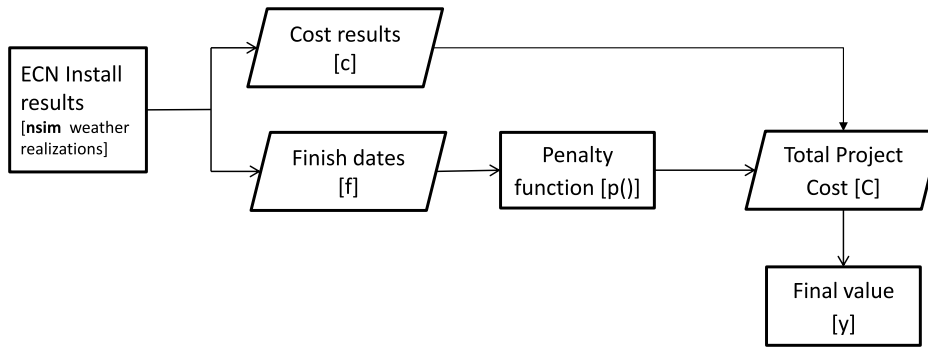


Figure 4.2: ECN Install output uncertainty handling

$$C_i = [c_i + p(f_i)] \quad (4.6)$$

$$y = \frac{1}{nsim} \sum_{i=1}^{nsim} C_i \quad (4.7)$$

Based on the reasoning from previous section, we see that ECN Install provides results for 100 different weather realizations. This number of weather realizations is represented by  $nsim$  term in the objective function (equation 4.4). Let us understand the final value calculation process with the help of equations 4.6 and 4.7. The subscript  $i$  in the above equations represent the unique weather simulation number. First, the results for total installation costs and end dates required for the study are extracted from ECN Install output file. Next, the end dates  $f$  are passed through a function  $p()$  to evaluate the end date exceedance (see section 4.1.3). Once this is complete, a total cost  $C$  is obtained for all the individual

100 cases. All the finish dates exceeding the target date are penalized, and a penalty cost is added with the installation cost results. Finally, the two parameters are converted into one variable with units of cost. It is necessary to find one value as the optimizer takes a single value for evaluating the quality of the solution. Ideally, a single value solution is not preferred in problems dealing with uncertainty. Due to the correlation between cost and finish dates and the requisites of the optimizer, the above approach is a practical method to account for uncertainty.

### 4.3. Genetic Algorithm

Let us understand the theory about the GA optimization procedure. After gaining some insight into the GA solver, the reasons for implementing a GA integer solver over the default one is presented to the reader.

GAs are a type of metaheuristic search optimization method based on Darwin's principle of natural selection and evolution concepts. The GA uses a version of the evolutionary method for converging to a final solution. Every GA works with a population of "chromosomes". These represent a chain of different design variables, called "genes" in GA terminology (refer to figure 4.3). Every chromosome embodies a solution to the problem under study with a fitness value. This fitness value quantifies the quality of the solution for any given problem.

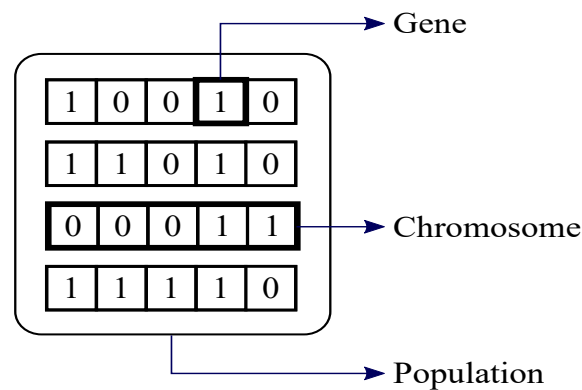


Figure 4.3: GA terminology

The algorithm was invented by Dr John Holland in the 1970s to find solutions to computationally difficult problems [40]. The modular structure of the algorithm allowed it to be implemented in a wide range of engineering applications. Even though evolutionary strategies (ES's) matured independent of GAs, both had several aspects in common. The primary difference between both the approaches is the way the solution evolves to an optimal choice. Unlike GAs, the ES usually does not operate with a population of chromosomes (individuals) but in its place make all the mutations on a single individual [40]. Both the methods converge to an optimal solution steered purely by the fitness function value. While both these fields had an autonomous beginning, they have grown together over time and eventually resulting in GAs being grouped under the evolutionary computation domain. The next section outlines the important terminologies used in the GA optimization field.

#### 4.3.1. Genetic Algorithm Terminology

This section describes a few essential terms for the reader to understand the GA solver.

##### Fitness function

The objective function is also known as the *fitness* function in GA optimizer. The MATLAB toolbox attempts to find the minimum value for any given combination of design variables (chromosome) in the function. The final value indicated by  $\mathbf{y}$  in figure 4.2 is the fitness value passed to the GA.



### Individuals, Population and Generations

*Individuals* are possible solutions to the problem represented as strings of design variables and referred to as chromosomes in figure 4.3. For example, if a problem comprises of 5 variables, then an individual will be a collection of these five variables. A *population* is an array of different individuals. For example, if the *population* size of a problem is 20 and the number of variables is 5, it is represented by a 20-by-5 matrix in the GA toolbox. The same combination of individuals can often recur more than once in a *population*. At every iteration, the GA executes a series of operators on the current population and generates a new population for evaluation. These specific operators are discussed shortly. Every consecutive population is termed as a *generation*. For instance, the population of a 20-by-5 matrix will undergo a sequence of computations, and a all new population of 20-by-5 will be generated for the process to iterate until an optimal solution is reached. The individuals in the current population are referred to as *parents* which are used to create the individuals in the next generation of a population, called *children*.

### Selection

A GA uses a fitness score to measure the quality of solutions for all individuals in a given population. The selection function picks parents for the next generation evaluation using the fitness value as a guide. Higher fitness scores have a better possibility of selection compared to lower scores. The highest score signifies the minimum fitness value for the design variables. Usually, the algorithm is more liable to select parents with better fitness scores. The roulette wheel or tournament methods are popular methods for selecting the parents. The readers can refer to the paper by Alabsi and Naoum [41] for learning more about different selection techniques.

### Recombination

The recombination operators work after the selection process. This is where the current population undergoes genetic recombination to form the new population. The plan here is to replicate the mixing of genetic material as seen in natural organisms. The recombination consists of two main components, the crossover and mutation operators [40].

The crossover operator characterizes the mixing of genes from two selected parents (chromosomes) to generate two new children. For better understanding, an example of single point crossover operation with two parents is shown in figure 4.4. The MATLAB GA optimization toolbox provides several crossover methods, and interested readers can refer to [42].

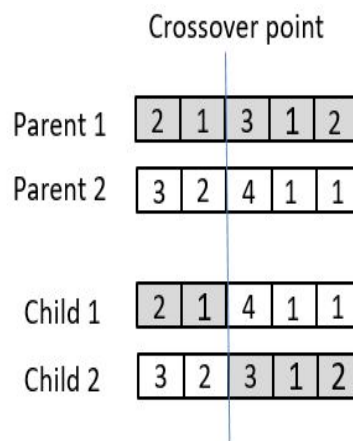


Figure 4.4: single point crossover operation

The GA incorporates an operator to overcome the premature convergence problem witnessed in many optimization techniques. This is often encountered when too many highly fit individuals fall in the parent pool very early in the simulation process, generating similar children for subsequent generations. The

crossover operator is not capable of generating offspring very different from parents as the genetic information passed over is dependent on the parents. A mutation operator is meant to solve this limitation in any evolutionary process. The operator makes random flips in one or more genes of the chromosome (individual) to maintain diversity in the population [40]. The figure 4.5 shows a sample mutation process. Refer to [42] for more options provided in the MATLAB GA toolbox.

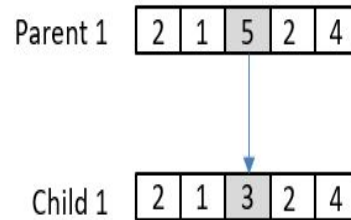


Figure 4.5: Mutation operation

There are numerous evolutionary schemes used in GA which determine the degree to which individuals in the current population are allowed to persist unchanged into the replacing population. The *replacement with elitism* is an extensively used scheme for solving optimization problems. Almost all the individuals are replaced, except the top quality ones which are preserved for the next generation. This allows the best solutions for the current generation to remain in the ones to follow, without being lost in the evolutionary process.

The genetic algorithm in the MATLAB toolbox generates three types of children for every successor generation. The figure 4.6 summarizes all the different recombination operations and the different individuals generated per generation. The next section covers the working of genetic algorithm based on the different components defined in this section.

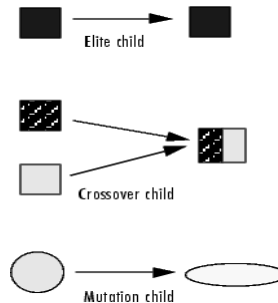


Figure 4.6: Different offspring for new population [4]

### 4.3.2. Genetic Algorithm Operation

The reader can refer to figure 4.7 to visualize the complete GA solver process. The algorithm begins with a randomly generated population of individuals. The initial population is passed into the fitness function where the current individuals of the population are ranked based on the fitness values. These fitness values are eventually passed to the selection operator to pick the parents for the next generation. The rank method is a default option where a fitness value is ranked from best to worst [43]. The population is then passed through the selection and recombination procedure to generate the population for the next generation. The selection operator is applied to pick the parents (individuals) for breeding the child chromosomes. At this point the elite individuals are chosen and passed to the next generation unchanged. The crossover and mutation operators are recombination procedures for creating the successor population (next generation) with the remaining members of the population. The breeding of new populations is iterated, where series of successive generations evolve towards a globally optimal

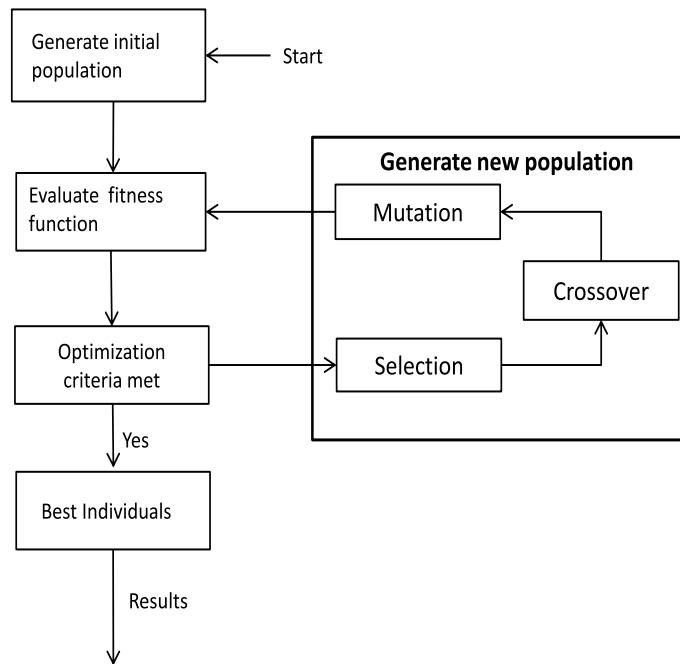


Figure 4.7: GA work flow diagram

solution [4]. The average fitness score moves towards a higher score until some stopping criterion for the algorithm is reached which will be covered in the next part of this section.

The above algorithm flow is represented by the optimizer block indicated in figure 2.2. For every individual created, the algorithm passes a vector of design variables to the objective function (optimizer function) where this data is converted into realistic variables in AP block (see chapter 3). The solution post-processed from ECN Install is passed back to the optimizer block as the fitness value. Hence, this completes the new architecture for this study as shown in figure 2.2. The GA terminates and outputs the best combination of the design variables indicated by the solution block (figure 2.2). The different methods to terminate the solver are discussed in the following section.

### Stopping Criterion

The genetic algorithm in MATLAB optimization toolbox provides a number of options for stopping the solving process. Various possibilities are listed below:

- **Maximum Generations:** The algorithm stops when the maximum number of generations during the simulation process equals the limit specified for maximum generations. For instance, if the generations limit is set to 100 the algorithm will terminate after reaching 100 generations.
- **Stall Generations:** The average relative change in the fitness value over certain number of preset generations is less than the stated tolerance value. For example, the stall generation value is set to 50 and the tolerance value to  $1e-03$ , if the fitness value during successive generations remains within the tolerance limit for 50 consecutive generations, the algorithm terminates.
- **Time Limit:** the GA stops the solution if the elapsed computation time (seconds) equals the time limit defined by the user.
- **Stall Time Limit:** similar to the previous case, the algorithm terminates the solution if there is no improvement in the fitness value during the stall time limit interval.
- **Fitness Limit:** The user is provided with an option to define the desired fitness value for the problem. The algorithm stops the simulation if the defined value in the current population is better than or equal to the fitness limit term.

The algorithm discontinues the simulation if any one of the above defined conditions are met. The user can define specific stopping criteria based on the problem type and instruct the optimizer to ignore the default limits.

### 4.3.3. MATLAB GA Integer Solver

The default MATLAB GA solver utilizes a continuous variable range for the optimization process. Sadly, the design variables for our problem cannot be implemented in the optimization solver in its default setup. Section 4.1 covers the different design variables used in the research work to confirm the above point. Notably, all the design variables in this study are discrete. This requires the optimizer to evaluate only integer choices and exclude all other cases. Fortunately, the GA solver provides the option of integer solver for such design variables. This part encapsulates the modifications in the GA integer solver over the default toolbox algorithm.

- Double(natural numbers) vector population type as referred in MATLAB toolbox is used over the default bit string(binary numbers) option. The difference between double vector representation and bit string representation is shown in figure 4.8. The optimizer solves faster with this restriction as the integer bounds are managed with ease when the individuals in population are also represented in similar format.
- The solver utilizes the binary tournament choice as the option in the selection operator step. In this method two parents are selected randomly from the current generation and the one with superior score is picked as the parent.
- To enforce variables to be integers the algorithm uses a distinctive creation, crossover and mutation function. For more details about the functions refer to Deep et al [44].
- Unlike the default case, where the fitness value is used as a guide for finding the best option, a penalty function is used as reference within the integer solver. The penalty function is developed to restrict the optimizer to select only integer variable solutions in the algorithm. It is combined with the binary tournament selection function to pick individuals for later generations. If the individual is feasible, the penalty value is used as the fitness value. Else the member is ranked last among the in-feasible individuals in the population and discarded.

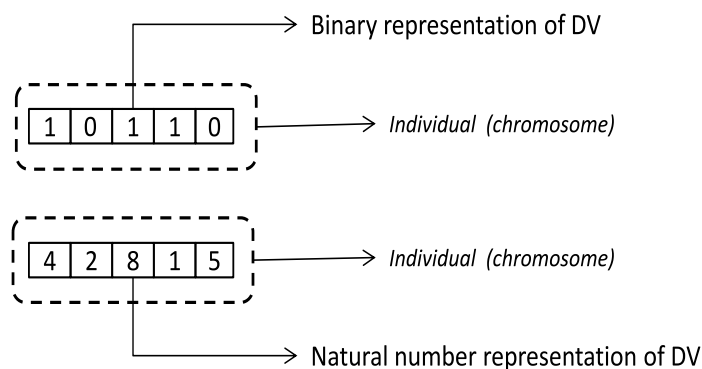


Figure 4.8: Design variable (DV) representation in GA population

Even though the integer GA solver demands using fixed selection and recombination operators the advantages outweigh the limitations. The manual implementation of integer constraining the variables is time-consuming and susceptible to random modeling error. Hence, it makes a logical argument to use the in-built solver provided in MATLAB toolbox.

## 4.4. GA Parameter Tuning

While the genetic algorithm is effective in managing the OWF installation scheduling problem, the GA's main control parameters need to be tuned to achieve paramount performance for installation problems. The selection of the parameters is a trade-off between quick convergence while preserving the exploratory control of the algorithm (avoid premature convergence). The population size, crossover fraction, and elite count are selected as important control parameters to study in this thesis [45] [46]. Let us recap all the above GA parameters with an example (refer to section 4.3.1). During the creation of new individuals for successor generation is underway, population size is the number of individuals in a given generation of GA. Elite count refers to individuals that carry over to subsequent generations without any recombination operations. The crossover fraction determines the fraction of the population that undergo crossover and mutation operations. To summarize, if we have a population size of 20, elite count of 2 and crossover fraction of 0.8; 2 individuals go unchanged to the next generation,  $0.8 \times 18$  is rounded to 14 by the solver to get the crossover individuals, and the remaining 4 are mutation individuals.

Table 4.3 summarizes the different parameters tuned for the GA and the respective selected ranges of values indicated inside '[]'. In the table *nvars* signifies the number of design variables. The choice for selecting the options for the tuning parameters is considered from multiple sources [46][47][48].

Control parameter	Combinations	Values
Population size	5 x (nvars), 10 x (nvars)	[25,50]
Elite count	5% (Population size), 10% (Population size)	[(1,2), (2,5)]
Crossover fraction	[0.7, 0.8, 0.9]	[0.7,0.8,0.9]

Table 4.3: Tuning parameters for GA

Table 4.2 shows the approximate time for the optimizer to converge to an optimal solution. Even while computing for single sequence installation problems the minimum convergence time is 2 hours or more. Hence, it is not practical to use the actual installation problem to tune the parameters. One of the solutions is defining an abstract problem resembling the actual optimization problem while providing quick results. The tuning process is done with a predefined problem with a known solution to understand the effect of changes in the different control parameters. The next section describes the abstract problem in detail.

### 4.4.1. Abstract Problem

The installation scheduling problem can be compared to the combinatorial optimization problem. The combinatorial optimization topic relates to obtaining an optimal entity from a finite set of entities [49]. In most problems in this category, it is not realistic to run an exhaustive search. Some popular problems in this category are the *assignment problem*, *traveling salesman problem* and *knapsack problem* to name a few.

The **knapsack problem** or **rucksack problem** resembles the installation problem for this study. It is defined as follows: For a given set of object types, each with a cost (value) and a weight, ascertain the number of each object type to add in the bag with the aim of maximizing the total cost and constraining the weight to less than or equal to a certain limit [50]. Let us understand the problem with a simple example.

Imagine a plan for a hiking trip; and therefore, you are interested in packing a knapsack with necessary objects for the trip. Let us assume there are  $n$  discrete object types considered essential for the knapsack; this could include a bottle, fruit, food, emergency light, etc. Every object type is given a set of two traits, a cost (value) and weight (or volume) parameter to rank the importance accompanying with the unit of a particular object type. Knowing that the knapsack has limited capacity, the problem

requires filling the sack with the optimal combination of specific object types which maximizes the cost value. The above example describes the simple knapsack problem case, let us see how this can be modified to represent the problem in this dissertation.

The 0/1 knapsack problem is a subset of the knapsack problem category. It differentiates from the usual knapsack problem regarding the number of objects selected per type. In the 0/1 knapsack problem case the number of object types are restricted to 1 or 0. The 0/1 knapsack problem is slightly customized for building the abstract problem for tuning the optimizer parameters. The customization is done for two aspects. First, in the default 0/1 knapsack problem one or nil option is selected per object type, whereas, in our problem one option per object type must be always picked. So, looking back at the above example, the default 0/1 knapsack problem may or may not include a bottle from the bottle type object for the hiking trip. But, for our problem it is a must that one bottle is picked for the trip. Secondly, the cost maximization problem for the default 0/1 knapsack problem is changed to a minimization problem for our case.

Let us assume set of  $k_j$  object types, with a weight  $w_j$  and cost value  $v_j$ , constrained by maximum weight capacity  $W$  for the knapsack problem.  $j$  represents the data for every unique object per type. Refer to figure 4.9 to visualize the problem representation in GA showing the different design variables.

$$y_{knapsack} = \text{Minimize} \sum_{j=1}^{j=5} v_j \quad (4.8)$$

$$\text{Subject to : } \sum_{j=1}^{j=5} w_j \leq W \quad (4.9)$$

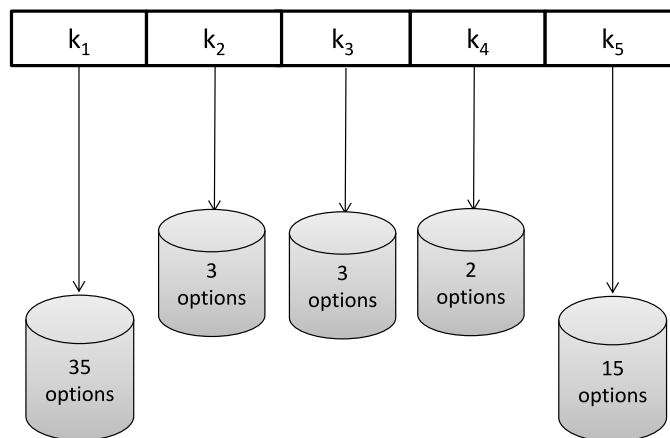


Figure 4.9: Knapsack problem representation in GA

The equations 4.8 and 4.9 constitute the objective and constraint for the knapsack problem. The following steps describe the problem implementation in GA solver:

- Step 1: A knapsack of fixed capacity considered for the abstract problem. Represent the design variables of a single sequence installation activity as objects in the abstract problem.
- Step 2: Next the number of object types for the knapsack is fixed. A Single sequence installation problem at max incorporates five design variables in this study. Hence, in GA double (natural numbers) string type with five variables is created for the abstract problem.
- Step 3: Next, a list of options for the different object types are created. The options per object type can be visualized in figure 4.9.

Installation problem design variable	Knapsack problem variable	Design variable bounds (options per type)
Start Date	$k_1$	Lower bound: 1 Upper bound: 35
Vessel division	$k_2$	Lower bound: 1 Upper bound: 3
Vessel type	$k_3$	Lower bound: 1 Upper bound: 3
Vessel number	$k_4$	Lower bound: 1 Upper bound: 2
Harbor	$k_5$	Lower bound: 1 Upper bound: 15

Table 4.4: Problem similarity

Step 4: Data storage created to include the various weights and costs values for different options per object type.

Step 5: A soft constraint check constructed on the total weight of the knapsack. If the weight exceeds the limit, a penalty value is added to the objective value.

Step 6: Finally, test problem run to obtain an optimal combination of design variables. The exact solution is known for verification of problem.

The design variable options are selected based on the variables from the installation problem as seen in table 4.4. The soft constraint for weight capacity is aimed at representing the target end date penalty function (in an installation scheduling). The options list for every object type is set with values to replicate multiple feasible solutions but only one optimal choice during the optimization procedure. The best option in every object type is given a cost value of 10 and a weight of 4. Thus, the optimal choice for the abstract problem yields a total cost value of 50 and a total weight of 20 for the five objects in the knapsack.

#### 4.4.2. Control Parameter Testing

A total of 12 different combinations of GA parameters are tested using the abstract problem. Table 4.5 shows the results obtained for the different parameter combinations. The first column shows the different combinations. Results in table 4.5 are the average of running the optimization procedure for each tuning parameter combination ten times, every time with different initial starting search points to eliminate the effect of initial randomness in the finally selected solutions [45].

S.no	Combination	Best objective value	Average objective value	Worst objective value	Run time(s)	Number of generations	Total function calls
1	[25,1,0.9]	50.011	51.083	66.974	2.14	66	1676
2	[25,1,0.7]	50.018	55.423	69.041	2.09	66.2	1681
3	[25,1,0.8]	50.011	52.884	67.301	2.17	65.2	1669
4	[25,2,0.9]	50.010	50.961	63.581	1.92	70.9	1798
5	[25,2,0.7]	50.013	53.840	68.339	1.84	59.8	1521
6	[25,2,0.8]	50.007	52.553	68.810	1.87	59.2	1506
7	[50,2,0.9]	50	51.046	66.068	2.54	63.3	3216
8	[50,2,0.7]	50	54.353	69.483	2.40	60.2	3061
9	[50,2,0.8]	50	52.510	68.171	2.50	62.6	3181
<b>10</b>	<b>[50,5,0.9]</b>	<b>50</b>	<b>51.069</b>	<b>67.364</b>	<b>2.34</b>	<b>58.5</b>	<b>2976</b>
11	[50,5,0.7]	50	53.740	69.051	2.47	59.9	3046
12	[50,5,0.8]	50	52.243	68.430	2.61	61.9	3146

Table 4.5: Parameter tuning results

The key columns to consider for selecting a particular GA parameter combination would be: best objective value, number of generations and total function calls. The population size of 25 was unable to find the global optimal value of 50. This is seen in best objective value column of table 4.5. On the other hand, the population size of 50 was able to find the global value for every iteration of the run.

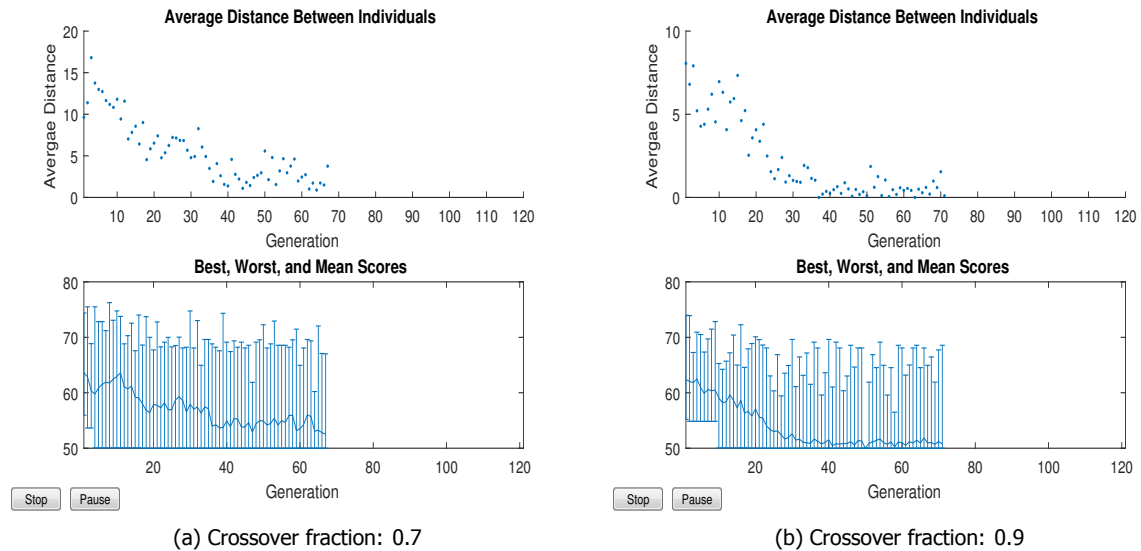


Figure 4.10: Influence of crossover fraction

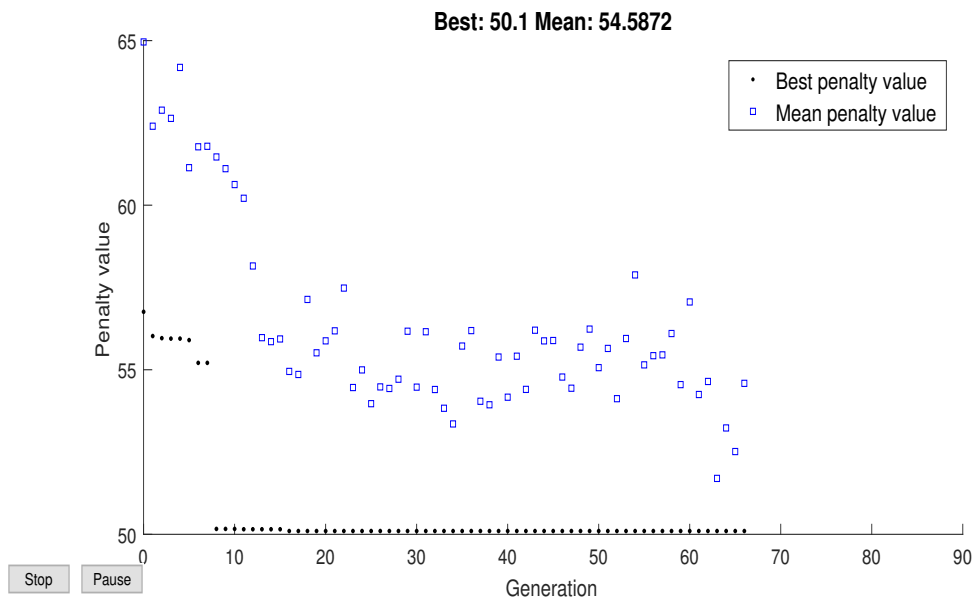
Likewise, when we compare the different crossover fractions, the crossover fraction of 0.7 and small population size produced the worst results overall. Figure 4.10 shows the diversity of individuals in population for combinations 5 and 6 from table 4.5. Usually, the diversity is high at the beginning of the optimization procedure and over few generations the individuals get closer to each other in the population. A population with high diversity has large average distance and the ones with low diversity have smaller average distance. It is clear from the graphs that the individuals are much closer in case of 0.9 fractions, while more dispersed for the 0.7 fraction. This is due to the higher mutation rate in 0.7 crossover fraction and thus also resulting in a higher mean and worst scores per generation. With 0.9 crossover fraction, the mutation individuals are low, hence the generation mean and worst scores are also lower. Similar trends as for a 0.9 crossover fraction were observed with 0.8 fraction results.

The variation due to the elite count was more profound in the low population cases but not noticeable in higher population cases. The combinations two and seven are used to study the difference with the elite count in the results. With a higher elite count, increased number of high-quality individuals could be retained for the subsequent generations and this allows to find the global optimal point more often. Figure 4.11 shows the case when the elite count is low with a small population and high mutation rate the GA solver seldom found the global optimal value and terminated the solver with a value of 50.1.

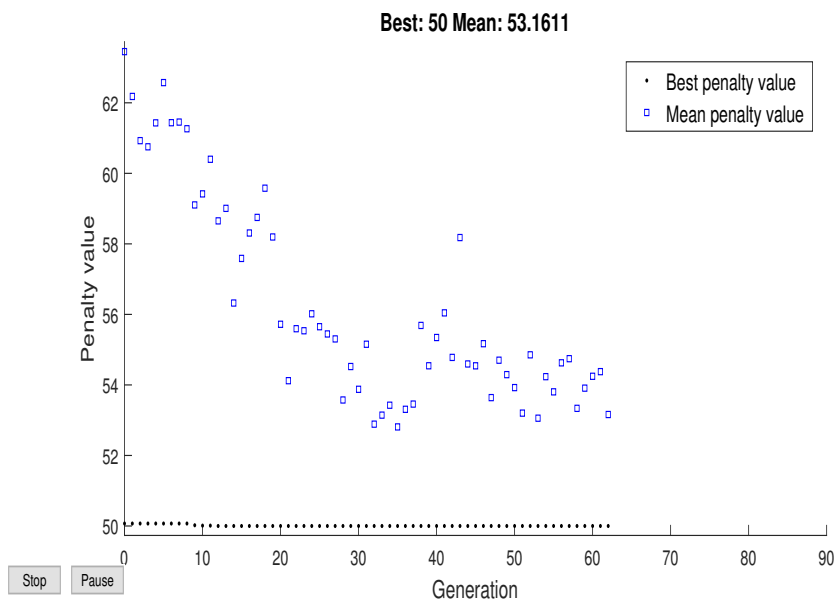
#### 4.4.3. Conclusion

Finally, based on this small study the combination 10 highlighted in table 4.5 is selected as the best control parameter combination for this study. This combination always managed to find the global optimal point. It required the least number of generations to converge and also has the lowest objective function evaluations when compared with large population combinations. Since the control parameter testing was only conducted for a single sequence case, the parameter values for multiple sequences were scaled based on reasonable engineering guess (discussed in section 5.4).





(a) Elite count: 5% of population size



(b) Elite count: 10% of population size

Figure 4.11: Influence of elite count



# 5

## Case Study

This chapter describes the case studies that were performed with the installation optimization set-up towards answering the thesis objective defined in section 1.2. The first section introduces the location used for simulating the case studies. A brief overview of the OWF market of Europe is given to the reader. This later allows formulating the various cases for this study. A set of 2 case studies are run to investigate the working of the optimizer with ECN Install in solving installation scheduling problems. The first case examines the optimizer choices based on variable input scenarios. This case comprises of 3 sets of single sequence activities to understand the different design variable choices and significance of target end date in the projects. The second case is extended for a more complex problem, where a complete wind farm installation is studied. It covers multiple sequence activities and its influence on the optimizer decisions.

### 5.1. OWF location

The case studies for this thesis study are investigated for the Borssele Wind Farm Zone (BWFZ) [5]. It is located in the southern part of the Dutch Exclusive Economic Zone (EEZ), shown in figure 5.1 below.

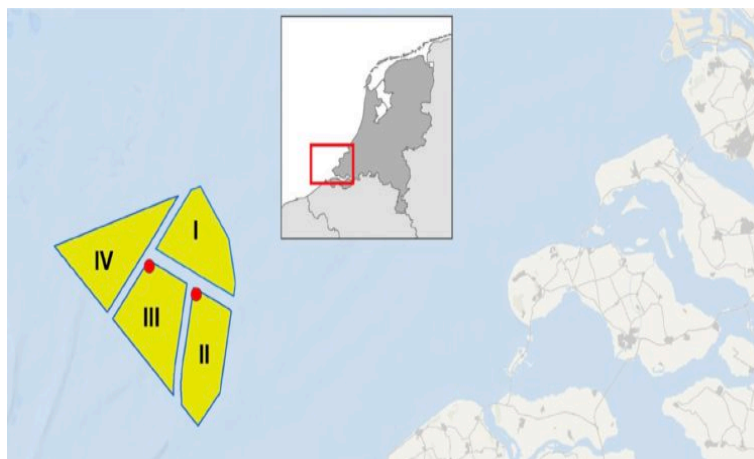


Figure 5.1: Borssele wind farm zone [5]

20 years of historical wind and wave data for the wind farm zone is collected and utilized as a fixed input for all the case studies. BWFZ is split into four wind farms which will account for a total capacity of 1400 MW. This location is used for constructing hypothetical wind farm installation scenarios to highlight the optimizer working with ECN Install. The location coordinates for wind farm zone I and II are acquired and set for all case studies in this chapter [51].

## 5.2. Market Overview

Section 3.4 described the essential sequences in an OWF building process. The installation of foundations is selected as the activity to model for the optimization analysis, since it helps look at the majority of design variables types in this research. Before looking into the case inputs, let us first understand the wind turbine market trends. Wind turbines have grown at a steady pace in the past five years, where the average wind turbine size in 2012 was less than 3MW, and by early 2017 it is already 4.8 MW [52]. Table 5.1 below summarizes various projects (European region) in the pipeline to be grid-connected within the next five years.

Country	Wind farm name	Number of Turbines	Foundation type	Turbine rated power	Farm size (MW)
Germany	Nordsee one	54	Monopile	Senvion 6.2 MW	334.8
	Arkona	60	Monopile	Siemens 6 MW	360
	Borkum Riffgrund 2	56	Monopile	Vestas 8 MW	448
	Merkur	66	Monopile	GE 6 MW	396
	Nordergrunde	18	Monopile	Senvion 6.2 MW	111.6
	Wikinger	70	Jacket	Adwen 5 MW	350
Netherlands	Borssele 1 & 2	94	Monopile	Siemens 8 MW	<b>752</b>
	Borssele 3 & 4	93	Monopile	Vestas 8 MW	<b>744</b>
UK	Dudgeon	67	Monopile	Siemens 6 MW	402
	Race Bank	91	Monopile	Siemens 6 MW	<b>546</b>
	Beatrice	84	Jacket	Siemens 7 MW	<b>588</b>
	Galloper	56	Monopile	Siemens 6 MW	336
	Rampion	116	Monopile	Vestas 3.5 MW	406
	Walney Extension	87	Monopile	Vestas 8 MW	<b>696</b>
Denmark	Kriegers Flack	70	Monopile/Jacket	8 MW	<b>560</b>
Belgium	Rentel	42	Monopile	Siemens 7 MW	294

Table 5.1: New projects in Europe region [6]

Few interesting trends can be ascertained from table 5.1. Firstly, the wind farm sizes are reducing below 100 turbines compared to farms of 2016 and prior [53]. This can be linked to the substantial increase in the individual turbine power ratings. Next, while looking at the foundation type proposed for the different projects, monopiles continue to dominate the market. Lastly, the total power output of the wind farms also sees an increasing trend where farms of 500 MW plus will be a standard soon. Based on the market insight gathered so far, the next sections discuss different installation scenarios to demonstrate the optimizer performance.

## 5.3. Case Study 1

### 5.3.1. Description

The first case is intended to be analyzed with a single sequence installation procedure. The monopile type foundations are used for modeling the sequences in this case. Three different foundation sizes are selected based on the market research. It is aimed at justifying the optimizer choices and study the specific decisions made by the optimizer.

The study is divided into 3 sub-cases, where the installation of monopiles and transition pieces are modeled for different wind turbine sizes. Even though the weight parameters for the foundations are location specific, table 5.2 considers average values from previous projects for cases 1A and 1B [6]. The values for case 1C are calculated from [54]. Table 5.3 summarizes the optimizer design variables and control parameters utilized for the 3 sub-cases.

Case number	Wind Turbine size	Monopile weight (mT)	Transition piece weight (mT)
1A	2-3 MW	500	200
1B	5-6 MW	900	300
1C	9-10 MW	1600	500

Table 5.2: Sub-cases for foundation installation

Design variables		GA parameters	
Design variable	Range	Control parameter	Value
Start date	(01-04-2017 till 01-07-2017)	Population size	40
Vessel division	1 to 3	Crossover fraction	0.9
Vessel type	1 to 3	Elite count	4
Harbor	1 to 7	Convergence criteria	Stall generations (40) 4.3.2

Table 5.3: Optimization parameter specifications

### 5.3.2. CASE 1A

This sub-case simulates a scenario with small foundations to be installed at the required wind farm location. The target end date is set as 1<sup>st</sup> September, 2017. The optimizer choice of design variables is listed in the table 5.4.

Design variable	Optimizer choice
Start date	11 <sup>th</sup> May, 2017
Vessel division	Division 3
Vessel type	Jack-up barge
Harbor	Vlissingen

Table 5.4: Optimal solution for sub-case 1A

Table 5.3 shows the range of variables that are considered for this case study. The components to install in sub-case 1A allows the evaluation of vessels in all the 3 divisions. The vessels in division 3 are capable of carrying 3 piles per trip, while the division 2 and 3 can carry 4 and 6 piles respectively. While the division 3 vessels are cheaper compared to other two divisions, they require to make additional trips to complete the installation work. Hence, the duration to complete installation activity differ between the different divisions. It is seen that the division 3 vessels require 24 loadouts to complete the installation of 70 foundation structures. While the division 2 and division 3 require 18 and 12 trips respectively. The optimizer selects a vessel from the smallest division. The cost difference between the different divisions are substantial, and the optimizer decisions prove this fact. To verify if the most optimal start date is selected, figure 5.2 shows the different start dates tried by the optimizer. Excluding the start date design variable, solutions for which the other design variables have the values of table 5.4 have been selected for this comparison.

The best starting date is highlighted in the red box. This is the same date shown in table 5.4 and the next section will discuss more about the shape of the diagram (seen in figure 5.2). Next, the vessel type choice is checked with different solutions. Figure 5.3 compares the different vessel types in Division 3 category.

A heavy lift vessel is very expensive to charter compared to a jack-up barge and jack-up vessel. The charter costs of the jack-up vessel and jack-up barge are more comparable for this division. Even though the workability of jack-up vessel type is more superior, the chartering costs for the jack-up barge are slightly lower, hence, resulting in lower overall installation costs. As the installation period span approximately for 2 months in the summer season the jack-up barge can complete the installation with lower expenses. The jack-up vessel could be a better option if the workability of the vessels were tested more. Likewise, the number of components carried per trip in different divisions did not make a

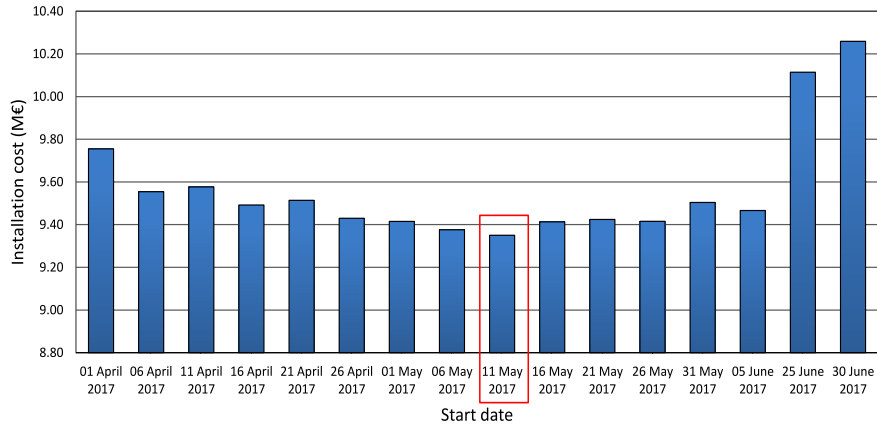


Figure 5.2: start date vs total installation cost

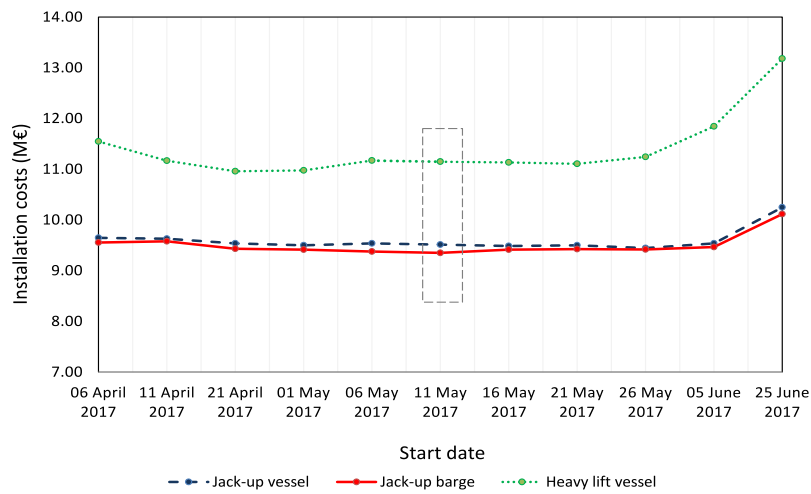


Figure 5.3: Vessel types vs total installation cost

difference in this sub-case results. Finally, the optimizer selects the Vlissingen harbor as the best port option since it is the closest onshore base to the wind farm.

### 5.3.3. CASE 1B

Similar to the previous sub-case this study is aimed at verifying the optimizer choices. The optimizer decisions are examined to check if the choices are different. The target end date is 31<sup>st</sup> August, 2017 for this sub-case. Table 5.5 reviews the optimizer choice for this sub-case.

Design variable	Optimizer choice
Start date	5 <sup>th</sup> June, 2017
Vessel division	Division 2
Vessel type	Jack-up vessel
Harbor	Vlissingen

Table 5.5: Optimal solution for sub-case 1B

The sub-case 1B results in the slightly different start date for the project. Figure 5.4 shows a similar plot to the one covered in the previous sub-case. The best start date is highlighted with a red block. The

start date of 30<sup>th</sup> June, 2017 will be used as a sample to demonstrate the target end date exceeding situation in the optimizer. It is marked by a dashed block for the reader in figure 5.4.

To recap, every start date evaluation provides a total of 100 distinct finish dates for different weather realizations. In many instances there are multiple simulations finishing on the same date. For ease of comparing, all the duplicate finish dates with their corresponding costs are averaged and grouped together. Figure 5.5 shows the different unique finish dates obtained after averaging the cost results for the above start dates of 5<sup>th</sup> June and 30<sup>th</sup> June. Considering 5<sup>th</sup> June, 2017, the latest finish date is 18<sup>th</sup> August, 2017 which is well within the target date of 31<sup>st</sup> August, 2017. The graph shows a nominal increase with late finish dates as the project duration is increasing and so would the total installation cost for the project. Looking at 30<sup>th</sup> June, there are specific finish dates which exceed the limit. The target end date mark is shown with a dashed vertical line to differentiate all the finish dates exceeding this point. Straightaway, all the finish dates after this mark are penalized, and this is seen with a sharp increase in the cost values. Hence, when the mean value for all the 100 different simulations are considered the overall result is more expensive compared to other start date options. This explains the height of 30<sup>th</sup> June, 2017 start date bar in figure 5.4.

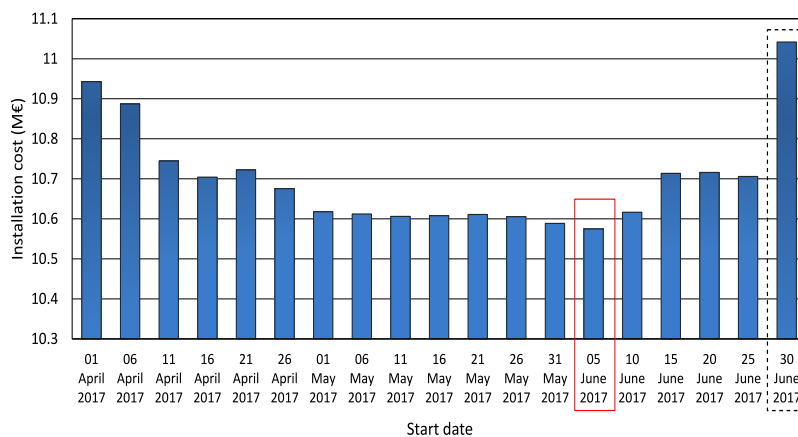


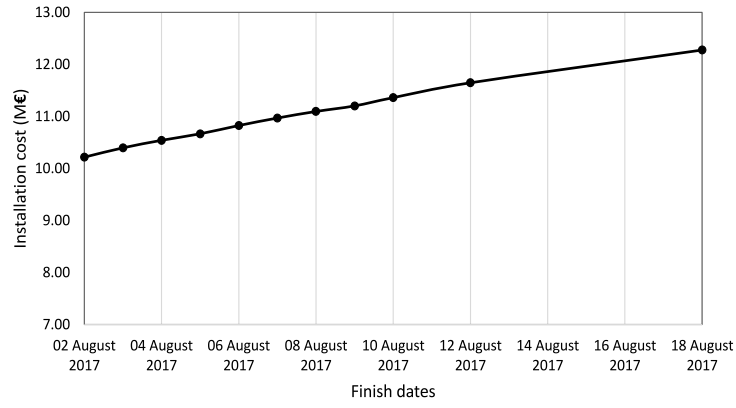
Figure 5.4: start date vs total installation cost

The optimizer selects a division 2 jack-up vessel type for this sub-case as seen in table 5.5. Since the heaviest component to install is 900 mT, division 3 vessels cannot be utilized for this installation activity. All the vessels in division 1 and 2 are evaluated to find the best choice. To verify this statement figure 5.6 is plotted to compare the jack-up vessels from different divisions. The cost of charting the division 1 vessel is more expensive compared to the less expensive division 2 vessel, and this is seen in figure 5.6. An average difference of 1.5 M€ for installation is noticed between the two divisions. The workability of jack-up vessels in the higher divisions are better compared to division 3 vessels. Thus, jack-up barges and heavy lift vessels are observed to be more expensive choices for installing components in this sub-case.

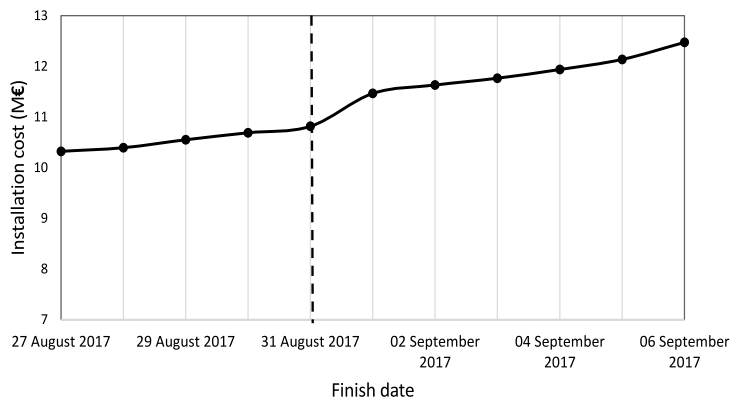
### 5.3.4. CASE 1C

In this last sub-case, an imaginary scenario of installing large foundations for a wind farm are simulated. The target date computed for this installation procedure is 10<sup>th</sup> October, 2017. Table 5.6 summarizes the optimal choice.

The installation costs for the project based on the different start dates are similar to the previous cases. Due to the weight of the component only division 1 vessel type is capable of carrying out the installation work. The optimizer selects the heavy lift vessel as the current jack-up barges, and jack-up vessels are not capable of installing components of this weight. The limited availability of vessel choice in the optimization procedure is also evident from the GA convergence plot. Figure 5.7 shows the number of generations required for the optimization procedure to stop. The optimizer finds the optimal choice by 8<sup>th</sup> generation while the stall generation limit is reached at 48 generations and GA solver terminates



(a) 05 June 2017 start date solution



(b) 30 June 2017 start date solution

Figure 5.5: Target end date comparison

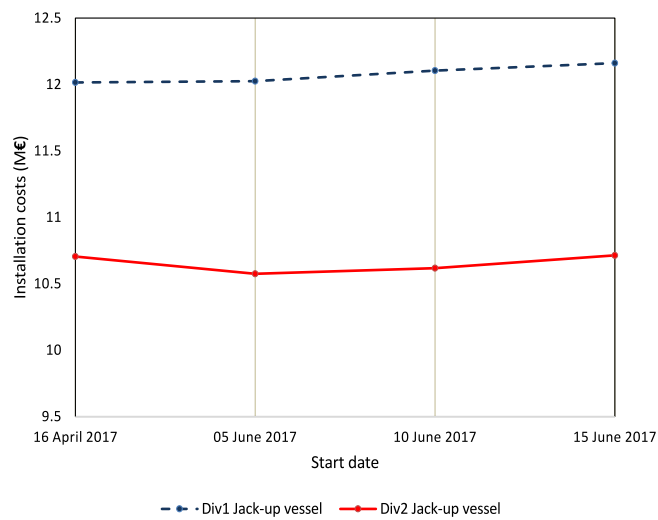


Figure 5.6: Division 1 vs Division 2 Jack-up vessels

the solution. The convergence is faster compared to the other sub-cases where GA solver took 51 generations for sub-case 1B and 60 for sub-case 1A.



Design variable	Optimizer choice
Start date	31 <sup>st</sup> May, 2017
Vessel division	Division 1
Vessel type	Heavy lift vessel
Harbor	Vlissingen

Table 5.6: Optimal solution for sub-case 1C

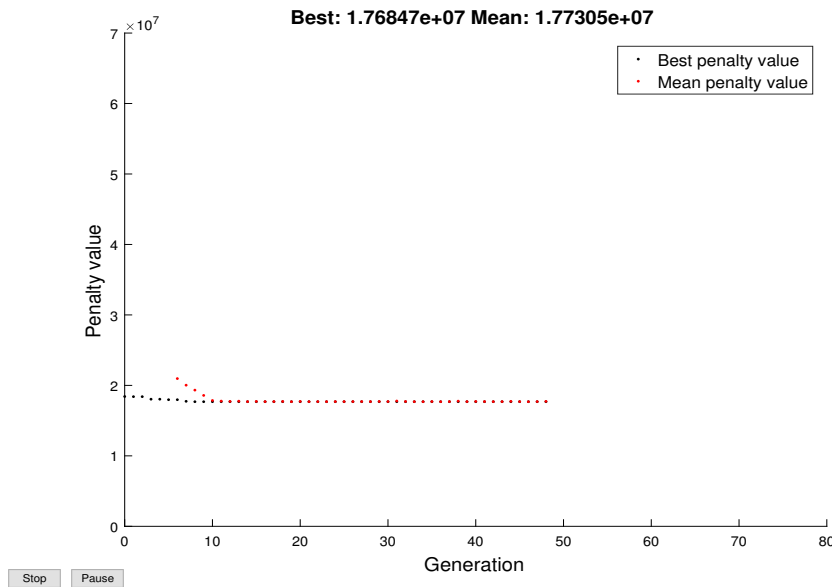


Figure 5.7: GA convergence plot

### 5.3.5. Discussion

The aim of constraining the optimizer to understand the choices in this case study is accomplished. The optimizer opts for suitable vessel type for installation based on the variation in inputs. The working of the target end date with penalty function is also checked with the sub-case 1B example. Even though the optimizer selected the smallest division vessel for sub-case 1A more case studies are required to determine the influence of number of loadout trips on the optimizer decisions. Sub-case 1C highlights the influence of component size on the optimizer decisions.

## 5.4. Case Study 2

### 5.4.1. Description

This case is an extension of the single sequence to simulate a complete wind farm installation schedule with multiple, interdependent sequences. The variables for vessel number and the pre-assembly combinations for the wind turbine transport will be covered in this case study. Refer to table 5.1 where the large wind farms are in bold for the reader. Interestingly, there would be many OWFs in the near future with the farm capacity exceeding 500MW. Thus, this case study simulates a large wind farm of 600 MW capacity keeping the future wind farms in mind. A total of 120 wind turbines are planned for installation each with a rated capacity of 5 MW. The NREL 5MW reference turbine power curve and specifications are used as inputs for ECN Install [55]. Similar to the last case study, monopiles and transition piece are used for this case too. The weight specifications of sub-case 1B are used as input here. The reader should note that the installation of export cable and high voltage station are excluded from the study (refer to section 3.4). The different sequences of activities simulated in this case study are explained with the help of figure 5.8. It is a generic representation of the sequence of activities modelled in this case study. The reader should be aware that multiple vessels are not shown

in this figure. The first sequence is used for dumping rocks at different wind turbine locations with the purpose of scour protection. Soon after the completion of the first sequence the foundation installation sequence follows it. Next, the infield cable installation process is scheduled. Once the cables are laid on the seabed the burying process is carried out. Finally, the wind turbines installation work completes the OWF installation work. Table 5.7 encapsulates all the different design variables and the GA solver control parameters set for the multiple sequence case study.

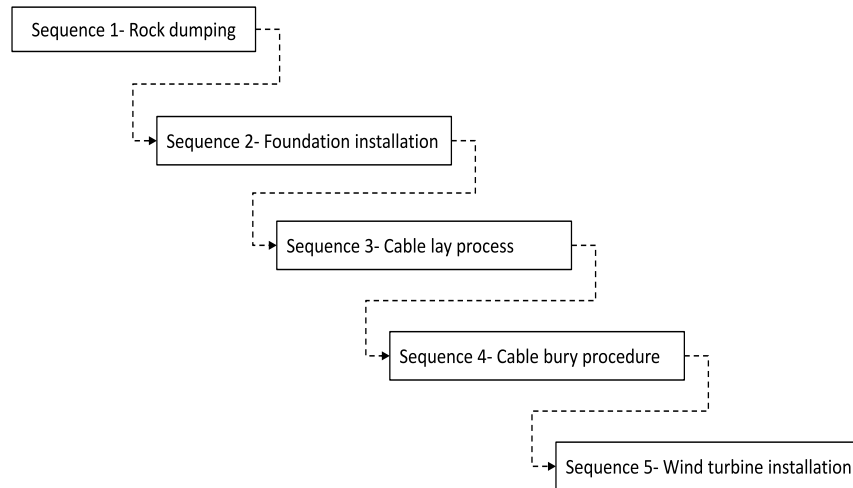


Figure 5.8: Sequence of installation activities

Design variables		GA control parameters	
Design variable	Range	Control parameter	Value
Start date	(See text)	Population size	90
Rock dumping vessel division	1 to 3	Crossover fraction	0.8
Foundation vessel division	1 to 2	Elite count	10
Foundation vessel type	1 to 3	Convergence criteria	Stall generations (40) 4.3.2
Number of vessels	1 to 2		
Harbor	1 to 7		
Cable lay vessel division	1 to 3		
Wind turbine vessel division	1 to 3		
Wind turbine vessel type	1 to 3		
Wind turbine vessel number	1 to 2		
Pre-assembly combination	1 to 3		

Table 5.7: Optimization parameters

A total of 11 design variables are used for this case study. The control parameters needed slight modifications to work for a complex installation scheduling problem. Even though this report presents only 2 cases for multiple sequence case, considerable number of testing was necessary before this could be done. Referring to table 4.3, the population size was first set to 110. With a couple of test instances the population size was reduced to 90. There was no evident drop in performance but the GA solver time is saved with smaller population size. This change translated to saving more than 3 hours of optimization simulation time. Similarly the crossover fraction was varied for a value of 0.8 as it was giving good results for single sequence testing too. Changing the crossover fraction to 0.8 improved the exploratory capabilities of the solver as more individuals participate in mutation operation. Due to restrictions on the project timeline, extensive control parameter testing was not possible for multiple sequence problem, and the above estimates of the control parameters are used for this case study.

Moreover, the multiple sequence case is split into 2 sub-cases. These 2 sub-cases are run with the same installation inputs except providing different start date variable ranges. Sub-case 2A is run for

the start date ranges from 01<sup>st</sup> May,2017 to 20<sup>th</sup> September,2017. Whereas, the sub-case 2B is given a start date range of 01<sup>st</sup> February,2017 to 21<sup>st</sup> June,2017. The different start date ranges are considered to study the seasonal changes on the optimizer choice. It will also allow to study the vessel choice depending on its workability specifications. Table 5.8 summarizes the results obtained for the 2 sub-cases. Sub-case 2A is chosen to investigate multiple vessel type design variable. Sub-case 2B is selected to probe into the wind turbine pre-assembly combination choice. These variables are highlighted in table 5.8.

Case 2A		Case 2B	
Design variable	Value	Design variable	Value
Start date	(01-05-2017	Start date	02-05-2017
Rock dumping vessel division	1	Rock dumping,vessel division	2
Foundation vessel division	2	Foundation vessel division	2
Foundation vessel type	Jack-up vessel	Foundation vessel type	Jack-up vessel
<b>Number of vessels(foundation)</b>	<b>2</b>	Number of vessels(foundation)	2
Harbor	Vlissingen	Harbor	Vlissingen
Cable lay vessel division	3	Cable lay vessel division	3
Wind turbine vessel division	1	Wind turbine vessel division	3
Wind turbine vessel type	Jack-up vessel	Wind turbine vessel type	Jack-up vessel
Wind turbine vessel number	1	Wind turbine vessel number	2
Pre-assembly combination	Tower, nacelle bunny ear setup, one blade	<b>Pre-assembly combination</b>	<b>Tower, nacelle-hub assembly, 3 blades</b>
Finish date	15 <sup>th</sup> September,2018	Finish date	12 <sup>th</sup> August,2018
Installation cost (M€)	95.7	Installation cost (M€)	94.8

Table 5.8: Number of vessels and Pre-assembly combination design variable study

#### CASE 2A

Table 5.8 shows the results for sub-case 2A. The optimizer selects 2 vessels for carrying out the foundation installation work. For example, to install total 120 foundations, 2 jack-up vessels of division 2 are selected for installation. Both vessels install 60 foundations each. Let us compare this scenario with when only a single vessel is chartered for installation of foundations. Table 5.9 summarizes the results of both the scenarios where all the other design variables are exactly the same as in the above table for this comparison. Scenario (**two vessel**) is the optimal case and (**single vessel**) is for the single vessel case. The choice of using single and two vessels for installing the foundations are compared based on the time required for the installation and the total cost for the complete project. The final project finish dates for both the scenarios are also tabulated.

Scenario	Foundation installation duration (days)	Total project finish date	Total installation costs (M€)
Two vessel	63	12 <sup>th</sup> September,2018	95.7
Single vessel	94	24 <sup>th</sup> October,2018	99.6
Difference	31	42 days	3.9

Table 5.9: Number of foundation vessel evaluation

Two vessels take 63 days to complete the installation process whereas a single vessel takes 94 days to complete the same procedure. While comparing the overall project finish dates, the difference is evident as expected but much larger. The selection of multiple vessels is more influential here due to the interdependency of multiple installation activities. The use of multiple vessels allows the following sequences to start earlier and eventually result in shorter installation period for the project. While the difference is only 31 days for the foundation installation activity, the additional delays accounted by the following sequences result in a larger difference in the final project finish date. Finally, the difference in

finish dates between the 2 scenarios reflects on the total costs too. The single vessel scenario results in 3.9 M€ more than the optimal choice.

### CASE 2B

The reader can refer to table 5.8 where the sub-case 2B results are shown. Since the optimizer tries various combinations of design variables to find a optimal choice, 3 such combinations from the optimization analysis is selected for evaluating the pre-assembly combination design variable choice. Table 5.10 provides a summary of the different combinations compared to understand the optimizer choice. Combination 1 is the optimal combination for case 2B. Where Combination 2 and combination 3 are other feasible solutions used for the comparison. The reason for selecting 3 different combinations is because the pre-assembly combination to transport on a vessel is not an independent decision and is influenced by the vessel choice. If necessary, the reader can refer to section 3.4 to recap about the different wind turbine pre-assembly combinations modeled in current work. Due to the above reasoning the vessel parameters for wind turbine installation procedure are highlighted in the table.

In combination 1, the optimizer selects a division 3 jack-up vessel with two vessels to install the turbines and carrying the tower, nacelle, blades separately on deck for every installation trip. The main advantage of this pre-assembly method is seen with carrying more turbines for installation compared to other pre-assembly combinations. On the downside, this option requires maximum crane lifts during installation. Combination 2 opts for bunny ear configuration with a single division 1 vessel choice. This pre-assembly option occupies more space comparing the previous pre-assembly option but requires fewer crane lifts. Hence, the optimizer selects a larger vessel to carry out the same installation activity. Finally, combination 3 selects a division 2 vessel carrying the same pre-assembly setup as combination 1 with one vessel used in the installation process. Comparing all these 3 combinations the cost difference between them is more than 0.5 M€. It is also seen that two vessels even though from a lower division complete the installation work faster than a higher division vessel with better workability restrictions.

GA parameter	Combination 1(optimal)	Combination 2	Combination 3
Design variable	Value	Value	Value
Start date	2 <sup>nd</sup> May,2017	27 <sup>th</sup> April,2017	2 <sup>nd</sup> May,2017
Rock dumping,vessel division	2	2	2
Foundation vessel division	2	2	2
Foundation vessel type	Jack-up vessel	Jack-up vessel	Jack-up vessel
Number of vessels(foundation)	2	2	2
Harbor	Vlissingen	Vlissingen	Vlissingen
Cable lay vessel division	3	3	3
Wind turbine vessel division	<b>3</b>	<b>1</b>	<b>2</b>
Wind turbine vessel type	Jack-up vessel	Jack-up vessel	Jack-up vessel
Wind turbine vessel number	<b>2</b>	<b>1</b>	<b>1</b>
<b>Pre-assembly combination</b>	<b>Tower, nacelle hub assembly, 3 individual blades</b>	<b>Tower, nacelle "bunny ear" setup, one blade</b>	<b>Tower, nacelle hub assembly, 3 individual blades</b>
<i>Total Installation cost (M€)</i>	94.8	95.5	96.8

Table 5.10: Wind turbine preassembly combination evaluation

### 5.4.2. Discussion

As seen in table 5.8, 2 sub-cases were run for different start date ranges. The sub-cases present different design variable combinations and varying installation costs. Sub-case 2A incurs a total of 95.7 M€ as project installation expenditure. While sub-case 2B results in a lower cost of 94.8 M€. The optimizer chooses the division 3 cable lay vessel for both sub-cases. This is accounted due to the low chartering cost for the vessel in this division. As a drawback, the division 3 cable vessel needs 2 trips to refill with new cable and finish the laying procedure. Even if a larger division vessel is used for laying process, the installation cost is at least 0.3 M€ higher compared to the optimal choice of division 3 vessel. Similarly, case study 2 highlights an interesting aspect about the choice of vessel type for the installation of foundations and wind turbines. For both the case 2A and case 2B Jack-up vessel type are the best choice for the installation work. It authenticates the popularity of jack-up vessel types in the OWF installation industry due to their purpose built functionality and superior workability when compared to jack-up barges and heavy lift vessel types in current study.

Referring to table 5.9 the different start dates design variable tried by the optimizer while all the other variables remaining same from the table. Figure 5.9 represents the trend observed with installation costs incurred for different start dates. The installation costs are average of 100 different realizations for every start date variable choice. It is seen that when the start date range is set from February to July (sub-case 2B) the optimal choice for the start date is in May. The plot shows the reduction in cost as it moves closer to May and then increases again. When the start date range is set from May to September (sub-case 2A) the optimizer again selects the best start date in May. With a delayed start in the sub-case 2A, the project cost continues with an increasing trend. The trends seen in both the cases are slightly different. In case 2A, all the start dates before 20<sup>th</sup> August have a increasing installation cost due to weather influencing the delays in the project. The start dates after 20<sup>th</sup> August are a combination of the weather affecting the project costs with the penalty value also added due to exceeding the set target date for the project. In case 2B, the start dates in February and July result in high installation cost only due to the weather delays and not because of penalty function. The reader should note that while the optimizer finds similar start dates for both the sub-cases, the optimal combination of the design variables and weather realizations are different in both sub-cases. Thus, the total installation costs obtained are also different for the sub-case 2A and 2B.

Let us refer to the figure 5.8 where the different sequences for this case study with their interdependencies are shown. Starting in the month of may for both the cases 2A and 2B result in the cable burying process falling in the winter season of 2017 to 2018. The burying process uses a ROV and a multi-purpose vessel for the installation procedure (refer to section 3.4). The hiring cost for these resources are relatively cheap when compared to other installation vessels in the project. Even though the delays encountered during cable burying process is high, the total influence on the project installation cost is acceptable. Hence, it results in the least installation costs when starting in May. This discussion also highlights the influence interdependency can have on multiple sequence projects. The start date plot (fig. 5.9) emphasizes the importance of start date variable and its influence on all other design variables in the study.

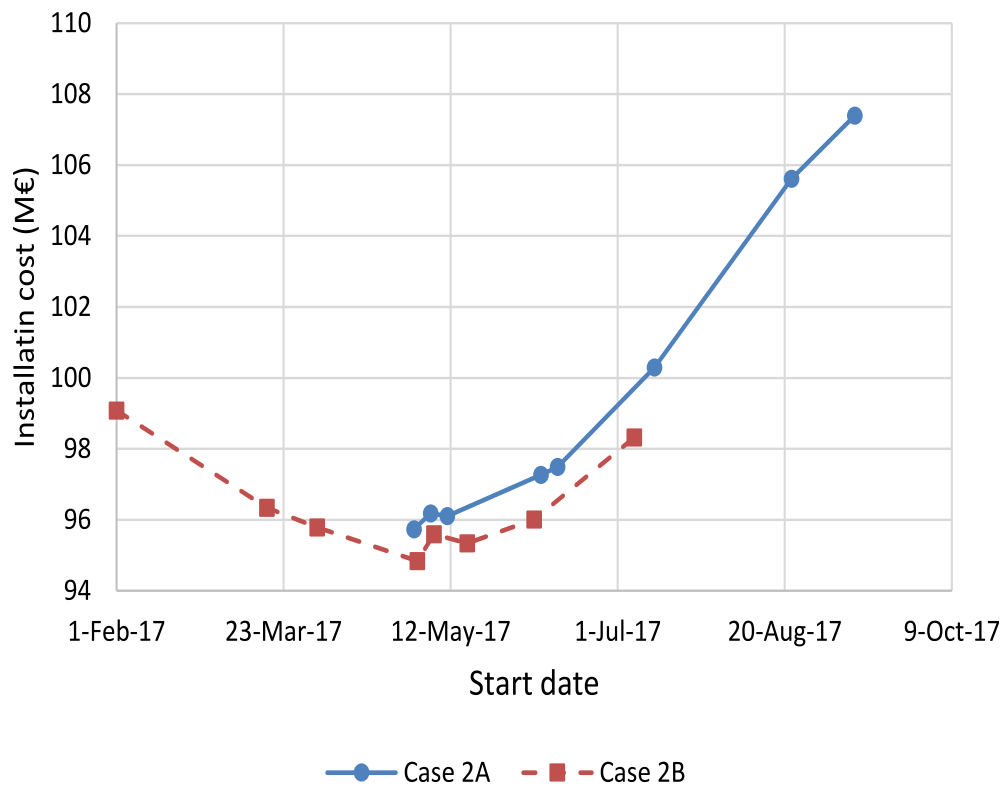


Figure 5.9: Sub-case start date ranges vs Installation costs

# 6

## Conclusions and Future Work

This chapter summarizes the learnings from this thesis study and gives some recommendations for future work.

### 6.1. Conclusions

The objective of the study was the development of an approach to obtain minimized cost for OWF installation procedure while having a target end date of significance. Consequently, the primary focus of the project was to provide flexibility in modeling OWF installation schedules and delivering optimal solutions in affordable computation times. The new approach developed with ECN shows promising results for optimizing OWF installation logistics with a target date set by the decision maker.

A concise literature review demonstrated the significance of the current research and the potential that metaheuristic approaches bring to solve installation scheduling problems. The genetic algorithm was chosen as the optimization procedure to use for this study. The objective of the optimization process all throughout this research was the minimization of installation costs. The target end date for any given project is implemented in the form of a constraint to steer the solution within the specified limit. The installation of wind turbines offshore in harsh weather conditions inexorably introduces a certain level of uncertainty in the project schedule. To better account for this uncertainty due to weather, a synthetic weather data simulator was provided by ECN for this research. The modular structure of GA in MATLAB toolbox allowed efficient customization to create the new architecture with ECN Install. The decision to use the Integer GA solver was favorable for the current study, which is supported by the case study results.

Furthermore, a significant part of the current work involved the building of a new architecture for running the optimization analysis with ECN Install. The novel approach required the addition of new blocks for Automated Planning (AP), Uncertainty Consideration (UC), and Constraint Evaluation (CE) to integrate the optimizer with ECN Install efficiently (refer to figure 2.2). The new approach obligated the need for blocks mentioned above in accomplishing the thesis objective. The AP block was constructed to prepare the installation planning based on the design variable combinations fed by the optimizer and eventually run this planning in ECN Install. Efforts were made to provide the possibility of housing a range of installation sequences, but, the limitation of working with pre-defined planning templates was inevitable. Nonetheless, profound care was taken while building these templates for different installation activities, since mistakes in the template would result in wrong optimization choices. Thus, all the templates were created based on research about the actual installation procedures employed in the offshore wind industry. Overlooking the limitations of the AP block, the approach worked well with GA optimization procedure to generate new planning for every individual combination of decision variables in quick times (few seconds). The AP block approach has shown promising results for future developments.

A UC block is provided to account for the variability in weather while interpreting the total installation costs. A compact investigation on studying the uncertainty due to weather in a project allowed to fix the final choice of simulating 100 different weather instances for every new planning generated during the optimization process. The choice of running a large number of weather realizations was reasonable to determine a more accurate mean for installation costs. However, the 100 unique results show a considerable number of simulations having installation costs higher than the mean value used for the optimization procedure. Though initially planned to incorporate the uncertainty variable in the form of a probabilistic constraint was not successful in this study with the GA solver, it is suggested to explore this approach for better quantifying the uncertainty in OWF installation projects.

The CE block is modeled to accommodate the target end date exceedance check. The CE block functions with the UC block to penalize any project scenario exceeding the target date set by the user. To the best of authors knowledge, there is no research in the literature on optimization of OWF installation logistics with a target end date requirement. The case studies reflect the importance of setting an appropriate target date and the influence of the penalty value on the total installation costs.

Furthermore, the current versions of ECN Install were only able to simulate installation planning with multiple sequences independent of each other. For this reason, a new method is developed to incorporate interdependency between the various installation sequences for the installation scheduling problem. This allowed a realistic evaluation of multiple sequence project in the new optimization procedure where the end date of the first installation sequence would impact the start of the following sequence. With the support of literature, the main control parameters affecting the performance of the GA were identified. These parameters include population size, elite count, and crossover fraction. A pragmatic approach is followed towards modeling an abstract problem for the GA control parameter tuning process. This was mainly preferred, as the abstract problem allowed quick evaluations and provided the possibility to study the parameter variations more extensively. This study shows the requirement for tuning the control parameters specific to the problem studied with the GA solver and recommends carrying out the testing with simple problems to obtain quick solutions. Consequently, the knapsack problem results pinpointed the same reality in this thesis.

Different categories of design variables were employed in this study. These include the start date, vessel division, vessel type, vessel number, harbor and pre-assembly combinations of the wind turbine during load-out. When evaluating all the different design variables, the start date was the most influential in this study. The variation in start date resulted in different combinations of other remaining design variables. In the current analysis of the installation logistics, the choice of the port was not a useful design variable, since in the optimization procedure it always resulted in the nearest selection. The choice of port might become less straightforward, and therefore a more interesting to study as a design variable when onshore logistics parameters are also included in the optimization procedure.

To summarize, the key result of this research to provide an approach to obtain the minimized costs for a given OWF installation strategy with a target date is efficiently achieved. Furthermore, the different case study results show the prospects of incorporating optimization procedure in OWF installation scheduling problems. Finally, even though the study focused on the optimization procedure, specific wind farm inputs could help evaluate the optimizer performance better and improve the model further.

## 6.2. Future work

The use of a metaheuristic optimization method in this project was unavoidable with the high level of complexity in installation scheduling problems. Even though the GA performed adequately for the current study, the overall analysis times are long and would increase with the addition of new design variables. It could be interesting to explore other metaheuristic methods like the PSO or ABC algorithms for solving OWF installation strategies.

This study focuses on a single objective to minimize the total installation cost for a project. It would be worthwhile to scale the problem to a multi-objective case where both cost and duration are optimized. Additionally, a significant improvement area is seen with the AP block implementation procedure. While the method is sufficient to function with the current versions of ECN Install, with more complex sequence interdependencies introduced in the future versions the AP block implementation will need



improvements. Also, the AP block work with pre-defined templates for constructing different installation sequences. This limitation can be removed by making more standardized activity blocks like travel, loading and installation blocks based on the type of installation. This can add more flexibility while creating schedules with AP block.

Likewise, the optimization approach implemented in this study assumes 100% availability of a particular vessel type, port or equipment while running the simulation. Populating the different vessel, port, and equipment libraries with actual resource data with availability information could result in diverse solutions. Also, the implementation of penalty function for the target end date can be explored more extensively to understand its influence on the optimizer choices.

Moreover, an area which could be further researched is the uncertainty quantification of weather for optimization study in installation logistics. Hence, a complete distribution of results could be used to find the optimal choice of design variables. Finally, extensive GA control parameter tuning could not be conducted for multiple sequence projects in this dissertation and it will certainly be beneficial to find the optimal values for interdependent sequences to obtain the best performance with genetic algorithm.



# A

## Appendix A

### A.1. Wind Turbine components and Resources

The various elements involved in a typical OWF are defined for gaining a better understanding of the complete installation procedure. The exact list of resources utilized is unique to the wind farm project and highly exhaustive. Hence, this section gives an overview of the most widely used components and resources in the offshore wind industry.

#### A.1.1. Substructure

The substructure is the component designed to support the wind turbine in offshore conditions. They can be broadly classified into two categories of floating or fixed bottom structures. Floating configuration is still in concept phase but could be very promising with interest in setting up wind farms in deep waters. Bottom fixed structures, on the other hand, have evolved from the oil & gas industry and customized for wind industry application. The different options are seen in the figure A.1 below. Even though there is a broad classification of the various substructures presented here, there are many design variations which are unique to the project and wind farm location.

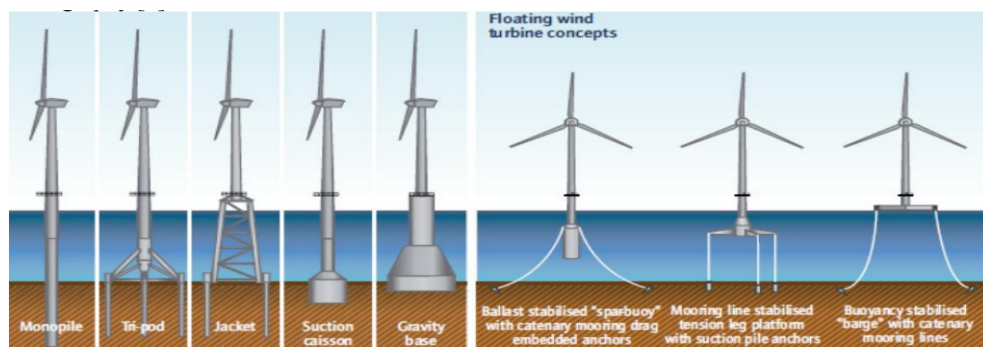


Figure A.1: Types of substructures [3]

#### Monopiles

Monopiles are the most extensively used foundation structure in the offshore wind industry till date. Even in 2016, there were 493 monopiles installed, constituting close to 88% of the total installed foundations for OWF's that year [56]. This preference is seen due to its lower weight compared to other foundation types and extensive usage in the Oil and gas industry. In addition, monopiles can be manufactured using standardized designs and assembly-line practices. A monopile is typically hollow cylindrical part of steel which is driven down into the sea bed to a certain location specific depth [33]. In

most cases, there is an additional element used to link the turbine tower with the monopile structure. This component is called the transition piece. It also acts as a landing base for the technicians to access the turbine. To ensure the verticality of the wind turbine and account for the slight degree of inclination after pile driving operation, there is a special cement called Grout applied between the monopile and the transition piece[57]. While grout connections are considered as industry regular, number of connections have failed, preceding to slippage and improper stresses in structures. Thus, new methods like bolting and slip joints are becoming popular with new installations[58].

### Scour Protection

Scour is a type of erosion of soil around the structure in the sea bed. This is especially significant in locations with tidal currents around the structure. Based on experience, it is stated that the scour hole can reach around 1.5 times the pile diameter [29]. In such cases, it becomes beneficial to prepare a rock bed around the structure to avoid the above scenario. Scour protection is applied to foundations which are secured to the sea bed, seen in the figureA.1.

### Jackets

These type of structures are increasingly becoming popular for deep waters where monopiles are not economical. Jackets are massive steel lattice tower with triangulated structures providing strength and required stability. Jackets are installed by fixing them to the sea bed with three or four pin-piles which are similar to smaller versions of monopiles. The steel needed to build jackets is less compared to monopiles in most cases; hence there is some material cost saving. The major drawback is seen to be the precise welding required for such large structures to resist long term wind and wave loads[59].

### Gravity Based Structure

Gravity based structures are concrete conical shape foundations with a flat base to place on the sea bed. They are typically secured with ballast to prevent against scour protection. They are a popular choice of foundation for shallow waters or tough sea beds where pilling is hard [60].

### Floating Structures

These structures are a viable option when the water depths are more than 40m. Typically the turbine is secured on a floating mass in the sea which could be a single cylindrical buoy or a semi-submersible platform. A significant advantage is seen in the installation phase where a complete turbine can be assembled onshore and installed in no time at the farm location saving both time and costs. On the contrary, the floating structure needs to remain straight at all times and withstand the harsh wind and wave conditions. There is substantial research being invested into floating structures which might have wide spread effects in the complete value chain [61].

#### A.1.2. Wind Turbine Components

The offshore wind turbines are very similar to the onshore machines used in the industry, with certain modifications to design to handle the offshore conditions. Size and noise regulations do not limit the offshore turbines compared to onshore turbines; hence much larger turbines are preferred to reduce the overall project costs. The average capacity of offshore turbines ranges around 5 MW where it is just about 2 MW for onshore application. Currently, 10 MW turbines are under testing for offshore application [62]. A typical horizontal axis wind turbine consists of various separate components which require being assembled before going into operation. The figure below shows these components for better understanding. There are multiple installation procedure followed in the industry are discussed in chapter 3.

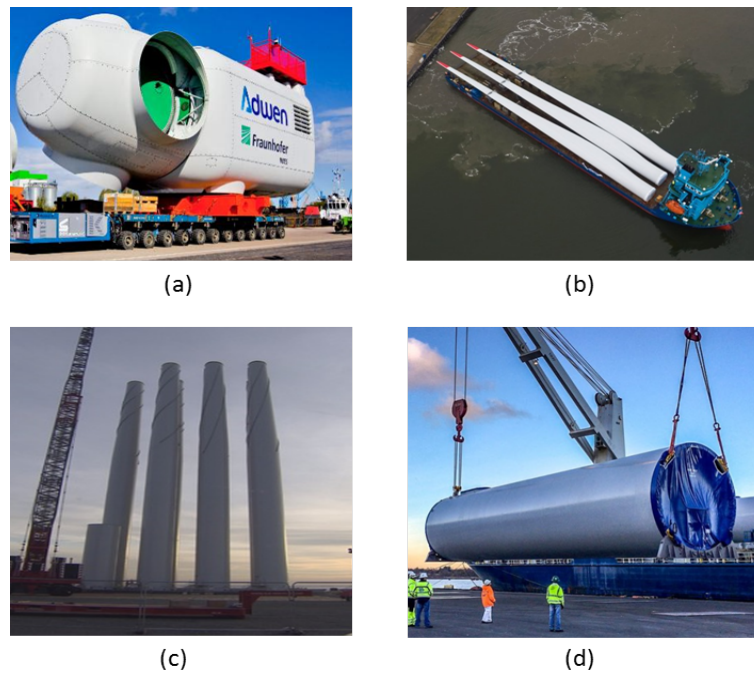


Figure A.2: Wind turbine components:(a) Nacelle & Hub, (b) Blades, (c) Tower, (d) Tower section

### A.1.3. Electrical Infrastructure

The electrical network of the wind farm can be imagined similar to the nervous system of a human body. The cable infrastructure plays a major role in determining the overall performance of the wind farm. They aid in connecting the offshore wind farm to the grid. The cabling networks are split into two types for installation procedure:

- Infield cable network
- Export cable network

#### Infield Cable Network

These cables form the connection between different turbines and also between turbines and substation in the wind farm. Based on the capacity of the wind farm different configurations are available to save project costs and also cater to the possibility of failures in the network to eventually avoid production losses[63].

#### Export Cable Network

The export cables are built to connect the OWF to the onshore or larger collector station. Based on the distance High Voltage Direct Current (HVDC) or High Voltage Alternating Current (HVAC) are preferred for the project [64]. Typically they have a much higher capacity and larger dimensions compared to infield cables.

Both the cable networks follow a similar installation procedure with slight variations which are discussed in chapter 3.

### A.1.4. Substation

The substation is a large transformer which collects the electrical energy from the network of wind turbines in the farm and transmits the energy to the grid. With wind farm moving further away from the shore the need for substations is becoming imperative. They are usually large cubic shaped structures which collect, transform and occasionally convert the power from the turbines before transmission.

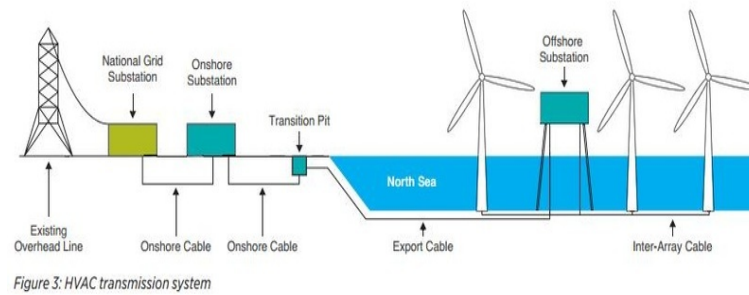


Figure A.3: Electrical infrastructure



Figure A.4: Offshore substation

### A.1.5. Vessels

Vessels are the most cost incurring component in the wind farm installation procedure. Over the past two decades of learning in the offshore wind industry the vessels have come a long way and have been purpose built for the required operations. Most vessels involved in the installation phase are expensive to charter and demand efficient planning to keep the overall installation costs in check. Some popular vessels used in the OWF installation process are shown below.

The most popular installation vessels used for foundations and turbines are the jack-up vessel categories. Next, closely followed by the heavy lift and Floating Sheerleg Crane types. The figure A.6(c) shows a Floating sheerleg crane installing a jacket at sea. Similarly, pictures of jack-up vessels are shown in figure A.7(b). The differences between the different vessels are discussed in chapter 3 based on the type of installation applied during the project build.

### A.1.6. Equipment

The installation of large components requires purpose built equipment to assist in the assembly process. Most equipment used have been adopted from different industries to aid the installation of Wind Turbines offshore. The following sections summarize some of the most popularly used types of equipment during the installation phase.

#### Cranes

Cranes are essential equipment part of the installation vessels in the market. They are used to lift the heavy and large wind farm components required to be installed. Few important parameters like lift capacity, radius and boom length play a major role in deciding the vessel capability for the necessary installation activity [15].



Figure A.5: (a) Rock dumping vessel,(b) Heavy lift vessel,(c) Multi-purpose vessel,(d) Cable lay vessel

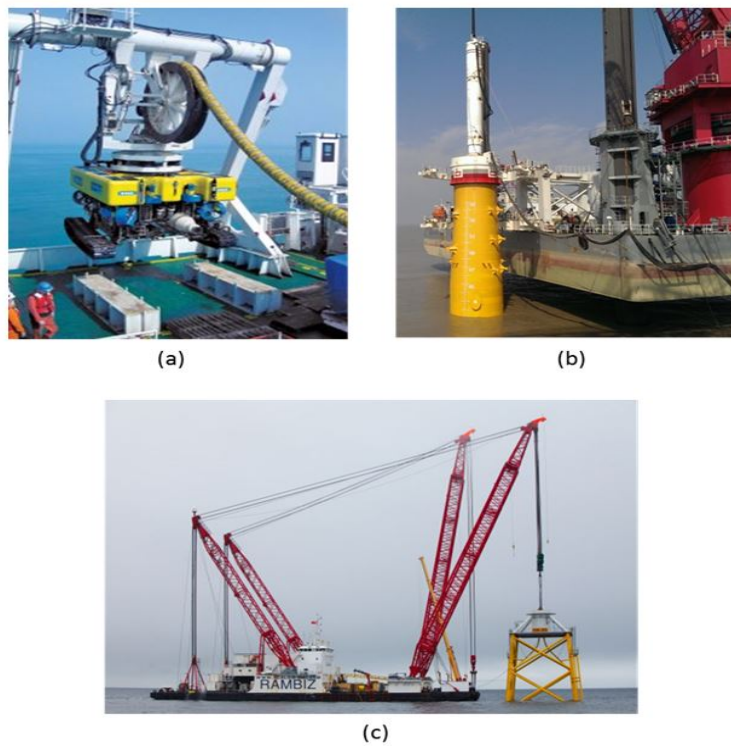


Figure A.6: (a) ROV ,(b) Pile hammer,(c) Crane

### Pile driving Hammers

Certain foundations which need to be hammered into the sea bed require a special equipment to help in this regard. The action of hammering the foundation in the sea bed is called piling. Various types of piling methods are available in the market based on the project preferences.



### Cable Lay Equipment

Cable lay equipment are specialized machines used during the cable laying operation in the farm. The Remotely Operated Vehicle (ROV) or the underwater plough are used to lay and bury the cables in the sea beds. There are also smaller ROVs utilized for survey and studying the cable lay path before the actual installation work is commenced. Figure A.6 shows a example for ROV used in the cable laying process.

#### A.1.7. Port

To achieve the best planning for installation procedure the location of the port is a crucial parameter. The distance of the port, port accessibility and ease of onshore logistics play a major role in efficient scheduling [15]. All the different OWF components are loaded-out to the offshore location for installation from a onshore base (port). The figure below gives a visual to the reader about the typical wind turbine component storage on port ready for load-out.

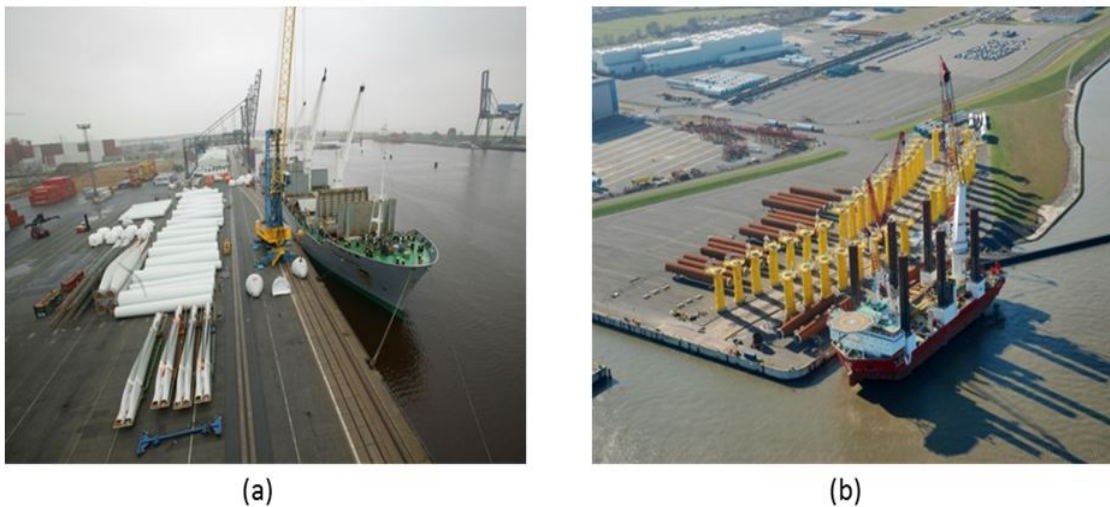


Figure A.7: Harbour use for OWWF installation

#### A.1.8. Working Technicians

Skilled technicians are the reason the complete installation work happens in the first place. In most projects, the installation work is carried out Twenty-four Seven to make the best use of the weather windows encountered. This translates to technicians required to follow 24/7 shift system to keep the installation activities rolling.



# B

## Appendix B

### B.0.1. Inputs and Planning

Inputs and planning module is primarily a setup block for the installation schedule. The basic parameters necessary for the complete planning process are stored in this section. The table below summarizes the inputs taken by ECN INSTALL tool.

Sub-module	Parameter
Wind Turbine	Turbine type, Rater power, Hub height, Number of turbines, Power curve
MetOcean Data	Weather data file, Resolution
Operational Bases	Port name, Distance to farm, Cost information
Components	Component names, Weight specifications
Equipment	Equipment cost and duration data
Vessels	Specific vessel cost and duration details
Working shifts	Different shift split-up details
Costs	Project management and fixed project costs

Table B.1: ECN Install Input parameters

The complexity and accuracy of the planning depend on the inputs provided as shown in the table above. This module is necessary for generating a planning for the desired installation procedure. Before moving to next section, this is a good time to define few relevant terms which will frequently be used in the report. The offshore wind farm installation procedure is highly repetitive and allows for iterating the repeating activities once they are defined initially. The planning process in the INSTALL tool is classified under STEP, GROUP and SEQUENCE levels to represent the same. The Sequence is the first level in the installation planning. This level defines the significant installation activities to be carried out multiple times in a wind farm. For example, the installation of support structures or cable installation for OWF is classified under sequence level. Next is the Group level which is housed inside the larger Sequence levels. It encapsulates the sub-activities that take place in a Sequence. An example of this level is the loading of sub-structures on a particular vessel selected for installation in Sequence. Installation of cable between two turbine locations is another example. Finally, the smallest block of the planning is the Step level. These levels store the actual operation taking place in the group levels. The piling of a monopile is an example of Step level activity. The different levels can be visualized by referring to the figure [B.1](#).





of vessel between the harbor and wind farm. Finally, the Installation step which describes all the installation activities that take place in the project using the vessel and equipment. Depending on the user selection for every step specific options are enabled. Likewise, the model also demands the input information about the shifts used in the project. Where the loading and installation step types are classified as a shift-splittable category, which means that one technician's shift can start the step and a different one could complete it. Whereas in the case of traveling step type the shift is considered as non-splittable. It implies that if the step duration is more than the maximum shift duration the step is not performed, and an error is displayed. The above process is carried out starting from the first step to the last one for the planning created by the user.

While the ECN Install old, worked with only historical weather data the ECN Install used for this thesis incorporates a synthetic weather data generator. It is important to understand more about the weather simulator as it plays a significant role in the optimization process. As mentioned in the introduction chapter installation activities for OWFs involve uncertainty due to weather conditions. Meaning, wind and wave conditions are stochastic events and inherently random. Historical data is capable of capturing only part of this irregularity in the time series. Hence, if an only small number of weather data are used for the evaluations, it would result in the creation of prejudice in the output results. To overcome the limitations, a new stochastic weather simulator is developed in-house to run a large number of independent time-domain simulations for any project the decision maker intends to evaluate. The reader can acquire more details about the actual procedure followed to create this weather simulator by referring to report by C.F.W. Stock-Williams [65]. To conclude, the weather simulator integrated with ECN Install trains on the time series data provided by the user and generates the synthetic weather realizations starting from the project start year till five years ahead of the start year.

# C

## Appendix C

This section describes the method followed for storing input data and the installation planning in the ECN database template. Later part shows the approach followed to prepare the planning file for simulating it in ECN Install with different weather realizations. The first section shows the process of storing inputs and planning data created by AP block.

### C.1. Data handling in ECN INSTALL

It is important to understand how the different user inputs and planning is handled inside the ECN INSTALL Matlab platform. ECN Install uses a pre-defined template to store the various OWF inputs and planning information. The Database.mat shown in figure C.1 is the described template necessary for simulating any planning. This MAT file is a large set of structures/cells which store all the necessary information from the front end GUI or planning from AP block before running the simulation in ECN Install.

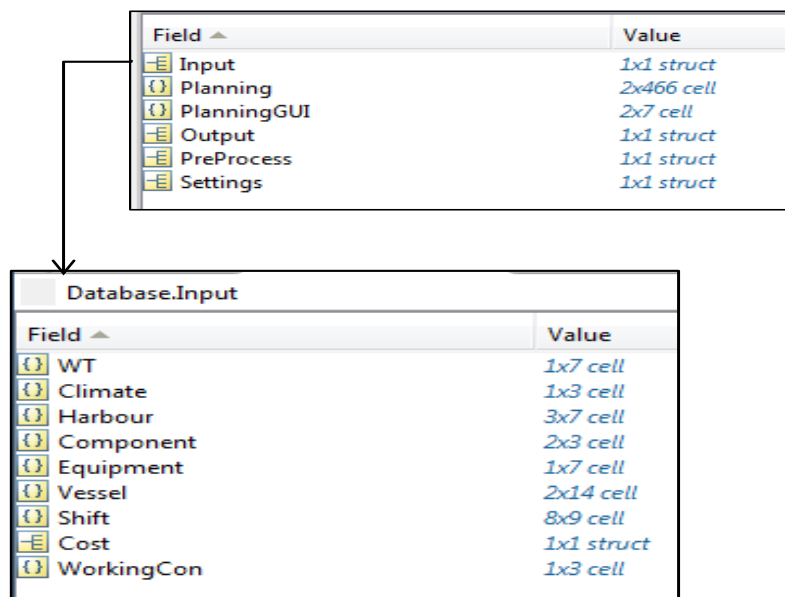


Figure C.1: Database template structure

The **Input** structure in figure C.1 stores all the input information for an installation project. The Planning field is expanded in format of the **PlanningGUI** which stores information in the different levels (SEQUENCE, GROUP, STEP) shown in figure C.2.

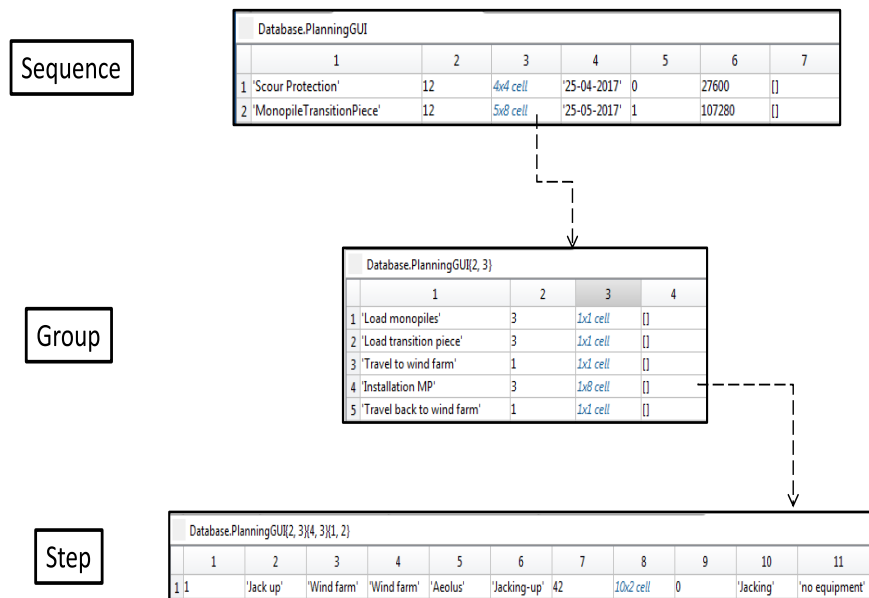


Figure C.2: Activity levels defined in ECN Install

The **Output** structure is empty in the beginning of the simulation and the results calculated at the end are stored in this structure. The **Pre-Process** stores the data which is explained in Pre-Processor block in section B.0.2. Figure C.1 also shows the procedure to store the inputs from the user in the *Database.Input* structure. The field names are self-explanatory about the information split in the various cells and structure. To avoid and confusion, **Cost** structure in the Inputs is exclusively used for accounting for *fixed costs* and *project management costs* in the installation procedure. The **WorkingCon** stores the information about permit restrictions for particular installation in project. It means no STEP is executed if the concerned sequence of activity falls inside the permit restrictions (not used in this study).

## C.2. Simulation settings for ECN Install

Once the necessary installation project information is stored in the Database.mat file, it is then stored in a higher level MAT file called AppSettings. Figure C.4 shows the AppSettings structure. The Database file is saved into the Database structure (refer to figure C.3). The **ProcessingSettings** is also an important field for the current study. The weather simulation information is fed at this location.



Figure C.3: Planning data flow diagram to ECN Install

The NSims field marked in the figure take the input for the number of different stochastic weather time series to use during the ECN INSTALL simulation. The RES field defines the weather variable

AppSettings file

Field	Value
Database	1x1 struct
AccessList	1x5 cell
DatabaseTemp	1x1 struct
ProcessingSettings	1x1 struct

Field	Value
WeatherSettings	{}
PlotSettings	{}
ExcelSettings	{}
GanttPreSettings	{}
GanttPostSettings	{}
SimulationSettings	''
NSims	50
RES	10

Figure C.4: Settings file in ECN Install

resolution with a certain number indicating the resolution desired (6/10/15/30/60 minutes, where RES = 10/6/4/2/1). For the current research a resolution of 30 minutes is utilized due to large optimization running time. Setting the resolution below 30 minutes increases the simulation time of every weather realization in ECN Install. For example, if the resolution is set to 10 minutes, the weather window matrix for the planning is computed for every 10 minutes. This consumes more time when compared to creating weather windows of minimum 30 minutes. This eventually increased the optimization procedure run time beyond the available limit (less than 24 hrs).





# Bibliography

- [1] [Global wind energy council](#), (), accessed: 2017-08-20.
- [2] *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*, Tech. Rep. (International Renewable Energy Agency(IRENA), 2016).
- [3] M. J. Kaiser and B. Snyder, *Offshore wind energy cost modeling: installation and decommissioning*, Vol. 85 (Springer Science & Business Media, 2012).
- [4] MATLAB, *Global Optimization Toolbox*, Tech. Rep. (MathWorks,Inc, 2017).
- [5] *Borssele Wind Farm Zone, project and site description*, Tech. Rep. (Netherlands Enterprise Agency(RVO.nl), August 2015).
- [6] [Offshore wind farm database](#), Accessed: 2017-10-12.
- [7] [Paris climate change agreement](#), Accessed: 2017-04-10.
- [8] [Global wind energy council](#), (), accessed: 2017-06-25.
- [9] *Offshore wind - Global wind 2015 report*, Tech. Rep. (Global wind energy council, 2016).
- [10] [Global offshore wind installation by 2020](#), Accessed: 2017-09-28.
- [11] [European commission, climate action](#), Accessed: 2017-04-15.
- [12] B. Scholz-Reiter, H. Karimi, M. Lütjen, J. Heger, and A. Schweizer, *Towards a heuristic for scheduling offshore installation processes*, in *Proceedings of the 24th International Congress on Condition Monitoring (COMADEM)* (2011) pp. 999–1008.
- [13] [Roland berger sees europe offshore wind at 40 gw by 2020](#), Accessed: 2017-08-16.
- [14] [Flow cost model](#), (2017).
- [15] E. Uraz, *Offshore Wind Turbine Transportation and Installation Analyses*, M.eng. thesis, Gotland University (2011).
- [16] E. Rosenauer, *Investment costs of offshore wind turbines*, Tech. Rep. CSS14-27 (Center for Sustainable Systems, 2014).
- [17] B. Scholz-Reiter, J. Heger, M. Lütjen, and A. Schweizer, *A milp for installation scheduling of offshore wind farms*, *International Journal Of Mathematical Models And Methods In Applied Sciences* **5**, 371 (2010).
- [18] M. Lütjen, H. R. Karimi, *et al.*, *Approach of a port inventory control system for the offshore installation of wind turbines*, in *The Twenty-second International Offshore and Polar Engineering Conference* (International Society of Offshore and Polar Engineers, 2012).
- [19] A. Ait-Alla, M. Quandt, and M. Lutjen, *Aggregate installation planning of offshore wind farms*, in *Proceedings of the 7th international conference on communications and information technology (CIT' 13)*. Cambridge (US) (2013) pp. 130–35.
- [20] Y. T. Muhabie, J.-D. Caprace, C. Petcu, and P. Rigo, *Improving the installation of offshore wind farms by the use of discrete event simulation*, *Improving the Installation of Offshore Wind Farms by the use of Discrete Event Simulation* (2015).
- [21] C. A. Irawan, D. Jones, and D. Ouelhadj, *Bi-objective optimisation model for installation scheduling in offshore wind farms*, *Computers & Operations Research* **78**, 393 (2017).

- [22] P. Collet and J.-P. Rennard, *Stochastic optimization algorithms*, arXiv preprint arXiv:0704.3780 (2007).
- [23] S. Luke, *Essentials of metaheuristics*, Vol. 113 (Lulu Raleigh, 2009).
- [24] [Particle swarm optimization](#), Accessed: 2017-07-14.
- [25] [Genetic algorithm optimization](#), Accessed: 2017-07-14.
- [26] I. F. Vis and E. Ursavas, *Assessment approaches to logistics for offshore wind energy installation*, Sustainable energy technologies and assessments **14**, 80 (2016).
- [27] [Great circle distance](#), (), accessed: 2017-06-15.
- [28] [4c offshore port database](#), (), accessed: 2017-06-14.
- [29] M. Zaaijer and J. Van der Tempel, *Scour protection: a necessity or a waste of money*, in *Proceedings of the 43 IEA Topical Expert Meeting* (2004) pp. 43–51.
- [30] [Gemini windpark installation animation](#), Accessed: 2017-08-10.
- [31] M. Conconi and G. Corbetta, *WP Framework/ Industry Challenges Report- supply chain and logistics*, Tech. Rep. (EWEA,GDG,A2SEA, 2014).
- [32] [Floating monopiles to owf location](#), Accessed: 2017-08-10.
- [33] [Monopiles support structures](#), Accessed: 2017-08-14.
- [34] *Cable Burial Risk Assessment Methodology: Guidance for the Preparation of Cable Burial Depth of Lowering Specification*, Tech. Rep. (The Carbon Trust, 2015).
- [35] [Cable lay by siem offshore contractors](#), Accessed: 2017-08-10.
- [36] [4c offshore artificial island agreement](#), Accessed: 2017-09-21.
- [37] MATLAB, *66 kV Systems for Offshore Wind Farms(Tennet, NL Offshore Wind Farm Transmission Systems)*, Tech. Rep. Report No. 113799-UKBR-R02, Rev. 2 (DNV GL Energy,NL, 2017).
- [38] N. J. Choi, S. H. Nam, J. H. Jeong, and K. C. Kim, *Cfd study on aerodynamic power output changes with inter-turbine spacing variation for a 6 mw offshore wind farm*, Energies **7**, 7483 (2014).
- [39] [Hywind pilot park](#), Accessed: 2017-09-06.
- [40] J. McCall, *Genetic algorithms for modelling and optimisation*, Journal of Computational and Applied Mathematics **184**, 205 (2005).
- [41] F. Alabsi and R. Naoum, *Comparison of selection methods and crossover operations using steady state genetic based intrusion detection system*, Journal of Emerging Trends in Computing and Information Sciences **3**, 1053 (2012).
- [42] [Crossover and mutation options in matlab ga toolbox](#), (), accessed: 2017-07-08.
- [43] [Fitness scaling](#), (), accessed: 2017-09-08.
- [44] K. Deep, K. P. Singh, M. L. Kansal, and C. Mohan, *A real coded genetic algorithm for solving integer and mixed integer optimization problems*, Applied Mathematics and Computation **212**, 505 (2009).
- [45] A. Alajmi and J. Wright, *Selecting the most efficient genetic algorithm sets in solving unconstrained building optimization problem*, International Journal of Sustainable Built Environment **3**, 18 (2014).
- [46] S. D. Dao, K. Abhary, and R. Marian, *Maximising performance of genetic algorithm solver in matlab*. Engineering Letters **24** (2016).

- [47] J. Wright and A. Alajmi, *Efficient genetic algorithm sets for optimizing constrained building design problem*, *International Journal of Sustainable Built Environment* **5**, 123 (2016).
- [48] [Ga options list and respective default values](#), Accessed: 2017-09-14.
- [49] [Combinatorial optimization](#), Accessed: 2017-10-14.
- [50] D. Pisinger, *Algorithms for knapsack problems*, (1995).
- [51] [Borssele wind farm](#), Accessed: 2017-10-15.
- [52] I. P. et al., *The european offshore wind industry - key trends and statistics 2016*, (January 2017).
- [53] [List of offshore wind farms](#), Accessed: 2017-10-10.
- [54] K. Hermans and J. Peeringa, *Future xl monopile foundation design for a 10 mw wind turbine in deep water*, (2016).
- [55] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, *Definition of a 5MW reference wind turbine for offshore system development*, Tech. Rep. (National Renewable Energy Laboratory (NREL), Golden, CO., 2009).
- [56] *The European offshore wind industry, Key trends and statistics 2016*, Tech. Rep. (Wind Europe, 2016).
- [57] [Transition piece](#), Accessed: 2017-08-15.
- [58] B. van Gelder and D. Pulles, *Kci's double slip joint, smart alternative for grouted and bolted connections*, *Magazine for THE OFFSHORE WIND INDUSTRY* **Vol VI, no 02** (2015).
- [59] G. Michels, *Mass production of offshore-wind-jackets requires new industrial solutions*, *salzgitter ag*, (2014).
- [60] M. Esteban, B. Couñago, J. López-Gutiérrez, V. Negro, and F. Vellisco, *Gravity based support structures for offshore wind turbine generators: Review of the installation process*, *Ocean Engineering* **110**, 281 (2015).
- [61] IRENA, *Floating Foundations: a Game Changer for Offshore Wind Power, International*, Tech. Rep. (Renewable Energy Agency, Abu Dhabi, 2016).
- [62] L. Kitzing and P. E. Morthorst, *Trends in offshore wind economics – the past and the future*, in *Proceedings - 14th Wind Integration Workshop* (2015).
- [63] R. T.-O. L. F. AG Endegnanew, HG Svendsen, *Design procedure for inter-array electric design*, Tech. Rep. (EERA-DTOC consortium, 2013-01-29).
- [64] K. Meah and S. Ula, *Comparative evaluation of hvdc and hvac transmission systems*, in *Conference: Power Engineering Society General Meeting, IEEE* (2007).
- [65] C. Stock-Williams, *Development of a Stochastic Weather Simulation Capability*, Tech. Rep. (ECN, Netherlands, December 2016).