Modelling the installation of offshore wind farms

Defining the installation of offshore wind submarine power cables using a discrete event simulation based logistics model

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TUDelft

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by

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Preface

This thesis marks a transition point in my life, where I end my studies as a master's student and begin my journey as a proactive graduate ready to find new solutions to the challenges faced by the world. Writing this report was a challenging task and required a lot of determination. I believe that I found this determination thanks to some amazing people who supported me along the way.

Special thanks to my supervisors Dr. Michiel Zaayer and Clym Stock Williams. Thank you Clym, for giving me the experience of working with TNO and to be involved in the project. Thank you Michiel, for the guidance and patience throughout the whole thesis. I think that this project was a wonderful experience overall. To my dear friends in Delft, it has been such a great time with you between the courses, exams, projects, and student team activities. Thanks alot Marloes. Your support has been so empowering for me, especially during the last months of the thesis. My friends from the home, thank you guys for all the motivating calls and discussions. Finally I would like to thank my parents and my brother, who were always there for me. I love you all.

Gopan Gopalan Achary Venkitachalam
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Abstract

A gap in the understanding of offshore wind submarine power cables is responsible for 70-80 % of failures in recent times [5]. The failures originate from the phases of design, manufacturing, installation and operations. Joint industry collaborations such as the Cable Lifetime Monitoring project that form the background for this thesis, are aimed at developing knowledge of these failures [5]. The origination of failures from the installation phase of power cables is of particular interest. In order to do so, a model has to be developed first to understand the processes involved in an installation plan, as well as their time and resource costs. Logistics and planning tools such as ECN Install are utilized for this purpose and provide the medium for capturing the installation processes for submarine power cables.

This thesis aims to describe the installation of power cables using a discrete event simulation based logistics model such as ECN Install. The first part of the thesis focuses on a literature review to categorize all aspects of power cable installation. Here the stages of a project, the installation processes, assets, methods and influencing weather parameters are identified. From this literature review it is found that the most important stage of a power cable installation project is the Marine Installation Program [9]. The decisions leading to the development of a Marine Installation plan are mapped for modelling. The second part of the thesis deals with applying the knowledge acquired into the logistics model. Here, the model assumptions are set in order to create an accurate depiction of the installation processes. The third part of the thesis investigates the influence of input uncertainties on the model as a means to understand the relationship between the different aspects of a power cable installation project to its Marine Installation Program. A sensitivity study is performed to quantify the impact of different uncertainties on a Marine Installation Program. The final part of the thesis has the analysis of a historical case study. Here the Marine Installation Program of the Gemini export cable is constructed.

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1 Introduction

In this introduction, the background, motivation, approach and structure of the thesis are presented. Section 3.2 explains the background of the thesis by introducing the industry collaboration aimed at increasing the reliability of power cables for the offshore wind industry. Here, the role of installation is touched upon leading to the motivation of the thesis. This is followed by Section 1.2 where a closer look power cable installation is provided to introduce its main aspects. This leads to framing the objectives for research, which are specified in Section 1.3. Section 1.4 is a guide to the chapters of the report.

1.1. Joint Industry Project: Cable Lifetime Monitoring

The background of this thesis project lies in framework of JIP:CALM (Joint Industry Project: Cable Lifetime Monitoring) [5]. JIP:CALM is a collaborative industry effort aimed at increasing the reliability of offshore wind submarine power cables by reducing failure rates originating from their four sequential phases; design, manufacturing, installation, and operation [27]. Initiatives such as JIP:CALM are based on studies which indicate that most offshore wind farm losses, and 70-80% of insurance claims [1], pertain to cable failures at each of these four phases. Figure 1.1 summarizes the types of claims of the power cable failures by different offshore wind industry parties.

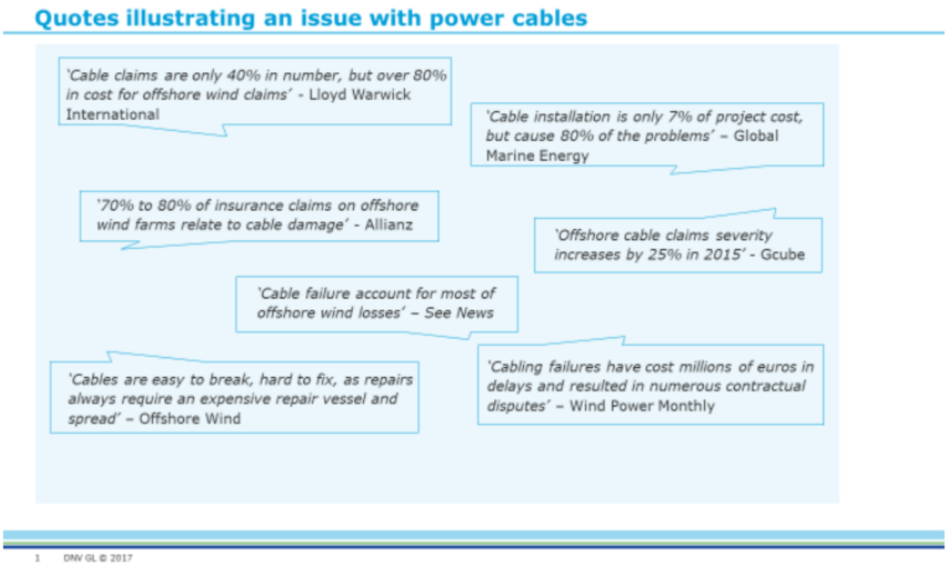


Figure 1.1: Quotes illustrating the motivation to improve the reliability of power cables for offshore wind farms. [27]

According to JIP:CALM failures in the design and manufacturing phases originate due to out-dated industry standards, testing guidelines, sea-bed burial optimization tools, and cable integrity monitoring systems. These out-dated factors result in sub-optimal handling methods, which lead to failures in the installation and operation phases. Through an extensive study of the processes within each of the four phases, JIP:CALM proposes to pinpoint and mitigate failure causes to increase the reliability of offshore wind power cables by introducing recommendations and improvements in the form of updated standards, guidelines, optimization tools, and monitoring systems.

The scope of the thesis lies within the power cable installation phase study of JIP:CALM, which aims to develop improved power cable installation practices and guidelines, that result from implementation of developments from the design and manufacturing phase studies. In order to investigate these potential improvements, the need arises to first study current industry practices by EPC (Engineering, Procurement, and Construction) companies, and to create a model power cable installation. This model is built and appended to ECN Install, a discrete event simulation based logistics tool for offshore wind farm installation and planning tool [19][12].

1.2. Problem analysis: Modelling power cable installation

Offshore wind farm power cable installation is a challenging process which requires systematic analysis due to its dependency on numerous project-specific conditions. These can consist of decision variables such as environmental conditions (water depth, sea-bed and weather conditions), asset specifications (wind farm size, cable type, vessel fleet, port location), and decision-making sequences. A logistics model such as ECN Install, when used as a tool, can assist the decision-maker to investigate individual (or sets of) dependent variables of a process to assess their influence on performance metrics of interest. This leads to conclusions about the effectiveness of the process in study, and its implication on the project costs and installation performance indicators.

Currently missing is the means to model and evaluate the effectiveness of the logistics of offshore wind power cable installation using ECN Install. Although methods and descriptions on the process of power cable installation exist in literature, they have not been implemented as a logistics model problem. Additionally, the different strategies for carrying out the process of cable installation, have not been compared, or investigated for an optimal standard.

1.3. Research objective

The core research question and its sub-questions for this master thesis can be summed up as:

"How can the processes and strategies used for the installation of offshore wind farm power cables be modelled and analysed using a logistics model?"

- *What are the stages, variables, constraints, and assets involved in offshore wind power cable installation?*
- *How can installation processes be captured, modelled and simulated in a logistics framework?*
- *What are the factors that impact the installation of power cable installation and how can they be incorporated into the model?*
- *How can the model be applied to a real case study for simulation and validation?*

1.4. Chapter guide

- **Chapter** 2 consists of a literature review on power cable installation aimed at developing an understanding of the process and establishment of a theoretical reasoning structure as a base for the decisions to be made in the modelling.
- **Chapter** 3 explains the framework of the model constructed for power cable installation. The structure of the model is described along with its base assumptions.
- **Chapter** 4 analyses the capabilities of the built model by investigating the impact of input uncertainties and their relationship to the model outcomes.
- **Chapter** 5 aims to test the theoretical understanding of power cable installation and the modelling principles and observations developed by performing a case study.
- **Chapter** 6 highlights the key conclusions of the research performed and addresses the recommendations for future work.

2

Power cable installation for offshore wind farms

This chapter elaborates on the literature review aimed at understanding power cable installation for offshore wind farms. Section 2.1 provides an overview of a power cable installation project and identifies the most important stage for the model. Next, the installation processes, assets, methods, and weather parameters are outlined in Sections 2.2, 2.3, 2.4, and 2.5 respectively. Finally, the decision logic for power cable installation is constructed and discussed in Section 2.6.

2.1. Overview of a cable installation project and focus of literature

A successful cable installation plan is the result of a series of complex multi-disciplinary engineering and project management tasks [22]. Understanding the overview of a cable installation project in this thesis is instrumental to narrow the scope of the literature review for identifying the key information required for structuring the modelling process, and for developing the necessary assumptions that form the input state for simulations. This section aims to define the stages of a power cable installation project and highlights the stage most relevant for the remainder of the literature study.

2.1.1. Stages in a power cable installation project

By assuming the perspective of an installation contractor, a power cable installation project can be broken down into four stages [9], as summarized in Figure 2.1.

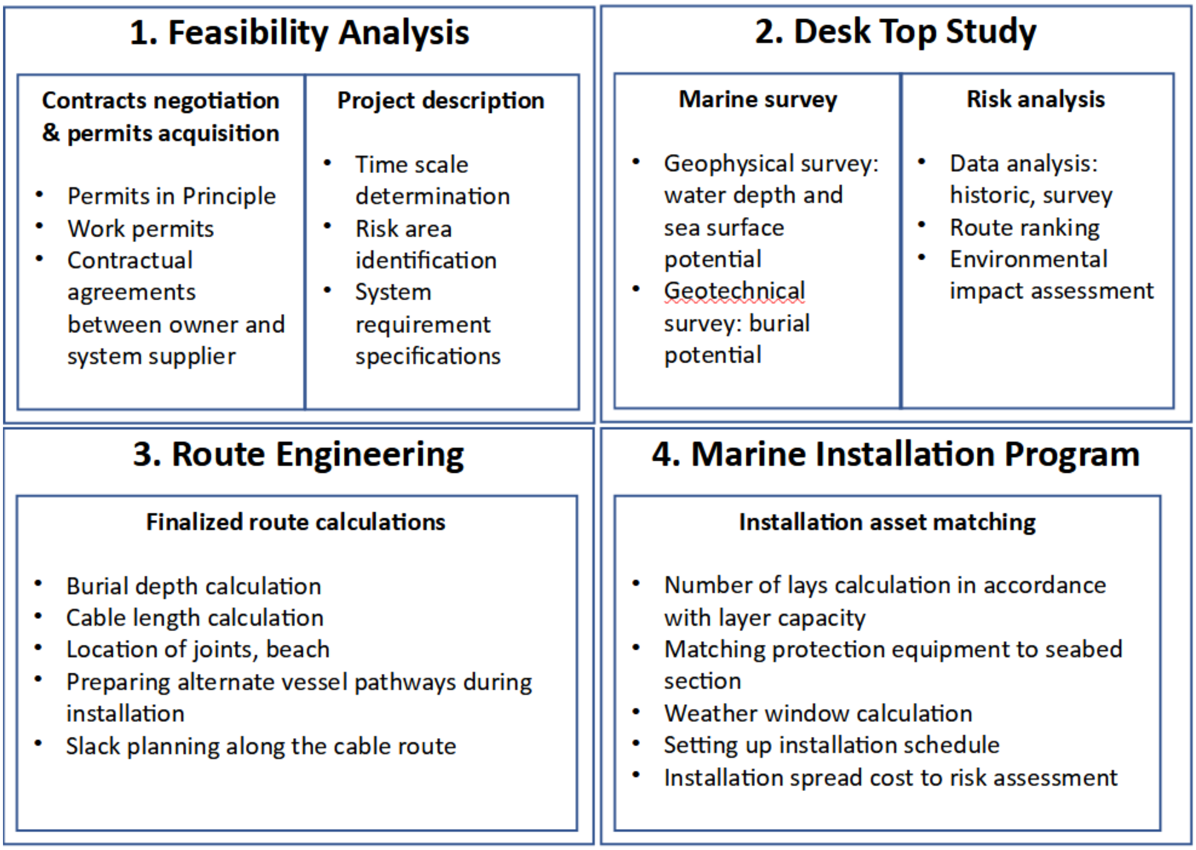


Figure 2.1: The four stages of a cable installation plan listed in order with their key objectives [9].

The first stage aims to analyse the project's feasibility. The objectives of this stage are twofold; Firstly, to secure the necessary documentation pertaining to work permits and the contractual obligations to be fulfilled by the installation contractor. Secondly, to set a target project deadline for cable installation as specified by the owner. In this stage, details such as the preferable cable system location, choice of topology, and commercial motivations in the design are conveyed by the owner to the contractor. The owner proceeds to arranging the required permits to facilitate work in those planned areas. At the end of the first stage, the contractor receives a set of possible cable routes adhering to the design principles set by the project owner.

The second stage, which is referred to as a DTS (Desk Top Study), has the contractor perform a detailed marine survey and risk analysis for a set of routes given by the owner at the end of the first stage. The marine survey consists of a water depth and burial potential assessment per feasible route. The burial depth requirements and their corresponding equipment are determined. The marine geo-physical and geo-technical surveys are conducted in a combination of on-site visits, historic data analysis, and depending on availability, information from the project owner. The marine survey data feeds into the risk analysis which investigates the potential cost and time implications of the water depth and burial potential over regions of a route. Additionally, the risk analysis reviews the possibilities of future developments over the cable installation site such as fishing activities.

The third stage is where the route engineering calculations are made. The input to the route engineering stage is the highest ranked route at the end of the DTS. Firstly the final lengths of cable required is calculated and the requirement for armouring based on the burial assessment is determined. After this, slack plan is set along the route. This determines the laying vessel's payout and transit speed based on the sea-bed contour characteristics and cable dimensions such as weight per unit length.

The final stage of an installation project is called the MIP (Marine Installation Program). This is the essentially the finalized solution space for the cable route where the applicable installation assets are matched to the route characteristics based on the requirements indicated by the previous the route engineering phase and scheduled for deployment along the route. An installation schedule is set with the project time-line in mind and an installation spread is assigned within a planned budget.

2.1.2. Literature review focus: the Marine Installation Program stage

The planning and execution of processes in the MIP stage in a power cable installation project is most relevant to the thesis and therefore to the scope of the literature review. The information for the remainder of this literature review has thus been organized with the aim of elaborating on the installation tasks, assets, methods and weather parameters that are of significance to this stage. This information will be summed up in Section 2.6, with a representation of the sequence of decisions that results in the implementation of an installation plan.

2.2. Installation processes

The installation processes for the power cable system of an offshore wind farm (inter-array, inter-platform or export cables) are defined and elaborated in this section. It is these tasks that when combined form the complex process plans in the MIP stage. The installation process that form a power cable installation plan consist of:

- Cable loading
- Land-fall
- Cable laying
- Cable jointing
- Cable pull-in

The installation task descriptions are provided below:

2.2.1. Cable loading

The power cable is first loaded onto the layer before it transits to the start point of the cable route to begin the installation process. Cable loading is performed in two methods, namely direct and indirect [3]. With direct loading the cable layer is positioned to a cable manufacturer's quay. On the other hand, with indirect loading, the cable is fed into the layer in storage tanks or drums for transport to the installation location. Direct loading is more commonly used mainly due to its ability to accommodate larger lengths of cables when compared to indirect loading which typically requires the manufacture of non reusable drums per cable section [29]. Thus, installation contractors design their cable layer storage systems (turntables/carousels) and cable manufactures locate their plants close to port to facilitate direct loading. For this thesis the direct loading will be referred to as loading.

Loading is often the most time consuming task in the installation plan and can take between days to weeks [29], depending primarily on the start date of the operation, loading equipment used at the quay, the dimensions of the cable, and the layer carousel capacity. If not planned or performed according to plan, a slight delay in the loading schedule has the possibility to push the entire project's time line by a significant margin by delaying the proceeding installation tasks and altering their weather window opportunities [8]. To minimize project delays for the entire cable installation process, every loading operation is governed by technical requirements [3], which can be summarized into three points namely:

- A well defined loading plan to match the suitable equipment to the cable dimensions. The system of equipment comprises of wheels, generators, pulleys and torsion prevention machines to avoid kinks on the cable.
- Testing at the time of loading which is performed in accordance to regulations such as the DNVGL-RP-0360 [7]. The description of testing is not covered within the scope of this thesis.
- Measures to meet the MBR (Minimum Bending Radius) of the cable's inner diameter to prevent failures while loading. Such failures are likely to occur when the cable loading system does not synchronize.

The three technical requirements stated above translate to the most important aspect of a cable loading operation which is to maintain equipment synchronization. When synchronized without errors, loading is performed at a planned rate which typically falls between 3-20 m/min [29]. This is selected based on attributes of the cable such as its weight per meter, its permissible MBR, and the equipment capacity [3].

2.2.2. Land-fall

The Land-fall operation is performed when the power cable is pulled in from the cable layer and connected to a designated onshore termination point. The land-fall area is referred to as the beach [29].

The process of land-fall begins after up to months dedicated to preparatory work done at the beach. This work consists of the creation of passage ways to facilitate cable pull-in to the onshore termination point at the time of land-fall. The scale and time taken is dependent mainly on the distance between the onshore termination and substation connection points. Tunneling is performed for distances less than 1200 m [3]. Greater distances require HDD (Horizontal Directional Drilling). For this study, the time and resources dedicated to the prerequisite activities leading to land-fall are not counted as part of the installation.

Once the preparatory work is complete, the general steps taken for land-fall can be enumerated as follows:

1. The layer transits and positions itself at an offshore point from the beach. The proximity of this offshore point to the beach is determined by the suitable water depth surrounding the beach which determines whether the layer is a self-propelled vessel or a barge.

2. Once the layer is positioned, the layer guides a messenger wire to the shore as its tension is monitored.

3. Once the messenger wire is in place the cable is released via attached flotation devices. This is performed so that the cable is also positioned above its planned lay route on the sea-bed.

4. Once the cable is floated along its route to the beach it is pulled-in to the onshore termination point where it is connected to the onshore cable via a beach joint.

Two methods of land-fall exist namely direct and indirect [3], based on the distance between the layer's offshore position and the onshore termination point. Direct land-fall is performed when the distance is less than 3 km. In this method, the steps 1 to 4 are implemented as indicated above. For indirect land-fall, when the distance is greater than 3 km, steps 3 and 4 are coordinated with the assistance of a workboat. For most offshore wind power cables, the beach location is chosen to facilitate direct landfall in an effort to reduce complexity during the installation process. Land-fall typically requires between one to two days for completion provided weather conditions are favourable and is always proceeded by the laying operation.

2.2.3. Cable laying

The cable layer pays out the cable over the designed route. The cable is guided from the layer's motorized carousel through a drum and into a chute before it is positioned on the sea-bed. A brake system controls the pay-out rate.

While laying, a slack plan is followed to ensure minimal tension on the sea-bed. The slack plan is set and optimized during the route engineering phase. On following the slack plan, the lay speed throughout a cable route can vary between 0.25 and 3 kn [9][3]. A more elaborate description of slack is given in Section 3.6.2. The lay speed is further influenced by limiting weather parameters such as the wave height, wind speed, and current.

2.2.4. Cable jointing

Cable joints are used to connect sections of cables along the route. They take a significant amount of time for manufacture, and deployment. The most used joints in an offshore wind farm power cable system are beach joints and infield joints. Beach joints are assembled as part of the land-fall process to connect the export cable to the onshore termination point. Infield joints are manufactured on board the layer in a specially designed jointing house or onshore at the production plant [29]. They are installed to connect cable sections on the sea-bed. The process of installation takes between one to ten days. They can be attached to the end of a cable, then left on the sea-bed to be connected to the next cable section. Alternately, a cable section can be left on the sea-bed to be recovered later for jointing with the next cable section. The typical time taken for the installation of an infield joint is about 80 h [18].

2.2.5. Cable pull-in

Pull-in is the operation of securing the cable into a termination point at a wind turbine, or an offshore substation. Pull-in is performed by guiding the cable underwater from the layer to an entry point with a guide wire and a J-tube.

2.2.6. Cable protection: Sea-bed trenching and cable burial

Trenching and burial tasks together build up the cable protection mechanism. On trenching, a corridor of suitable depth is created in the sea-bed using suitable equipment. Cable burial is undertaken either simultaneously during sea-bed trenching, or separately. In most offshore wind farm installation literature, the terms for trenching and burial are used interchangeably due to the assumption that natural sedimentation is the intended outcome of a trenching operation. This however is not true always due to the existence of different installation methods that require different equipment for either processes and a clear difference of time between the two tasks making them sequential and not simultaneous. In this thesis sea-bed trenching and cable burial are categorized as unique tasks to make them separable the modelling stage. Both the trenching depth requirement and burial method are pre-decided in the route engineering phase. Most commonly used burial depths are in the range of 1-10 m for all equipment [8][16].

2.3. Installation assets

The installation assets used for power cable installation are categorized into vessels and equipment that are utilized for implementing the required installation tasks.

2.3.1. The cable layer

The power cable installation plan is centered around the chosen cable laying vessel. A typical cable laying vessel used nowadays by offshore wind installation contractors is designed with the following technical requirements [9][3][29] in mind:

- A class 2 DP (Dynamic Positioning) system for accurate laying along the planned route.
- A carousel capacity between 4000 to 8000 t suitable for housing single or multiple cable sections coupled with a linear cable engine system of wheels with the ability to withstand up-to 2 t of load while paying out.
- Software tools designed to control and monitor slack in real time during the lay operation [14].
- A jointing room for the assembly of installation/field joints.
- A crew capacity of 80.

Depending on the operating water depth a barge, or a self-propelled installation vessel is selected. Cable laying barges are suitable for water depths of upto 10 m [13][23]. Cable laying vessels are suitable and most optimally utilized for all water depths exceeding 10 m [22][16]. Whenever a cable laying operation ensues, a pre-designed slack plan is followed. This is based on the sea-bed topology which is mapped in the route engineering phase.

2.3.2. Cable protection vessels and equipment

The cable protection equipment is selected based on the installation method which is elaborated in the next section. Here, the details of the spread and equipment are summarized.

- **The plow:** The plow is utilized for cable protection when the planned burial depth over the route falls between 1 to 10 m [9][3]. It is towed by the laying vessel typically at a speed range of 0.5-1 kn [3]. The design of the plow is such that the cable is paid out from the cute in the layer and over the plow frame. As the plow is dragged it simultaneously lays and buries the cable. The suitable water depth for the plough ranges from 30 m till 500 m for offshore wind farm power cables [3].
- **The ROV (Remotely Operated Vehicle) sledge:** This device is used for cable protection when the required burial depth along the route falls between 1 to 10 m [9][3][23]. It is suitable for water depths less than 30 m. The ROV Sledge is towed by a support

vessel which follows the route of a laid cable. The burial tool is designed to withstand currents of upto 3 kn and with a burial operation speed in the range of 400 - 600 m/h (metres per hour) [3].

- **The SS (Self-Supported) ROV trencher:** The self supported ROV trencher is utilized for the same burial depth requirements as the plow and the ROV Sledge. However it is applicable for cable protection only in cable route parts where water depths fall within 10 m [16]. The trencher follows the path of a laid cable autonomously with its own cable feed system and jet cutting tool at the positioning end. The typical travel speed for a self-supported ROV trencher falls in the range of 0.5 - 2 kn. [23].

- **The TSHD (Trailing-Suction-Hopper) dredge:** When burial depths of greater than 10 m are planned in parts of the cable route for optimal cable protection, the trailing suction hopper dredger is used. The travel speed for the dredge falls between 2 to 3 kn during the process [25]. The TSHD creates the trench along the cable route prior to the burial process. It then follows suite to perform the back-filling to complete burial after the laying process [22].

2.3.3. Supportive marine engineering activities

Supportive marine engineering activities are performed in addition to the installation tasks classified in Section 2.2. The requirement of supportive marine engineering tasks is determined based on the cable route properties and are assigned in the route engineering phase. This can include tunneling, HDDs, crossings, and additional protection measures when required. Supportive marine engineering activities are unique to each project.

2.3.4. Support vessels and equipment

Support vessels and equipment are deployed in cable installation project for different circumstances such as:

- **Pre-installation activities:** These include activities such as pre-lay grapnel runs which are performed to clear obstacles prior to cable laying. This is done using a grapnel towed by a multi-purpose vessel [10].

- **Special engineering tasks:** These are planned during the route engineering phase such as cable crossings, HDDs outside the beach, and boulder dumping.

- **Crew and equipment transport:** When required, crew-transfer vessels are deployed for changing work shifts. Vessels such as pontoons can be used to transfer equipment such as ROV trenchers to their required locations.

2.4. Installation methods

Power cable installation methods are derived by changing the execution order of sea-bed trenching, cable laying, and cable burial. In this section, these installation methods are introduced. The factors that govern their choice are explained in Section 2.6.

2.4.1. SLB (Simultaneous Lay and Burial)

The cable laying vessel or barge pulls a plow for simultaneous lay and burial. The layer is the only required vessel for implementation. This method is most commonly used for deep water cable installation projects where water depths exceed 200 m [3].

2.4.2. PLB (Post Lay Burial)

This is the most commonly applied method of installing offshore wind farm power cables. The cable is first laid by the layer. A support vessel then follows the laid cable path and tows an *ROV Sledge* which utilizes the applicable burial tool to achieve a burial depth between 3-10 m [3][23]. For shallow water depths a self supported ROV trencher is used to bury the cable.

2.4.3. TLB (Trench Lay Burial)

This method of installation is utilized for larger burial depth requirements which are typically above 10 m below the lowest historic sea-bed depth [23][25]. A trench is first excavated along the cable route using a dredge. Once the trench is ready the layer positions the cable over the trench. This is followed by burial which is done through back-filling.

2.5. Weather parameters for cable installation

Recognizing the relevant weather parameters and identifying their relationship with the cable installation assets is significant for the modelling phase. From literature is was noted that for executing any installation tasks an associated constraining wind speed, wave height, or current is to be noted. Cable laying vessels can spend idle time offshore ranging between hours to weeks until suitable weather conditions during cable installation [29]. The time spent idle offshore can thus exceed the ideal time required for installation. For the laying vessel, the incident wind speed and wave height impact the stability of its laying chute. For cable protection assets, the incident wind speed and wave height impact the stability of the vessels, and the currents on the other hand affect the trenching equipment used underwater [9].

Wind speed and wave height constraints are the most important weather parameters for all cable installation assets and activities due to their combined role on vessel dynamics for every installation task. For cable layers, an incident wave height induces a vertical movement at the laying chute due resulting in a periodic force due to acceleration. This adds up to the force experienced by the cable due to self weight [29]. This is monitored in real time according to the slack plan which controls the forward motion of the layer accordingly. When higher wave heights with shorter periods increase this force by producing a larger acceleration on the layer's chute, the resulting tension on the cable at the sea-bed may require the layer to stop the laying process momentarily or reduce its speed to less than 1 kn . Although the vessel is designed to operate at a higher limiting wave height the laying chute is sensitive to lower wave height values. In summary, for cable layers, the weather constraints are defined on the laying operation based on the slack plan, which controls the motion of the cable layer, based the interaction between the forces induced on the laying chute and cable due to the incident waves. A deeper insight into the interaction between the cable layer and the incident wave height during the lay process is captured in Chapter 4, Section 4.3.

The impact of current speed as a constraint is most significant for towed cable protection equipment such as the ROV sledge and the plow, which are designed to work a limiting current value of upto 3 kn [25].

2.6. Decision logic for power cable installation

The acquired knowledge on the different stages, assets and constraints involved in a power cable installation project was used to construct a decision logic. The decision logic serves as a learning outcome of the literature review and functions as a tool for justifying steps taken during the MIP stage in a cable installation project. This also forms a guideline for structuring the model for a particular installation case and assists with developing the key input assumptions for a given scenario.

2.6.1. Hypothesizing the interaction between the contractor and cable supplier

Figure 2.1 depicted the stages involved in the planning of a power cable installation project from the perspective of a contractor. It was identified that at the route engineering stage, the cable length for a given route in the offshore wind farm is finalized, and that in the MIP stage, the number of lays is calculated. On viewing these tasks it is intuitive to conclude that a method exists for calculating the number of lays. A key input for the installation model and the decision made on its implementation in any scenario is knowing how the MIP is related to the cable supply order. No information was available in the literature on this aspect of power cable installation. Thus, on developing the decision logic for power cable installation three perspectives for formulating the logic were hypothesized based on assumptions pertaining to the interaction between the contractor and the cable supplier. The perspectives were derived as a result of assumptions made due to the lack of information about the relationship between the contractor's MIP to the cable supplier's production sequence. This is summarized in Figure 2.2.

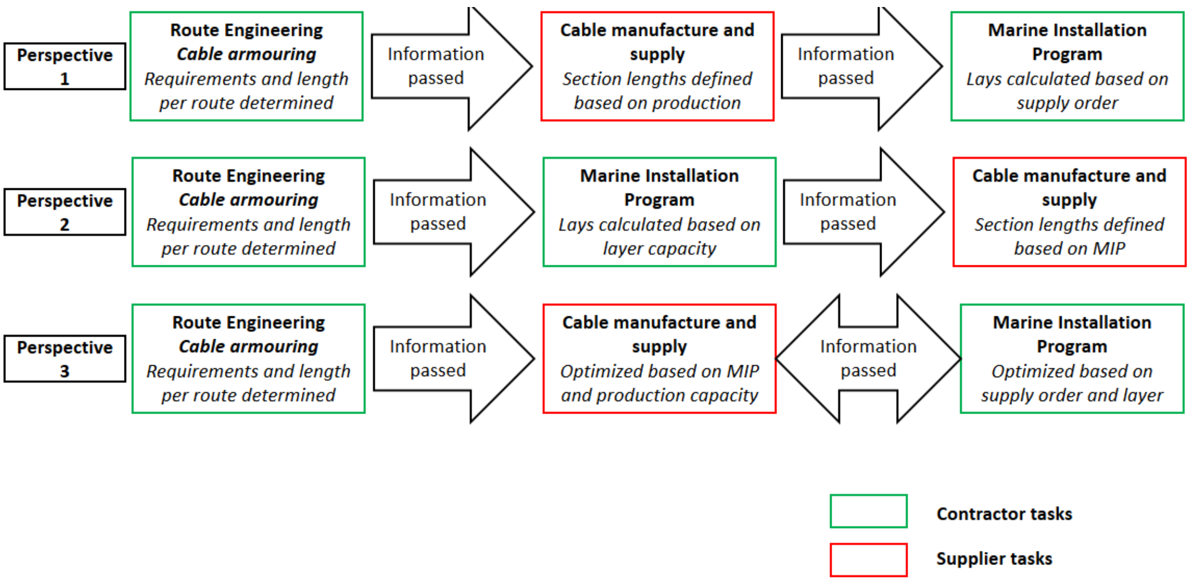


Figure 2.2: The three perspectives hypothesizing the interaction between the contractor and the cable supplier.

The first perspective originates in the assumption that the cable manufacturer dictates the cable construction and supply order when given the total route distance, and the contractor designs the MIP in accordance to the order of receiving the cable sections. The first perspective seems to fit into the stage description in Figure 2.1.

The second perspective originates in the assumption that the cable sections are supplied in lengths to the contractor for installation as a function of the limiting capacities of the layer used over the route. In other words the route lengths determine the supply order of the cables, and the limiting manufacturing length of a cable section is equivalent to the maximum capacity of the cable layer if the layer requires multiple loading instances for installation. Therefore with the second perspective, the MIP and the number of lays is calculated first over the route, then the cable sections are manufactured to their lengths accordingly. The MIP dictates the supply order of the cable.

The third perspective stems from the assumption that the cable supplier's production order and the contractor's MIP are together designed and optimized interactively so that the installer is able to utilize the installation assets effectively. The third perspective possibly mirrors reality.

2.6.2. MIP represented in the form of a decision tree

The logic was designed to facilitate all three perspectives was thus laid out in the form of a decision tree shown in Figure 2.3.

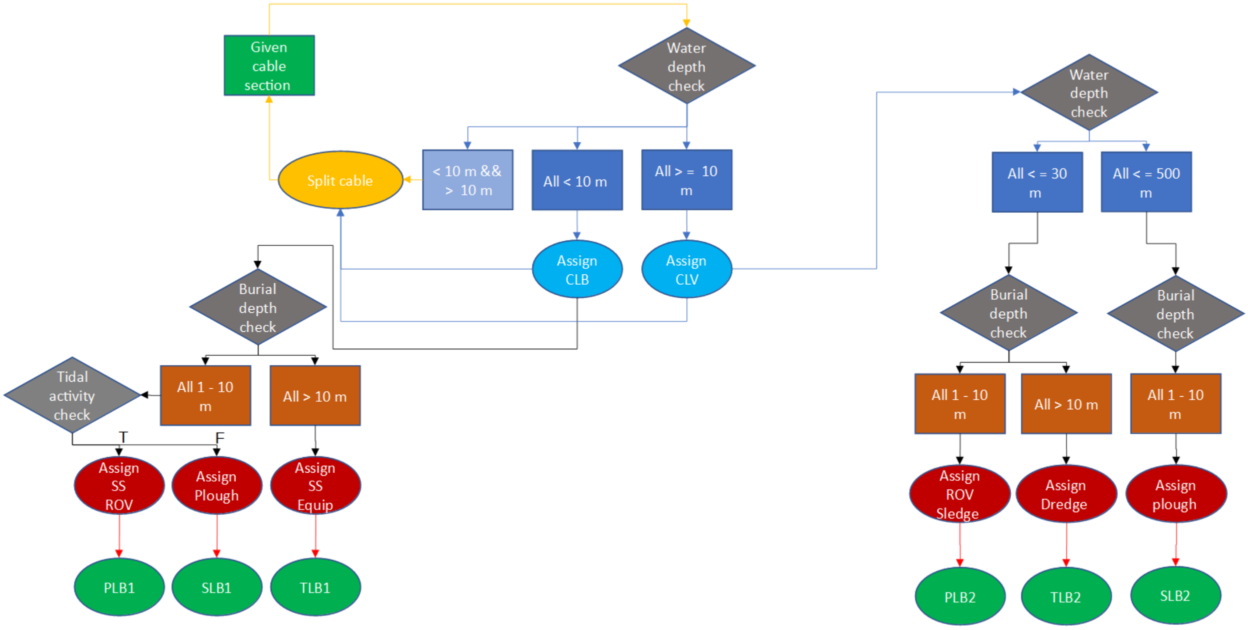


Figure 2.3: Decision tree representation for installation method choice in a MIP.

The logic has been designed in the form of a decision tree to incorporate the set of outcomes that determine the plan for an MIP for a given power cable section. This representation allows it to capture any of the three perspectives explained in Section 2.6.1. The route engineering and marine survey observations are broken down to the route water depth and the required burial depth.The decision tree derives all installation plan possibilities by connecting the installation assets to the observations made at the route engineering and marine survey phase of the project.

In total the logic traces the decisions made leading to 6 installation methods designated as **PLB**, **SLB**, and **TLB** followed by **1** or **2**. The installation methods are derived as a result of the route engineering circumstances and the number is assigned based on the requirement of a cable laying barge or a cable laying vessel. This is determined by the water depth.

3

Power cable installation model

This chapter describes the construction of the model used to describe power cable installation. Firstly the motivation behind the application of a logistics model is stated in Section 3.1. A background on the tools used for construction is given in Section 3.2. This is followed by a summary of its architecture in Section 3.3. The model process structures, base assumptions, and weather window calculation logic are defined in Sections 3.4, 3.5, and 3.6 respectively.

3.1. Application of a logistics model for power cable installation

The literature review on power cable installation provided an insight into the requirements for setting up a MIP. This serves as the basis for the inputs and assumptions for capturing the processes of power cable installation using a logistics model. This section aims to build an understanding about how a logistics model can be applied to capture power cable installation and how its implementation can be improved for capturing the installation processes.

Firstly, a brief introduction is given to dynamic analysis tools, which are typically used by contractors to model power cable installation accurately. Dynamic analysis tools form the industry standard for modelling due to their physics based mathematical modelling approaches which produce reliable estimations of weather windows required per installation task. Secondly, the motivation behind choosing a logistics model for describing power cable installation, is laid out. Here, the installation processes are represented as a logistics events and the goal is to analyse their time and resource costs. The representation of these installation tasks as logistics events requires the incorporation of dynamic modelling principles for reliability.

3.1.1. Industry standard for high fidelity power cable installation modelling

Power cable installation is a complex marine engineering task. Installation contractors use high fidelity ocean engineering dynamic analysis tools to build mathematical models for laying and protection calculations. Two most notable examples of dynamic analysis tools that set the industry standard are *MakaiLay* and *Orcaflex*. Both tools' modelling paradigms are built over the principles of forces acting on cables specified by E. E. Zajac [30]. For the lay process, the application of a mathematical model for describing the dynamic interaction between the cable, ship, and sea-bed results in an accurate estimation of the slack required along the route (Figure 3.1). The accuracy in slack calculations along a route provides a reliable estimation of the time required for the operation, and thus the weather window inputs for the MIP.

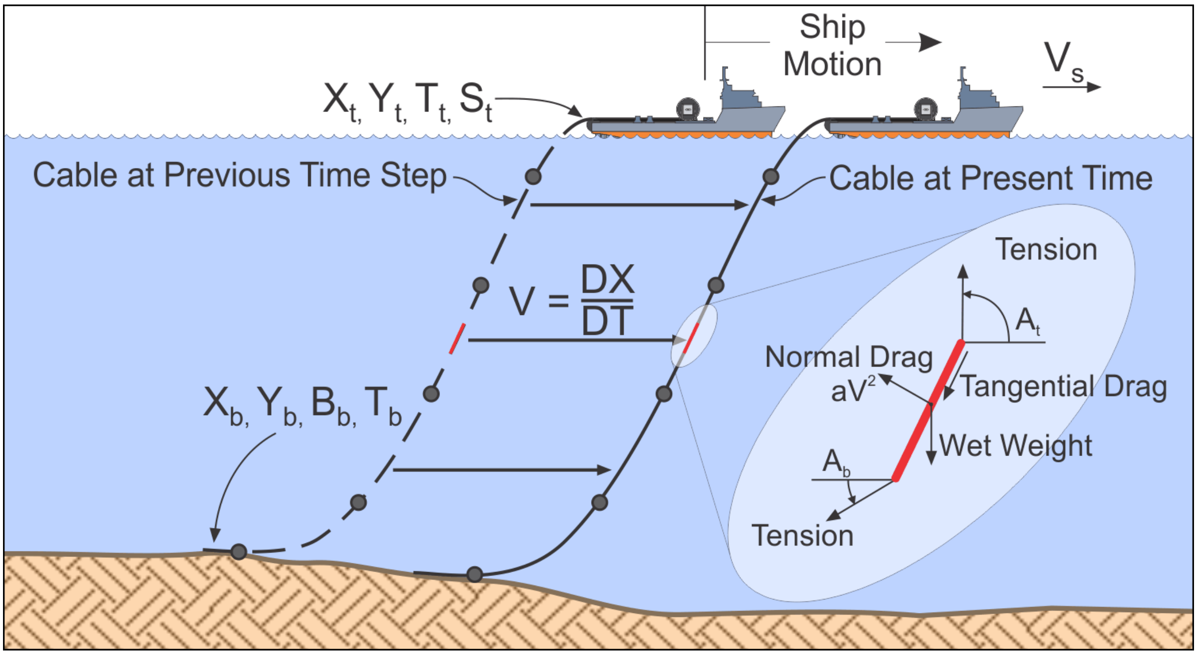


Figure 3.1: Representation of the dynamic forces experienced by a cable during the lay process captured on high fidelity mathematical models such as Makailay [14]

Similarly for the cable protection processes, dynamic analysis provides the required weather window estimations since an calculations of the burial depth are based on the physical relationship between the sea-bed material and the utilized equipment properties.

The relationship of dynamic analysis models with respect to the MIP phase can be summarized as follows:

- Dynamic analysis modelling calculations feed into the development of a MIP by giving accurate figures on the time required per installation tasks. These help to set the time required for the MIP.
- These tools also assist with monitoring the progression of an installation activity such as laying by monitoring the slack control in real time to provide adjustments along the route that occur due to changing sea-bed properties.
- Dynamic analysis tools are focused on fitting the most feasible marine engineering solution to the cable route for the MIP.

3.1.2. Motivation behind the implementation of a logistics model for analysis

A logistics model when applied to study power cable installation for an offshore wind farm, is concerned with analysing the marine engineering activities during installation from a logistics level where the objective is to analyse the resource costs of a project as opposed to an engineering driven dynamic analysis which is performed by the tools described in the previous section. From a logistics level, analysis of a proposed MIP is proceeded by the representation of all installation activities through logistics events. The performance metrics of concern from this perspective are the logistic solution's time, and resource management strategies. Applying a logistics level perspective is also concerned with investigating how a MIP fits well with time-line of the entire offshore wind farm installation campaign, and the responsibilities of the contractor and the cable supplier.

A dynamic analysis tool when applied to study power cable installation on the other hand, is concerned with devising the suitable engineering solution for the MIP. The emphasis of modelling power cable installation from an engineering perspective is on capturing the fine technical details such as dynamics. Time and resource optimizations are performed here for the engineering solution as opposed to the logistics solution. In other words, a dynamic analysis is used to set the inputs for designing a MIP whereas a logistics model is concerned with studying its outcome through simulation of different cases or plan strategies.

In summary the relationship of a logistics model to the MIP can be summarized as follows:

- A logistics model is concerned with assessing a Marine Installation Program from a logistics solution point of view. The outcome would be to comment on the feasibility and compatibility of a MIP with respect to the over-all offshore wind farm installation plan.
- A logistics model represents the engineering activities in a MIP as logistics events. Therefore the requirements for inputs into the model would be weather windows and installation asset deployment orders.
- A logistics model enables the ability to simulate scenarios of the MIP while taking into consideration the influence of the interaction between the contractor and cable supplier.

As a conclusion to the first section, the reason power cable installation is modelled using dynamic analysis tools is because installation processes such as cable laying and protection activities occur with a continuous interaction with the sea-bed properties such as the contour, material, and its dynamic behaviour. These interactions are better captured with the help of a dynamic model. When representing these installation tasks as logistics events, the model is bound to have a few limitations that need to be addressed and improved for increased reliability. Therefore, principles and assumptions from dynamic models need to be integrated.

3.2. Background information on ECN Install and UWISE ML

This section aims to provide a general background on how power cable installation is captured in a discrete event simulation environment. Firstly, the UWISE ML (Unified Wind Farm Simulation Environment) modelling language which will be used to describe the installation processes [28], and the ECN Install tool which serves as the discrete event simulation engine for the logistics model, are introduced. After this introduction, the architecture of the tool is summarized prior to the description of how they were implemented for modelling the installation pf power cables.

3.2.1. Discrete event simulation based logistics model for installation

Logistics represented by a discrete event simulation has been utilized as a tool for offshore wind farm installation modelling [21]. In a discrete event simulation approach, the logistics events during an offshore wind farm installation project are modelled and the installation tasks are depicted as a function of these logistics events. A sequence of logistics events describing an installation process is analysed in combination with the influence of location specific weather characteristics, vessel and equipment attributes, and installation strategies [21].

A basic outline of the working of a discrete event simulation can be described as follows. When discrete event simulation is applied to describe offshore wind farm installation, the progression of an installation task is calculated based on the passage of discrete time steps. An installation process is represented by block of time. Vessels and equipment descriptions are provided as inputs to the installation process. The process description in a discrete event simulation is a representation of an installation task described by the time it requires [15]. The representation of power cable installation processes, and the assets involved in a discrete event simulation is a summary of the ECN Install tool's framework.

3.2.2. ECN Install

The base concept of ECN Install is the utilization of discrete event simulation based logistics model as a method for simulating the installation of an offshore wind farm [12][19]. The discrete event simulation tool, ECN Install has been developed by TNO for modelling and simulating the installation of offshore wind farms. The tool enables the user to implement an installation plan for an assessment of its time and cost performances.

ECN Install simulates an installation plan in discrete steps that replicate the transport, logistics, and marine engineering activities. Each activity is assigned a time required and its corresponding weather parameter limitations. The inputs for a simulation comprise of weather information in the form of an hourly time series file, geographic coordinates of ports, wind turbines and substations, installation assets and their operating constraints, and the planned start and end dates of a project. A weather driven simulation on ECN install has the installation processes executed using the discrete event simulation engine under the influence of the weather constraints defined. The tool executes each installation task by finding the suitable weather window.

In summary, the value of installation simulation using this tool can be stated in the following points [11]:

- Estimation of the cost and time efficiencies of an installation project from an project developer or installation contractor's perspective.
- Selection and discussion of a preferred installation plan based on the interests of the developer and installation contractor. This is facilitated by the tool with its capability to investigate the feasibility of different installation strategies.

- Optimization of the order at which the resources and assets are assigned to an installation plan so that time and cost efficiencies are maximized.

3.2.3. UWISE ML

UWISE ML (Unified Wind Farm Simulation Environment) is an offshore wind farm process modelling language [28]. The language forms the basis for constructing the logistics and marine engineering processes used for installation of an offshore wind farm in a discrete event simulation environment. This is done by classifying real-world installation operations into categories of building blocks. The building blocks in their simplest forms are designated as actions. Actions describe basic operations such as the transit of an installation vessel, the mobilization of an equipment, work done for a marine engineering task. A combination of the actions result in an installation operation. The utility of this approach for modelling can be summarized as [28]:

- An object oriented programming approach for modelling wherein a set of blocks representing an installation process can be defined, and shared. This achieves, robustness and flexibility while modelling.
- A simplified and user-friendly method of building offshore operations out a sequence of actions.
- The scope for increasing the fidelity of a complex installation process by varying the set of actions used to describe operations.
- The scope for describing the transport, logistics and marine engineering aspects of an installation plan.

3.3. Tool architecture of ECN Install

ECN Install's architecture comprises of a project plan input handler, an installation process planner, a discrete event simulation engine, and a post-processor [12]. The project plan input handler gathers input from the offshore wind project. This is given to the tool in the form of an input excel sheet. The installation process planner enables the assembly of UWISE ML blocks and their inputs to construct an installation scenario. Independent process blocks and the process flow are defined at this stage. The discrete event simulation engine runs the installation plan modelled with the process blocks, where each step takes into account the input weather conditions provided by a deterministic hourly data-set [6]. Weather window calculations are performed per task and the resulting project delays and costs are calculated. The post-processor provides a user-friendly representation of the simulation results in the form of an out-put excel sheet containing the log of installation processes coupled with a Gantt chart. The inputs and outputs of a simulation are described below.

3.3.1. Inputs

The inputs for a simulation to be defined by the user consist of:

- **Project description:** The start and end date of the installation project are defined by the user.
- **Wind farm data:** The geographic coordinates of the foundations, turbines, and substations are defined according to the layout.
- **Weather data:** The wind speed, significant wave height, and current speed hourly time series data is fed into the simulation. The simulations run by matching the hourly weather

data time stamps to the total time required by the project starting from its specified start date till its target end date.

- **Vessels data:** The user defines the transit speed and limiting weather constraints for a given installation vessel.

- **Port data:** The user defines the port geographic coordinates.

3.3.2. Outputs

The output of a simulation consists of four parts:

- **Resource costs:** The first part of the output shows the working, waiting and fuel costs of the installation vessels used.

- **Resource utilization:** This part of the outputs is a detailed summary of the number of working days, number of transits, and number of harbour calls per installation vessel in the project. This is a useful metric for comparing two installation plans or for tracking and minimizing the waiting hours of a ship where necessary.

- **Schedule of events in a perfect weather simulation:** This is a tabulated list of events executed as per the installation plan with the assumption that no limiting weather conditions occur during any phase of the project. The usefulness of this simulation is threefold. Firstly to identify the base time required for some installation operations. Secondly to determine the ideal time of completion for the project. The finally to establish a base case for comparison against different weather conditions and simulation inputs.

- **Schedule of events under the influence of weather driven simulation:** A tabulated result section which captures the start and end date of the installation plan executed, under the influence of limiting weather conditions. This simulation result is meant to mirror reality. The schedule of operations observed at the end of a weather driven simulation showcases the time taken per installation process; namely its core duration and its associated weather delay. The weather delay for an operation is caused by the waiting time required for finding the suitable weather window for the execution of a process. Understandably, this waiting period varies based on the length of the weather window required for an installation task and the time of the year at which an installation task is planned among other factors.

3.4. Power cable installation operations defined with UWISE ML

This section aims to explain how the power cable installation tasks explained in Section 2.2 are modelled using UWISE ML. First a brief introduction to the key UWISE ML blocks used is given.

3.4.1. UWISE ML actions utilized

The key UWISE ML actions used and their attributes are briefly explained in this section. A UWISE ML action or a sequence of actions together forms the representation of a logistic or marine engineering task. The most important actions used for power cable installation modelling are summarized in Table 3.1 [28]:

Table 3.1: Table describing the different set of UWISE ML actions.

UWISE ML action	Description	Effects	Parameters
Transit	Setting the destination for a movable entity (vessel or equipment) and travelling to it.	The vessel or equipment executes a coordinate specified motion. The time required is influenced by the distance, vessel speed, and constraining weather conditions.	- Destination - Route - Speed
Work	The work block is a representation of an activity.	Entities perform the work in accordance to the specified weather window and constraints.	- Duration - Actors
Cable transit	Setting the destination for a cable laying vessel to simulate a continuous cable installation process such as lay or protection	The vessel or equipment executes a coordinate specified motion. The time required is influenced by the distance, vessel speed and constraining weather conditions.	- Destination - Route - Rate/Vessel speed
Transfer	Moving an entity between two places. For example between the port and the vessel	The entity is stored in a different object and can travel with the vessel.	- Entity to be transferred - Destination (vessel) - Duration

3.4.2. Power cable installation tasks modelling

The power cable installation tasks defined in Section 2.2 were modelled by assigning the UWISE ML actions individually or composite combinations and sequences. This is summarized in Table 3.2:

Table 3.2: Table summarising the utilization of UWISE ML actions for the different power cable installation processes.

Cable installation task	UWISE ML action(s)	Inputs	Entities
Cable loading	- Work	Cable loading rate	- Cable layer - Port
Land-fall	- Work (multiple)	Weather window per sub-task	- Cable layer - Beach location
Cable laying	- Cable transit	Vessel speed during lay	- Cable layer - Cable route
Cable jointing	- Work	Weather window	- Cable layer - Joint location
Cable pull-in	- Work	Weather window	- Cable layer - Pull-in substation/ wind turbine foundation
Cable protection	- Cable transit	Vessel/equipment speed during cable protection	- Cable protection vessel/equipment - Cable route

The UWISE ML actions were assigned such that the input parameters fits into the information required to execute the process. It must be remembered that in a discrete event simulation, an installation task is represented by the time required for its completion. Therefore the most important input for every cable installation task is its weather window.

Besides the installation tasks represented above, all vessel logistics operations were represented using the transit action with the inputs defined as the vessel speeds. The combination of installation actions and vessel logistics orders result in an installation plan.

3.4.3. Power cable installation method modelling

The power cable installation methods discussed in Section 2.4 have been modelled by assigning a sequence to the installation tasks contained. Figure 3.2 showcases the process flow for a PLB installation method. Figures 3.3, and 3.4 show the SLB and TLB installation methods.

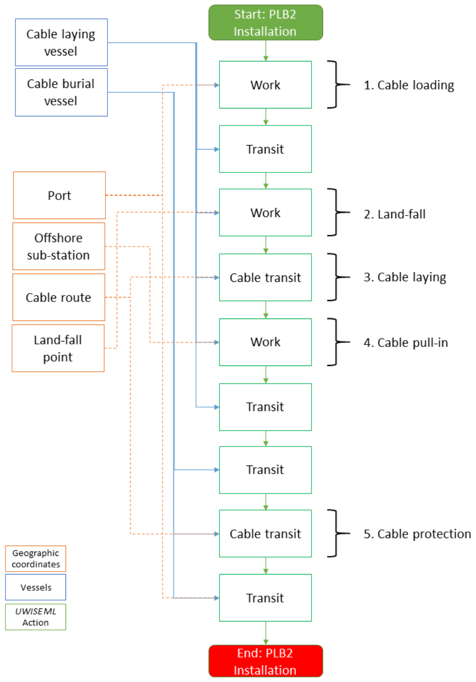


Figure 3.2: Installation process flow for the PLB (Post Lay Burial) installation method.

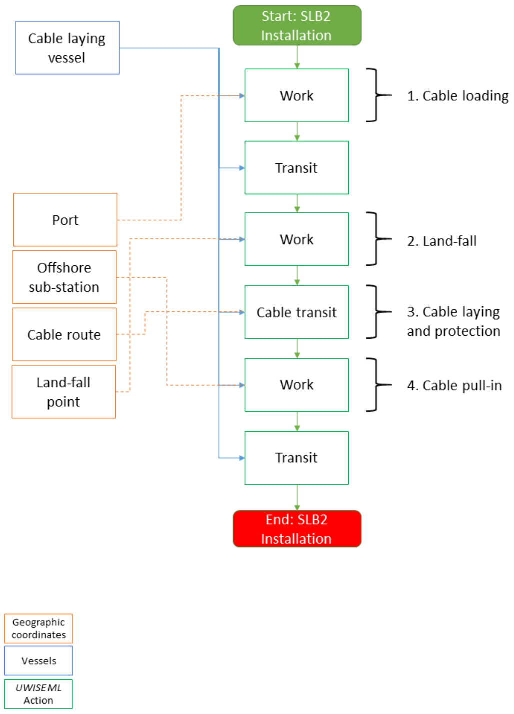


Figure 3.3: Installation process flow for the SLB (Simultaneous Lay Burial) installation method.

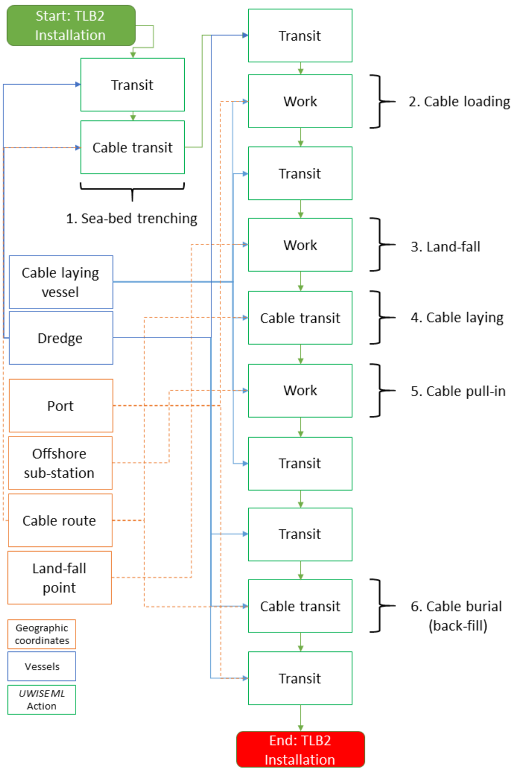


Figure 3.4: Installation process flow for the TLB (Trench Lay Burial) installation method.

3.5. Model base assumptions

The base assumptions in this model, that dictate the installation process, and the project circumstances surrounding a MIP are:

- The installation of offshore sub-stations, wind turbine foundations and beach work required for landing are assumed to be complete at the beginning of implementing a MIP.
- The scope of the installation activities modelled excludes preparatory work done onshore with the exception of power cable loading. Power cable loading is considered part of the installation task due to the involvement of the cable layer.
- Sea-bed morphology properties are assumed constant at the time of the route engineering phase and at the time of implementation of the MIP.
- The crew working shifts are assumed to be 24 hours by default. This is due to the lack of clear knowledge in literature about optimal crew working shifts specifically for power cable installation activities.
- The cable supply chain performance on land is assumed to be perfect. This implies that there is never any delays in the delivery schedule, or shortages in the inventory or production capabilities of the supplier. The transport networks on land are assumed to be reliable and compatible with the installation project goals.
- The installation tasks that formulate a power cable installation method are assumed to occur sequentially and not in parallel under any circumstance.

3.6. Model structuring and weather window calculation logic

This section elaborates on the classification of power cables used in the model and the conceptual basis for cable laying calculations performed. The last part of this section provides a brief overview on how weather window calculation is performed for installation tasks

3.6.1. Power cable classification for all installation scenarios

In order to account for a multitude of power cable installation scenarios, and for the ease of structuring the installation process flow, power cables sections have been classified in this model based on their position along the cable route. The positions are demarcated based on the supplied cable section's two termination points. This is summarized by Figure 3.5.

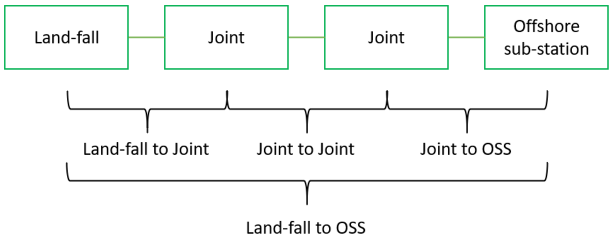


Figure 3.5: Classification of the different types of power cables used for an MIP.

3.6.2. Conceptual basis for cable laying to formulate logistics model inputs

In Section 3.1, it was mentioned that on capturing power cable installation in a logistics model environment where installation processes are represented as a function of the time, the requirement of reasonable estimations for weather windows is key for the reliability of simulations for any form of analysis. It was also mentioned that dynamic models capture power cable installation tasks more accurately and thus produce reliable weather window estimations. This leads to the conclusion that in order to accurately simulate power cable installation processes in a logistics environment, some calculation methods used in dynamic modelling have to be incorporated to build weather window inputs. This sub-section aims to elaborate on how some dynamic analysis elements have been integrated into the structure of some cable installation tasks; in particular cable laying.

Cable laying over a designated route is set based on a slack plan which ensures that the tension in the cable is minimized on contact with the sea-bed. The slack plan is the most critical aspect of the laying process [9]. This is because it determines and sets the relationship between the cable layer's transit speed and cable payout rate throughout the route [9]. Knowing this relationship is a crucial input for the model.

In general, slack (s) for a cable is defined as the percentage change a power cable section's length to be paid out from a layer with respect to the length of the route. This is expressed in Equation 3.1.

$$s = 100 * \frac{L_{cable} - L_{route}}{L_{route}} \% \tag{3.1}$$

In other words, the slack plan determines the percentage of cable length to be positioned over the route as the lay task ensues along the route. The slack plan is monitored in real-time during the lay process, and is modelled for the estimation of the time it requires. The principle behind numerical modelling of slack considers the changing sea-bed topography. Therefore, the slack and in effect the vessels motion requires calculation per unit time over the traversed length of the route. This is represented by Equation 3.2, Where dL' represents the distance traversed over the sea-bed, dL the length of the cable laid at an instantaneous time interval [9].

$$s_{instantaneous} = 100 * \frac{dL' - dL}{dL}\% \tag{3.2}$$

The above expression can build a simplified relationship connecting the cable laying vessel speed to the cable payout speed. Simplification implies assuming that dL' and dL are constant along the route at every instance of time. This means that the instantaneous vessel speed and the cable payout rate are constant. The slack expressed in terms of vessel speed and payout rate is given in Equation 3.3 [9]. This leads to the expression for cable layer speed in Equation 3.4.

$$s = 100 * \frac{V_{payout} - V_{transit}}{V_{transit}}\% \tag{3.3}$$

$$V_{transit} = \frac{V_{payout}}{s + 100} * 100 \tag{3.4}$$

Equation 3.4 is important for modelling cable laying in a logistics environment because it gives the cable transit action input a clear description on what the vessel transit speed could be during the lay process and therefore a reliable weather window. The slack is assumed constant under this simplified approximation.

3.6.3. Weather window calculation for installation tasks

The weather window is for an installation task is defined as the amount of time available under specific weather conditions that enable its facilitation [7]. The specific weather conditions are defined by constraining weather parameters for equipment and work. The weather constraints which are also referred to as operational limiting conditions by DNVGL-RP-0360 recommended practices [7], dictate the availability of a weather window in an installation plan. Constraints are defined by the working limits of the assets for power cable installation. For power cable installation tasks weather windows are calculated and classified based on the DNV-OS-H101 marine engineering operations guidelines [20]. The approach for calculating weather windows for a power cable installation activity is expressed in Equation 3.5.

$$T_{weather\,window} = T_{required} + T_{contingency} \tag{3.5}$$

The time required for an installation task is determined in this model by the input time or rate at which the activity takes place. For example, when setting the time required for cable laying, the rate of laying provided as input to the UWISE ML action determines this. This is applicable to all installation tasks that require an input rate. The contingencies are defined as per the number of factors that affect the time of the operation. This includes the operation's execution time margins, and other uncertainties such as error probabilities [20]. Contingencies are specific to the installation task. The definitions for the time required per installation task and their associated contingencies are defined in Chapter 4 more elaborately.

4

Power cable installation model analysis

This chapter aims to identify what are the aspects of power cable installation within the framework of the model structure and assumptions, that can be studied to understand the relationship between the inputs and outputs of a MIP. This begins with the identification of model input uncertainties which are defined in Section 4.1. Next the classifications of uncertainties are elaborated in Sections 4.2, 4.3, and 4.4. A cable installation scenario is modelled in Section 4.5 for a sensitivity study described in Section 4.6.1.

4.1. Model input uncertainties

The power cable installation model framework requires a specific set of inputs defined in Section 3.3. The inputs are a representation of the structure of a MIP. When modelling an installation scenario, it is important to identify the sources of uncertainty per input. Identifying uncertainties helps define their impacts on the MIP. This section aims to define the scope and properties of model input uncertainties that are expected during a MIP.

4.1.1. Input uncertainties and their role in analysis motivation

Input uncertainties for the model are the set of reasonable discrete numerical values or ranges that influence the model's ability to account for the contingencies in an MIP. Identifying the sources of uncertainties in the model can be useful for modelling a MIP accurately. Furthermore, the addition of uncertainties in a model can help in the analysis of the following:

1. To understand the sensitivity of an MIP to changes in the inputs.
2. To develop a quantitative sense on time and resource cost per installation activity. This can serve as a learning outcome for creating a general analysis framework that can be utilized for future case studies.
3. To identify project bottlenecks and plan optimization strategies based on the uncertainties observed.
4. To estimate the contingency time per installation activity for weather window calculations.

In summary,input uncertainties enable the modelling of a MIP in most realistic way. In this chapter, it is of interest to understand the sensitivity of an MIP to changes in the input uncertainties.

4.1.2. Categorizing input uncertainty sources in a Marine Installation Program

The previous section discussed how the input uncertainties help with analysing various aspects of a MIP. This sub-section identifies the sources of input uncertainties. On modelling a power cable installation scenario, the project and asset specifications are defined in ECN Install's environment, and the installation tasks with UWISE ML actions. The uncertainty sources from these inputs are listed below:

- The project, cable route, port, and installation asset specifications defined as entities in ECN Install.
- The input data per installation task (UWISE ML action(s)), known to the user while modelling a specific scenario.
- The input data per installation task (UWISE ML action(s)), unknown to the user while modelling a specific scenario.
- The input data range per installation task (UWISE ML action(s)), that is intrinsic to its nature. The range exists as a result of factors such as how the process can be achieved with different equipment, different usage of equipment, and different environmental conditions.
- The installation method sequencing and order defined per set of UWISE ML actions.

Listing the uncertainty sources above enables their categorization into three major forms. These are; ***Process uncertainties***, ***Asset constraint uncertainties***, and ***Installation strategy uncertainties***. These three uncertainty categories build a framework for the sensitivity analysis for a MIP. The three forms of uncertainty are elaborated in the following subsections.

4.2. Process uncertainties

Process uncertainties pertain to the UWISE ML action block inputs that are used to define installation tasks. These are illustrated below in Table 4.1. The determination of an process uncertainty and its margin for a sensitivity study is based on a logic flow resulting **four stages**. The **first stage** deals with noting the description of a task and its input requirements in a MIP. This is followed by the **second stage** where the known input values and ranges from literature are identified, (as covered in Section 2.2. The **third stage** deals with identifying the unknown information required to determine the inputs for an installation task. Unknowns are identified based on two factors. The first factor is the unavailability or inaccessibility on the physics of an engineering task in literature. The second factor is the limitation of incorporating dynamic influences on engineering task in a discrete event simulation engine used in the logistics model (which was discussed extensively in Chapter 3). The combination of the two factors determined per task in the third stage lead to the **fourth stage**, which pertains to the model assumptions set to establish alternatives or simplifications to physics based estimations per task, and to offset the limitations of utilizing a logistics model to describe complex cable installation tasks.

The outcome of these four steps is determining the process uncertainties per installation task wherein both the potential rate of its execution due its dynamic behaviour, and user unknowns are both incorporated. Additionally, knowing the process uncertainties per installation tasks plays a crucial role when designating the contingency time $T_{contingency}$ for weather window calculations. An example of the four steps described above to identify process uncertainties per installation task can be summarized as follows for cable laying:

First stage: Cable laying requires a slack plan as an input in a MIP. The input requirement for a slack plan as per the model is the vessel transit speed.

Second stage: The slack over a route defines the transit speed of the cable layer. The model requires transit speed as an input to define the cable laying process and this is determined from the Equation 3.1. This serves as the connecting relationship between slack, payout rate, and the vessel transit speed.

Third stage: The unknowns when it comes to determining the transit speed of the cable layer in this model hinges on the relationship between the cable layer's payout rate and the slack distribution over the route. The cable layer's payout rate input margin is assumed to fall between 0.6 - 1.2 m/s. This value is based on a dynamic model analysis for cable laying [26]. Although this range is based on values used in a model, it is more reliable for estimating the vessel transit speed margin for two reasons. Firstly, the data available for transit speeds of vessels during the lay operation (0.25 - 3 kn) is based on the total set of observable values. This pertains to a transit speeds that correspond to a broad set of slack values, vessels, equipment, and different sea-bed conditions. Accurate slack calculation over a cable route can only be performed with a dynamic analysis tool and for this reason, for the ease of calculation in this model slack is assumed to be constant or to fall within a small margin. The second reason is that in the model where the payout range has been derived from, a realistic set of assumptions were provided for the dynamic analysis where the forces on the cable and lay conditions were given. The consideration of these factors makes the range available from [26] more reliable when compared to the generic vessel transit values given in [29].

Fourth stage: The model's approach for estimating the cable layer transit speed for a given cable section is based on the assumption of a constant or very narrow slack distribution coupled with a margin for the payout rate of the layer between 0.6 - 1.2 m/s.

The remaining cable installation processes and the approach to define and determine uncertainty is elaborated in extent in Table 4.3.

Table 4.1: Process uncertainties per installation task.

Installation task	Marine Installation Program process requirements and inputs	Literature data	Unknowns	Model assumptions	Sources of process input uncertainties
Cable loading	- A cable loading plan is required as a process input for the loading task.	- Cable loading is most commonly performed directly at the port - The cable loading rate is calculated based on the cable weight per unit length, and loading system constraints. - Literature data indicates that loading rate for power cables falls typically between 3 - 22 m/min [29]. - For a given cable a loading range is planned based on its weight and the cable loading system maximum speed - Heavier cables have smaller loading rate speeds planned	- Theoretical relationship between planned loading rate and cable characteristics - The safe loading rate for a given cable loading system to prevent synchronization errors	- The lower the loading rate, the lower the chances for synchronization errors - Weight per unit length of the cable has an inverse relationship with the planned loading rate	- The margin for a planned loading rate range for a given cable
Land-fall	- A land-fall method plan along with beach work preparations complete at the time of implementing the MIP	- Beach preparation work requires months prior to land-fall which includes tunneling or HDD which is determined based on the distance between onshore termination point and the onshore substation point - Land-fall method is determined based on the distance between the cable layer and the beach onshore termination point which is decided at the route engineering phase [3]	- Time taken per task in a land-fall operation - Time taken for floating, rate at which the floating operation process is likely to occur - Time taken for the pull-in process, rate at which the pull-in process onshore is likely to occur based on the cable weight, surface friction, and maximum safe pulling force applied by the equipment - Time taken for onshore joint installation - Land-fall operation for parallel power cables	- Direct land-fall operation maximum time for completion assumed to be approximately 48 h - Indirect land-fall operation maximum time for completion assumed to be approximately 60 h - Beach work assumed to be ready at the time of installation - Floating operation rate assmued 0.5 m/s - Pull-in operation rate assumed 0.5 m/s - Onshore joint assumed to be ready at the time of installation - Land-fall operation done individually per cable section	- Time required per event - Percentage change in time required
Cable laying	- Slack plan is the primary driver for the lay operation	- A cable layer's average speed during the lay operation falls between 0.25 - 3 kn [9]. - The speed of the cable layer varies according to the slack plan which is modelled dynamically at the route engineering phase, and monitored in real time during the process. - The slack value range for a power cable section along a particular route is set based on the terrain characteristics. This typically falls between 1-2 percent for most power cables [3]. - The slack value for a power cable relates the the cable payout rate and the vessel speed - In an SLB installation scenario, typically vessel speed is 0.5 kn [9]	- The relationship between cable properties and payout rate - The translation of instantaneous slack calculation values to the instantaneous vessel speed - Average vessel speed for a route can not be determined as a fixed value because slack is re-monitored during the lay process	- A constant payout rate is assumed for the layer - A constant slack margin for throughout the route - The layer travel speed margin is based on the constant slack and payout rate assumptions - Sea-bed properties constant during the laying process	- The range of average laying speed for a given route
Cable jointing	- Joint type and assembly location	- Cable layers are equipped with a jointing chamber were a cable joint is assembled offshore when required - Most commonly used joints for power cables is the infield/offshore joint which is assembled offshore - The total time taken for installation of a infield joint is 80 h [16]. - Joints can be installed at the end of a cable section, or the cable section can be left on the sea-bed to be recovered at a later stage for the jointing process	- Time taken for sub-processes in the assembly and installation of a joint - Relationship between type of joint required and cable dimensions	- Weather window for joint installation includes joint assembly and cable connection	- Percentage change in jointing weather window
Cable pull-in	- Safe distance between cable layer and platform pull-in point	- Cable pull-in process is facilitated by means of a guide wire and a J-tube to control the trajectory of the cable to the platform	- The time required for cable pull-in - Safe distance between vessel and platform	- Weather window for cable-pull in assumed to be 16 hours	- Percentage change for pull-in weather window
Cable protection	- Cable installation method detemines the cable protection method and process	- Cable protection equipment is assigned based on the burial depth requirements along route - Cable protection is performed based on the installation method - The nominal cable burial rate of a typical ROV Sledge is 600 meter per hour [9] - In case of a TLB installation method, the dredge maintains an average speed between 2-3 kn [25].	- Relationship between the sea-bed composition and burial rate - Burial depth modelling at the route engineering phase	- Nominal rates per equipment assumed as average value throughout the route - Sea-bed properties assumed constant and unchanged throughout cable protection operations	- Marginal change in the average rates per protection equipment

4.3. Asset constraint uncertainties

Uncertainties stemming from ***Asset constraints*** pertain to the relationship between the inputs that define the properties of the installation assets, power cable, sea-bed, and their interaction with weather parameters. ECN Install data inputs define asset specifications and constraints, which are stored as entities for the Discrete Event Simulation engine.

Asset constraints have been defined as an uncertainty criteria due to their requirement as correct input in the case of a specific installation asset. Both these aspects are explored below in depth.

4.3.1. General approach for setting operational limits of installation assets

For vessels, these are the operational limits and transit speed. In this study, the sources of data inputs for the transit speed and operational limits of vessels are subject to the availability of publicly accessible information. Therefore, the impact of this uncertainty category is of particular interest especially when the motivation of analysis is to reconstruct a historical case study. This is because the specifications of the assets used in a historical case are required as inputs for accurate validation.

It is intuitive to think for all installation vessels, higher operational limits are desired so that the marine installation activities are executed more extensively as they are hindered less by weather disturbances. For power cable installation vessels and equipment, wave heights, wind speeds and current speeds are of relevance when it comes to defining operating constraints. The operating wave heights are defined as per the specification of vessels and equipment from few publicly accessible documents provided by installation contractors [16], however most are kept confidential presumably due to competitive reasons.

4.3.2. The case for assigning operational limit uncertainty for cable layers

The straightforward method for defining the operational limits for installation vessels is based on its design limits, or based on the maximum wave limits that obstruct installation work offshore. These are defined as inputs for entities in ECN Install. The limiting offshore work wave limit is sufficient for most vessels, with the exception of cable layers.

For cable layers, the laying process is not constrained exclusively by the limiting offshore work wave height. Assigning the this wave height as a constraining limit for laying results in an oversimplification of the input for asset constraint, and can lead to potential underestimations in the criteria for weather window calculations.

The reasoning behind the insufficiency of assigning a limiting offshore work wave height as an upper limit is due to the dynamic interaction between the laying chute and the power cable which extends from outside of the ship and maintains contact with the sea-bed. The laying chute is under vertical motion alongside the vessel in the presence of an incident wave height. This induces an acceleration, and consequently a force on the cable which is added to the force due to self-weight [29].

4.3.3. Cable layer RAO as a contributor to asset constraint uncertainty

An estimation of the cable layer's true limiting wave height as a function of the interaction between the laying chute and the incident wave height can be discerned from the RAO (Response Amplitude Operator) factor for a vessel. This is expressed by Equation 4.3.4 [29]:

$$RAO = \frac{H_{heave}}{H_{wave}} \tag{4.1}$$

The variables H_{heave}, and H_{wave} represent the heave motion distance, and incident wave height respectively. A cable layer's RAO is a reflection of its design and equipment properties expressed in terms of its dynamic movements when interacting with waves. In other words the layer's RAO relates wave characteristics to vessel movements [29] considering the influence of the laying chute. This is a very important criterion for cable layers and thus forms an ***asset constraint*** input uncertainty.

RAO is measured in m/m (metres per metre) movement of the vessel with respect to the incident wave height. The most key movement for a cable layer during the lay process is its heave, or in other words its vertical motion. An estimation of of the RAO heave limit for a cable layer with a payload capacity of 6000 t can be in the around 0.6 m/m [29].

4.3.4. Application approach for RAO to set asset constraint uncertainty margin

The application of RAO to set *asset constraint uncertainty* in the model inputs for a cable layer is best explained with an illustration. Equation 4.3.4 shows the relationship between RAO, *Vessel motion*, and the *Incident wave height*. **The objective will be to assign a suitable range for asset constraint of a cable layer based on the limiting wave height for the laying chute.**

The following steps have been applied to set the uncertainty range for cable laying wave heights.

1. For a given cable layer; the design wave height for the vessel if known can be equated to the upper limit for cable laying chute.

2. The RAO for the cable layer is dependent on its payload capacity and is in principle constant.

3. The lower limit for the cable laying chute can be assigned with a percentage based margin *(10-15 %)* deviating from the upper limit.

4. The selection of this percentage margin for the cable laying chute can be based on the relationship between the vessel's RAO and the cable weight per unit length.

5. If the cable weight per unit length is high (such as for an armoured cable *50 - 100* kg/m [23] [8]), then it is logical to conclude that the laying chute is likely to experience higher magnitudes of dynamic forces and therefore the limiting wave height margin tends further from the upper limit.

6. If the cable weight per unit length is low (estimation: < *50* kg/m), then it is reasonable to assume that the cable laying chute for the same cable layer is likely to experience lower dynamic forces and therefore the limiting wave height margin tends closer to the upper limit.

4.4. Installation strategy uncertainties

Installation strategy uncertainties is a broad categorizations of the potential uncertainties in a MIP that are driven by the project level decisions. The phrase project level decisions here refers to those made individually by the installation contractor or in unison with the offshore wind farm owner and the cable supplier. This encapsulates modifications in an installation plan or optimization decisions to meet deadlines. Examples of events that have been categorized under *installation strategy uncertainties* are listed below:

- **Project timeline changes:** This includes changes in the installation deadline for the contractor that require modifications for the MIP [8].

- **Marine engineering solution changes:** This includes changes in the installation method for a power cable if applicable due to various reasons such as equipment failure or seabed property changes that lead to the changes in the cable protection requirements [8].

- **Crew working pattern changes:** This covers the decisions governing the working shifts [23].

- **Installation asset changes:** This pertains to the addition or removal of installation assets as a response to manipulating the efficiency of a MIP at the time of its execution [8].

- **Cable supply chain order changes:** This pertains to changes in the order of installation of cables governed by the supply order for power cables.

Installation strategy uncertainties are of relevance for historical case study reconstructions to analyse and measure the magnitude of project level decision changes on the resource and time of a MIP. For sensitivity studies, *installation strategy uncertainties* can be applied to study the potential impact of the above factors on the MIP and can assist the user to optimize the plan as a result.

In context of the model, *installation strategy uncertainties* are implemented by a combination of changing the entity definitions on ECN Install, and the order or sequence of the UWISE ML process flow.

4.5. Modelling a cable installation scenario with input uncertainties

The model input uncertainties have been defined based on the analysis motivation described in Section 4.1, and categorized in Sections 4.2, 4.3, and 4.4 based on their relationship to a MIP. This section elaborates on the construction and application of modelling assumptions to a general cable installation scenario where model input uncertainties are incorporated. The objective of such a scenario is to serve as a precursor to a sensitivity study in Section 4.6 where the impact of the *process*, *asset constraint*, and *installation strategy* uncertainties are quantified to establish a generalized understanding on the relationships between the inputs of a MIP and its time and resource utilization outputs.

Scenario input summary

Table 4.2 summarizes the scenario inputs.

Table 4.2: Summary of cable installation scenario model inputs

Marine Installation Program model inputs	Scenario parameter summary
Cable section specifications	- Cable length: 28.325 km - Cable type: Joint to Joint - Cable weight per unit length: 59 kg/m - Cable route distance from port: 15 km
Project duration	- 1 month deadline (March)
Installation methods	- PLB 2 (Cable laying vessel and ROV sledge)
Asset specifications	- Cable layer: (transit speed: 11 knots, design limit wave height: 3 m) - Support vessel towing ROV sledge; (transit speed: 12 knots, design limit wave height: 3m)

Cable specifications

The installation scenario consists of an export cable section with a length of 28.325 km. The cable specifications are based on the export cable used in the Lillgrund offshore wind farm [8]. The cable section is located between joints along the cable route. The distance of the cable laying start point from the port is 15 km.

Project specification

The installation project schedule is set with a deadline of one month for completion. The deadline is assumed to be set per contractual obligations of the contractor.

Asset specification

The installation asset base specifications, namely the vessel transit speeds and limiting wave heights are defined based on the the commonly used cable installation assets [16].

Installation method specification

The installation processes flow mirrors the method template for post lay burial using a cable laying vessel for laying and a towed ROV sledge for cable protection as defined in Figure 3.2.

Installation task process inputs with uncertainty ranges

The Table 4.3 summarizes the inputs per installation task.

Table 4.3: Table summarizing the installation task inputs and their reasoning

Installation task	Scenario input	Reasoning
Cable loading	- Loading rate: 5-6 metres per minute	- Guess value based on cable weight per metre
Cable laying	- Laying rate: 0.5 - 1 knots	- Slack assumption: 1 - 2 % - Cable payout rate assumed: 0.6 - 1.2 m/s
Cable protection	- Burial rate: 600 metres per hour	- Nominal rate for ROV Sledge
Jointing	- 80 hour weather window	- Installation time required for offshore joint

The cable loading range input for this particular cable section is 5-6 m/min [8]. The cable laying speed range was set based on an assumption that the slack over the route averaged at 1-2 %, and the cable payout rate was assumed to fall between 0.6-1.2 m/s. The cable laying speed calculations were based on Equation 3.1. The ROV Sledge burial rate was based on the equipment description given in [20]. Jointing time input was based on [18]. The uncertainty margins for all installation tasks are based around a 10 % deviation from mean input value per installation task. In addition to these installation tasks, the pre-lay grapnel run, a supportive marine engineering task performed prior to the lay operation, was assumed to take place. This was designated a 0.5 kn rate as a guess value.

Cable layer constraint wave height input and uncertainties

The cable layer constraining wave heights are assumed to fall between 1-3 m, where 3 m is assumed to be the limiting offshore work wave height for the cable layer. The advantage of considering a 1-3 m range for inputs is that it covers a range of RAO values.

Installation strategy inputs and uncertainties

In this scenario, the installation contractor has the option to vary the cable protection levels for the cable. This implies that the power cable cable section can be installed using alternate installation methods, which in this case are TLB2 (Figure 3.4), and SLB2 (Figure 3.3).

4.6. Cable installation scenario sensitivity study

This section discusses the MIP sensitivity study for the scenario modelled in Section 4.5. The sensitivity study was performed based on the three uncertainty categories; ***process*** (Section 4.2), ***asset constraint*** (Section 4.3), and ***installation strategy*** (Section 4.4).

4.6.1. Motivation and structure of sensitivity study

The objective of the sensitivity study for the power cable installation model is to assess the relationship between input and outputs. Understanding the changes in model outputs help to determine the model's ability to respond to input changes. Furthermore it helps with identifying the variation trend for a MIP variable. The sensitivity study for the scenario defined in Section 4.5 is consists of three tests:

- **Impact of installation tasks:** This is based on the ***process uncertainties*** defined in the model inputs per installation task. The study involves an the assessment of the effect of an change in the installation task inputs on the total time required for installation.
- **Impact of the cable layer operational limits:** This is based on the ***asset constraint uncertainties*** where the effect of the cable layer operational limits on the time taken for installation is studied. Here the output parameter of interest in a simulation is the weather delay.
- **Impact of the installation strategy:** This is based on the ***installation strategy uncertainty*** which in this case is defined as a change in the installation method choice for the cable section. The output parameter of interest in this sensitivity study is the relationship between installation method choice and the total time required for installation.

4.6.2. Sensitivity study implementation through simulations on ECN Install

The approach for performing the categories of sensitivity studies discussed above on ECN Install is distributed into two simulation set-ups. These are perfect weather simulations and weather driven simulations.

- **Perfect weather simulations:** The motivation behind running a perfect weather simulation, wherein weather constraints are not accounted for during the execution of installation tasks is that it enables the identification of the time required for the completion of an installation task. This is useful when studying the impact of installation tasks on the MIP.
- **Weather driven simulations:** The motivation behind a weather driven simulation is to identify how the installation scenario plays out with its input weather constraints and weather wind descriptions. This enables the study the effect of cable layer operational limits on the MIP.

The study of the impact of various installation strategies can be performed under perfect weather simulations or weather driven simulations depending on what requires to be investigated.

4.6.3. Impact of installation tasks

The sensitivity of installation tasks on the MIP was studied by introducing a 10 % margin over the input mean values per installation task. The simulations per change in installation task was run without the impact of weather window calculation delays in order to assess their impact on the total time required for installation. The total time required for installation is a raw measure of the work time and weather window required per task. When performing this sensitivity study, the goal is to identify which of the tasks has the highest impact on the time required for the MIP.

Figure 4.1 depicts a tornado chart where the change in installation time required is depicted based on a change in base case value inputs. The base case inputs are indicated in Table 4.3.

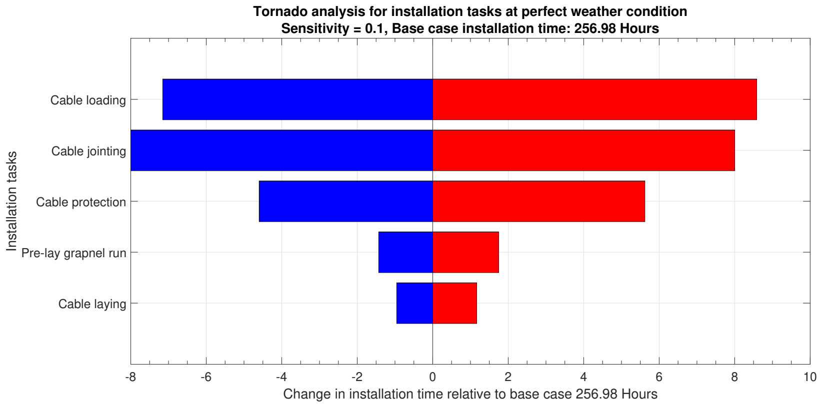
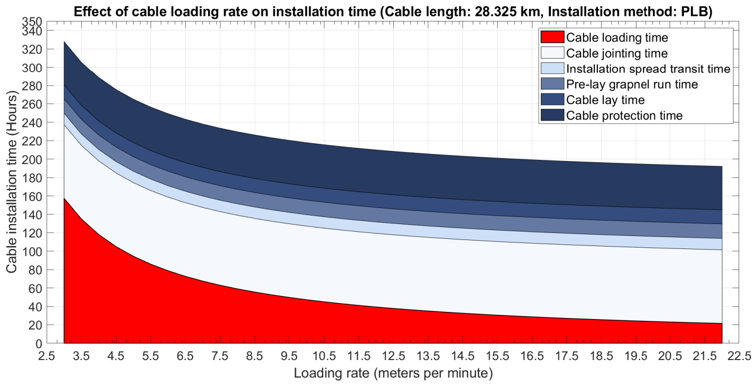
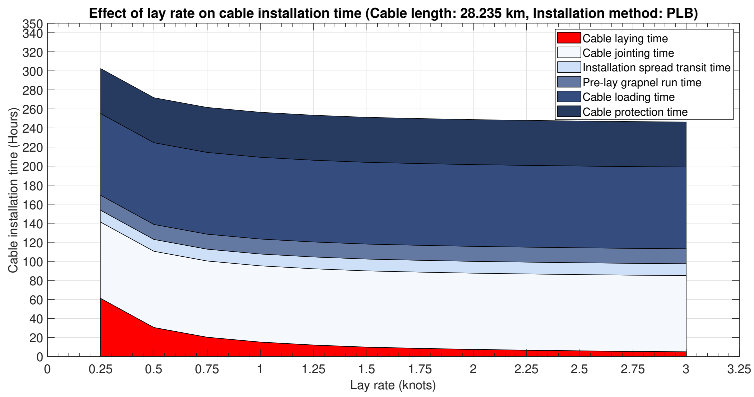


Figure 4.1: Tornado chart showcasing the impact of installation tasks on the total time required for the MIP. Base case inputs are indicated in Table 4.3.



(a)



(b)

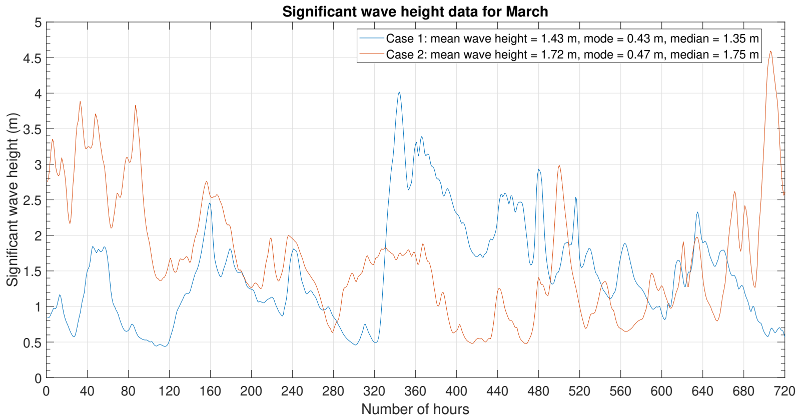
Figure 4.2: (a) Figure shows variation trend for cable loading rate and its impact on the total time required for installation with all possible load rates (3 - 22 m/min). [29] (b) Figure shows the variation trend for cable laying and its impact for installation with all possible cable laying rates (0.25 - 3 kn) [9].

The tornado chart results indicate that cable loading and cable jointing produce most sensitive changes on the time required for installation (approximately 4 %). Cable laying has the lowest sensitivity changes on the time required for installation (less than 1 %). Furthermore, it can be seen that the installation tasks with rate based model inputs (cable loading, laying, protection, and grapnel run) have a non-linear impact on the installation time required. It can also be seen that a reduction in the rates for these installation tasks shows a steeper gradient.

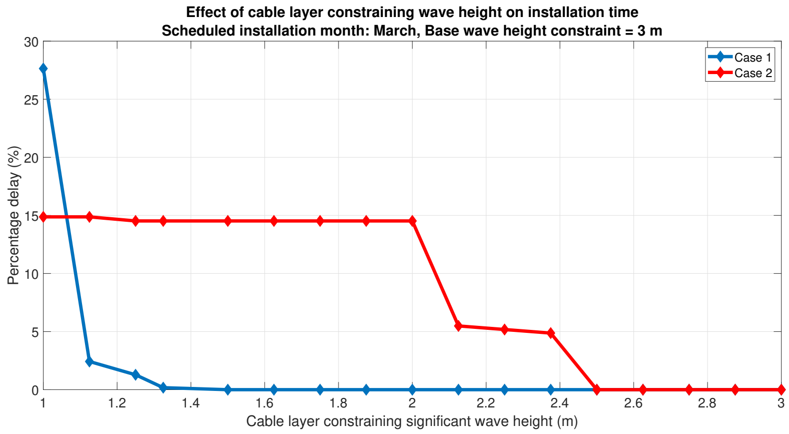
On setting the full range for cable loading (3 - 22 m/min) [29], and cable laying (0.25-3 kn) [9] the non-linear variation on the time required for installation can be seen in Figures 4.2a, and 4.2b.

4.6.4. Impact of the cable layer operational limits

The previous sensitivity study indicated that cable laying has the lowest sensitivity change on the time required for installation. However the input rate alone is not an accurate determinant on the influence of cable laying on the MIP. The second sensitivity study pertains to understanding the impact of the cable layer operation limit on the MIP by characterizing the percentage delay in the time required for installation with respect to variation of the constraining wave height.



(a)



(b)

Figure 4.3: (a) Figure shows two significant wave height hourly data forecasts for the same planned period of installation (b) Figure shows percentage weather delay incurred due to change in the operational limits of the cable layer.

The significant wave height is used as an hourly input in the model simulations in ECN Install. This sensitivity test had simulations set up per constraining wave height between a range of (1-3 m). The constraining wave height range was set based on the RAO characteristics of the cable laying vessel and the limiting wave height estimation method discussed in Section 4.3.4. Although a 10-15 % margin estimation for laying chute operational wave height is assumed, the graph was plotted for a larger range between 1-3 m constraining wave height ranges to observe potential percentage delay values for lower wave height constraints.

Two wave height data sets were utilized as the equivalent to forecasts for the installation period. The wave height data sets seen in Figure 4.3a correspond to values of hourly significant wave height from a time series file for the same location over a period of multiple years. Case 1 in the figure refers to the wave height data for March 2013, and Case in the figure refers to the wave height data for March 2014. The reason these two years of data-sets were selected was to replicate reasonable weather forecast outcomes.

Figure 4.3b shows the percentage delay with the installation time with different constraining wave heights under the two weather forecast scenarios. The results indicate a 15 % maximum delay and a sharp increase in the percentage delay after a particular limiting wave height value. The sharp increase is associated with the difficulty in finding a suitable weather window within the project duration that fits the operational limits of the laying process. For case 1 the sharp increase in the delay is after the limiting wave height reaches a value lower than the mean wave height (1.37 m), and for case 2, the percentage delay increases and stabilizes at a value close to the forecast mean (1.72 m).

This sensitivity study highlights several key conclusions:

- A higher constraining wave height for a cable layer is a desirable property. This is because the chances of finding the same weather window with a higher limiting wave height is greater than with a lower limiting wave height.
- The weather delay associated with constraining wave height is dependent on the forecast data and may not follow a specific trend.
- The impact of the additional time required for installation associated with cable layer wave height limits has the potential to be greater than the change in lay rate.

4.6.5. Impact of the installation strategy

The third sensitivity study deals with an assessment of the impact of installation strategy on the time required for installation. In Section 4.5 it was indicated that the scenario for installation strategy variation in this case was defined as the feasibility of alternate installation methods. Figure 4.4 shows the difference in time required for the MIP for the same cable section if the installation method was changed.

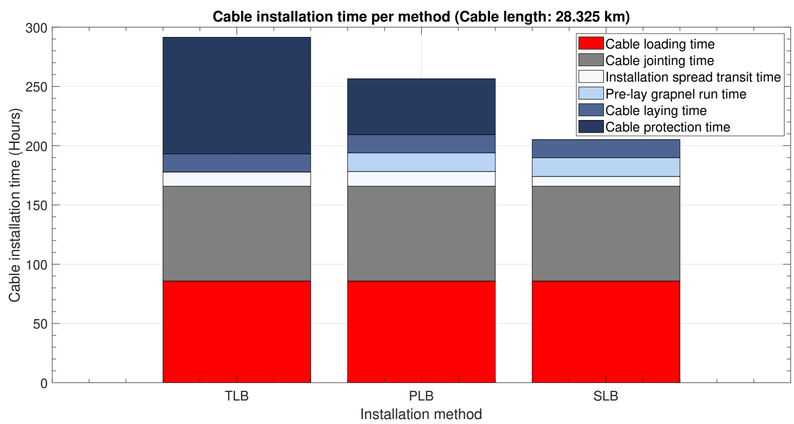


Figure 4.4: Change in the installation time required with different installation methods for the same power cable section.

The results above indicate that SLB produces lowest sensitivity to the time required for installation compared to the other installation methods. SLB consumes 66 % of the time required for installation when compared to TLB for the same cable section.

5
Case study: Gemini export cable installation

This chapter covers the application of the model for a historical case study. Section 5.1 highlights the summary as well as the motivation of the case study. Section 5.2 showcases the model set-up. The results of the case study and their reflections are discussed in Section 5.3.

5.1. Gemini as a historical case study for power cable installation

This section aims to provide an overview of the Gemini export cable installation project and the reasoning behind its choice for a historical case study.

5.1.1. Overview of installation activities

The Gemini offshore wind farm is one of Europe's largest, located 85 km from the northern coast of the Netherlands on the eastern boundary of the Dutch Exclusive Economic Zone [2]. Construction of the wind farm spanned over a period between 2014 and 2016 [2]. The installation activities of the Gemini offshore wind farm are depicted in Figure 5.1.

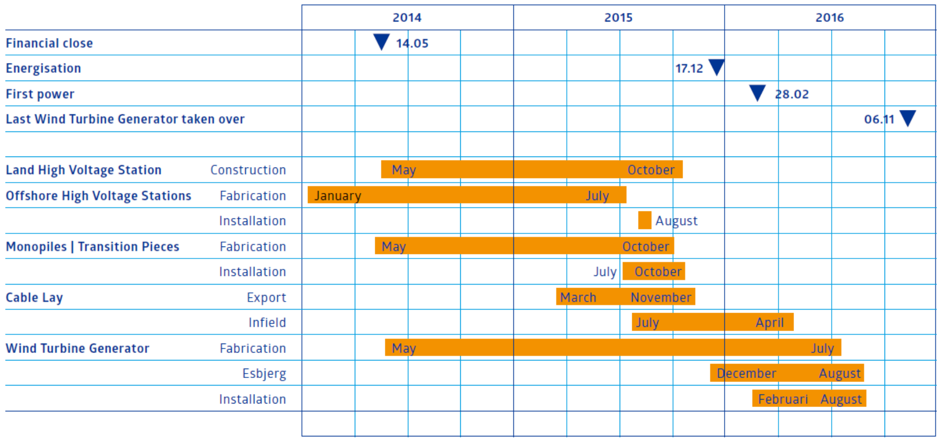


Figure 5.1: Gantt chart depicting the time consumed for the installation activities of the Gemini offshore wind farm. [24]

The export cable installation activities were contracted in an EPCI (Engineering, Procurement, Construction, and Installation) agreement by Van Oord [2][23]. It can be seen that the installation of power cables took place for a period of 14 months between March and April. This gantt chart will be utilized as the means to compare and analyse the model simulation results in Section 5.2.

5.1.2. Documentation on Gemini's Marine Installation Program

The key criterion behind the selection of Gemini for a historical case study is due to the availability of information on its MIP in the public domain. This is not the case for other offshore wind farm installation cases [10].

A method statement [23], published in 2012 is the most extensive document describing the MIP for the export cable installation. This document covers to a certain extent, the most relevant information for structuring the model for a case study. This can be summarized as:

- **Route engineering summary for installation method matching:** The water depth and burial depth requirements calculated along the cable route in the route engineering phase are summarized. Distinct zones along the route have been demarcated based on the average water depth and required burial depths.

- **Cable section data for setting the logistics and installation order:** The document contains a description of the total number of cable sections supplied at the port, thereby covering an installation plan set based on the cable supplier production capabilities and layer storage capacities.

- **Installation task summary for the model structure:** The position of the joints along the cable installation route is indicated, along with the required marine engineering tasks such as crossings, and horizontal directional drilling to facilitate the installation process.
- **Installation asset data for model inputs:** A detailed description of the required assets is given, which are matched along the installation route for the implementation of a particular method.
- **Project duration:** The target start and finish time period for most installation activities are mentioned in the document.

5.2. Export cable Marine Installation Program model

This section elaborates on the modelling steps taken and structure applied to simulate the MIP for the Gemini export cable. The inputs to the model are based on information available in the method statement document [23] and assumptions resulting from the learning outcome from Chapter 2 and Chapter 4. This implies that the input unknowns and uncertainties have been addressed with reasonable values, ranges, and margins. The process flow diagram for the installation is based on the model structure described in Chapter 3. The complete installation process diagram per cable section for the Gemini export cable is shown in Appendix A, Figure A.3.

5.2.1. Gemini export cable project summary

The export cable for Gemini consists of two 220 kV cables with approximate lengths of 93 km and 102 km from two offshore substations Buitengaats and ZeeEnergie to the beach located approximately 5 km to the west of the port of Eemshaven [23][2]. The project start and target dates based on the method statement are summarized in Table 5.1 and a visual representation of the export cable layout and installation activities is provided in Figure 5.2.

Table 5.1: MIP start and target end date based on the method statement [23]

Project start date	Project target date
March 14 2015	January 1 2016

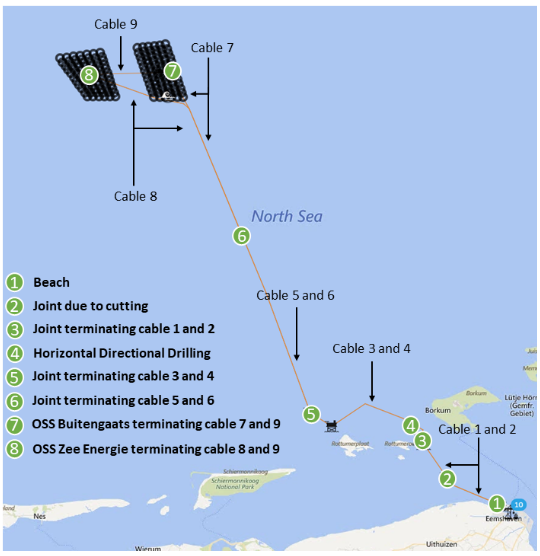


Figure 5.2: Summary of the Gemini export cable installation activities built on ECN Install.

5.2.2. Installation asset inputs

The installation assets utilized for the MIP are summarized in Table 5.2.

Table 5.2: Table summarizing the installation asset data used for the Gemini MIP.

Installation asset	Function	Transit speed in knots	Operational Constraint
Cable laying barge	- For lay of section 1 and 2	6.2 (Based on Vetag 8 CLB [23])	- limiting wave height: 2 m - limiting wind speed: 10 m/s
Cable laying vessel	- For lay of section 3, 4, 5, 6, 7, 8, and 9	12.4 (Based on Nexus CLV [23])	- limiting wave height: 3 m - limiting wind speed: 10 m/s
SS ROV trencher (burial equipment)	- For protection of section 1 and 2	0.5 (equal to equipment burial rate) (assumption based on [23])	- limiting wind speed: 10 m/s
Towing vessel	- For towing ROV Sledge - For protection of section 3, 4, 5, 6, 7, 8, and 9	11.5 (Based on support vessel [23])	- limiting wave height: 3 m - limiting wind speed: 10 m/s
ROV Sledge (burial equipment)	- For protection of section 3, 4, 5, 6, 7, 8, and 9	0.5 (equal to equipment burial rate) (assumption based on [25])	- limiting current speed: 1.53 m/s (assumption based on [25])
Dredge	- For protection of section 3 and 4 - For HDD work	12.5 (Based on TSHD Dredge [23])	- limiting wave height: 3 m - limiting wind speed: 10 m/s
Transport pontoon	- For transport of SSROV	11.2 (Based on transport barge [23])	- limiting wave height: 2 m - limiting wind speed: 10 m/s
Support vessel	- For route survey - For pre-lay grapnel run	11.5 (Based on support vessel [23])	- limiting wave height: 3 m - limiting wind speed: 10 m/s

For most of the installation assets, a description was provided in the method statement and therefore the transit speed inputs and operational constraints were available. Installation assets whose information was not available in the method statement were assigned inputs based on equipment data available from alternate sources [25].

5.2.3. Installation process per cable section

The export cable sections are broken down into a total of 9. Cable sections 1 and 2, 3 and 4, 5 and 6, have been assumed to be identical. The identical section pairs are positioned in parallel separated by a mean distance of 200 m along the route. Cable sections 7 and 8 diverge along the cable route to connect to the two offshore substations. Cable section 9 connects the two offshore substations. The details of the power cables are summarized in Table 5.3.

Table 5.3: Summary of Gemini export cable sections in the model.

Cable sections	Type	Length (km)	Installation method utilized
1 and 2	Beach to Joint	15.336	PLB1
3 and 4	Joint to Joint	22.273	TLB2 and PLB2
5 and 6	Joint to Joint	27.626	PLB2
7	Joint to OSS	27.639	PLB2
8	Joint to OSS	35.568	PLB2
9	OSS to OSS	10.071	PLB2

Cable sections 1 and 2

Cable sections 1 and 2 span approximately 15.35 km along the route starting from the beach to a joint. The installation method utilized for these two cables is PLB1 (Post Lay Burial 1), which means that for the laying operation a cable laying barge was utilized and for the burial operation a self supported ROV trencher was deployed after the laying process.

The installation of cable sections 1 and 2 begin with loading of the cable at Eemshaven to the laying barge before transit to the beach for direct land-fall. With all the preparations made, a direct land-fall takes place at the beach. This is followed by a lay operation along the route which ends with the assembly of a joint. The cable protection process then ensues after completion of the laying process when a self supporting ROV trencher is transported to the starting location of the cable route. The installation tasks for each of the cable sections and the installation of one section after the other in a pair are modelled as sequential.

Cable sections 3 and 4

Cable sections 3 and 4 are both approximately 22.3 km long and are positioned between 2 joints along the route. The burial depth requirements along the routes for cable sections 3 and 4 require the implementation of TLB2 and PLB2 methods for installation [23]. This is because the first 17.6 km of the route requires an average burial depth of greater than 10 m due to the high mobility of the sea-bed surface [23]. The remaining 4.7 km requires an average burial depth within 2 m. The installation activities for cable sections 3 and 4 begin with the deployment of a dredge to prepare the deep trenches required for laying the first 17.6 km of the cable. Once the trenches are prepared the cable is loaded to the layer for transit to begin installation. The lay operation continues until the assembly of a joint at the end. Following the lay operation, the dredge is deployed to back-fill the trench to complete the protection mechanism for the first part of the route. Then, a support vessel towing an ROV sledge is deployed to the second part of the route to perform a post lay protection.

Cable sections 5, 6, 7, 8, and 9

The cable sections 5 and 6 are installed between two joints. Cable sections 7 and 8 are installed between two joints and the two offshore substations. Cable section 9 is installed between the two substations. All five sections follow the same installation method PLB2 where the lay operation is followed by cable protection performed by a towed ROV sledge. The difference between each of these remaining 5 cable sections lies in the time taken for loading and the first and last installation tasks. For cable sections 5 and 6, these are jointing. For cable sections 7 and 8 these are jointing and pull-in. For cable section 9 two pull-ins take place at the beginning and end of the installation process.

5.2.4. Modelling supportive marine engineering activities

Supportive marine engineering activities are those that are performed as pre-requisites to an installation activity or as additional engineering activities required for the facilitation of the installation tasks defined in the model.

When modelling a historical case study it is likely to see the execution of such supportive marine engineering tasks. The relationship of supportive marine engineering activities to the power cable installation model framework defined in this thesis is that they are situational to the installation scenario and are more complex to categorise unlike the main cable installation processes classified in Section 2.2. As a result the reasoning for their occurrence was not captured as part of the decision tree logic built to define the model structure in Section 2.6.

Although their decision logic for the supportive marine engineering tasks is not represented in the model framework they can be modelled using the *UWISE ML* actions. For the Gemini export cable installation, these supportive installation tasks can be listed as:

- **An additional joint** installed at a 9 km point from the land-fall point in the route of cable section 1. The reason behind this is that the area surrounding the route made the traversal of the cable laying barge difficult, and hence the cable section had to be divided into two parts where one part was transported and positioned to the route using a modular transport vehicle [23]. The installation or requirement for this joint could not be reasoned with the installation model framework.

- **Multiple crossings** of the cable route over a set of power cables that required the set-up of tunnel ways for laying. These tunneling activities are required to be complete at the time of the laying activity.

- **Route survey** performed by support vessels for assessing the conditions of the cable routes prior to installation
- **Pre-lay grapnel run** performed by support vessels for clearing obstacles along the cable route prior to laying.
- **Horizontal Directional Drilling** performed at the transition point on the cable route between Cable sections 1 and 3, and Cable sections 2 and 4.

As for modelling these supportive marine engineering activities, a work action was assigned to the **additional joint** as described in Table 3.2. The route survey and **pre-lay grapnel** run installation activities were modelled using cable transit actions. The **crossings** were not assigned a *UWISE ML* action because they are assumed to be ready at the time of the lay operation.

5.2.5. Process inputs, assumptions, and uncertainty margins

In section 4.2, the reasoning behind the impact of installation process uncertainties, as a means to define the model input values or ranges was discussed. This was applied to the Gemini installation scenario for each installation process. Table 5.4 summarizes these input ranges.

Table 5.4: Summary of the installation process inputs and margins for the export cable.

Gemini Installation tasks	Guess value input	Reasoning
Cable loading	- Planned loading rate of 3 - 4 mpm	- Cable weight per unit 100-130 kg/m
Land-fall	- Direct land-fall weather window 48 h	- Based on the time required per sub-task
Cable laying	- Lay rate 0.5 - 1 m/s	- Based on a slack value assumption 1-2 % and a payout rate range between 0.6-1.2 m/s
Cable jointing	- Infield joint weather window 80 h	- Assumption that infield joints used most commonly
Cable pull-in	- Pull-in weather window 16 h	- No information available about pull-in time
Cable protection	- SSROV average speed 0.5 knots - ROV Sledge average speed 0.5 knots - Dredge average speed 2 - 3 knots	- Based on nominal equipment rates found in literature
Grapnel run	- Grapnel towing speed 0.5 knots	- No information available about speed
Route survey	- Vessel survey speed 0.5 knots	- No information available about speed
Horizontal Directional Drilling	- Weather window assumed to be 120 h	- Assumption based on the method statement description

The cable installation task inputs were chosen based on the availability of information in the method statement, and assumptions from the process uncertainty definition elaborated in Table 4.1. For the Gemini export cable installation scenario, the same cable type was used for all parts of the route, therefore the cable weight per unit (100-130 kg/m) was the same for every section. Therefore the planned loading rate between the range of 3-4 m/min was assigned for all sections. The type of joint used in the project was not known therefore a weather window of 80 hours was assumed [1]. The installation vessel properties such as the cable carrying capacity, limiting weather conditions, and transit speeds were known. A slack margin of 1-2 % was assumed throughout the entire route. The payout rate of the layer was assumed as between 0.6-1.2 m/s. This yielded a lay rate input range between 0.5-1 m/s. The equipment average trenching and burial rates were also unknown. These were assigned nominal equipment rates from literature [25][28].

5.2.6. Installation time required per cable section and weather window per task

The installation time required per cable section and the weather window per task are important for understanding the total time required for a MIP. This was was computed by running a simulation of the case in the absence of weather constraints. This yielded the following results depicted in Table 5.5.

Table 5.5: Total time required per cable section and per installation task excluding contingency factors.

Cable section	Installation total time required	Direct loading	Cable laying	Cable protection
1	242	73	- Barge: 8	- SSROV trenching/burial: 27
2	242	73	- Barge: 8	- SSROV trenching/burial: 27
3	224	106	- Vessel: 13	- Dredge trenching: 5 - Dredge backfilling/burial: 5 - ROV Sledge trenching/burial: 7
4	224	106	- Vessel: 13	- Dredge trenching: 5 - Dredge backfilling/burial: 5 - ROV Sledge trenching/burial: 7
5	288	132	- Vessel: 16	- ROV Sledge trenching/burial: 50
6	288	132	- Vessel: 16	- ROV Sledge trenching/burial: 50
7	223	131	- Vessel: 16	- ROV Sledge trenching/burial: 50
8	280	169	- Vessel: 20	- ROV Sledge trenching/burial: 62
9	118	47	- Vessel: 6	-ROV Sledge trenching/burial: 18

The installation time required per cable section increases with its length and this is due to the time spent for loading. The power cable loading process occupies up to 60 % of the total time required for installation of a cable section. It is interesting to see that Cable section 1 and 2, although much shorted than the remaining sections, still requires the second highest time for completion. This is attributed to the land-fall operation and the additional joint.

The loading, laying and protection time requirements are based on the average rates defined from the uncertainty margins specified in Table 4.3.

5.2.7. Model input sensitivity study

A sensitivity study was performed to understand the impact of the model inputs used for the MIP under the different uncertainty categories defined in Section 4.1.2. This in turn results in the identification of the extent to which the time required for installation is influenced. Based on the outcome of this analysis, the weather windows durations per installation task can be finalized for simulation. The sensitivity study approach per category can be elaborated as follows:

Impact of installation process input uncertainties on the time required for installation

The process input uncertainty margins were based on a 10 % deviation from the mean values reasoned as inputs in Table 5.5. The results of the process input uncertainties on the total time required for installation is represented in Figure 5.3.

The cable loading task has the highest impact on the uncertainty in the installation process as it occupies between 50-60 % of the total time required for installation per cable. The impact loading has on the time required for installation is an additional 4.8 % increase. This translates to a potential addition of 123 hours. A reduction of loading time per cable by 10 percent reduces the total installation time required by 156 hours. The remaining installation tasks have an impact of less than 1.5 % on average.

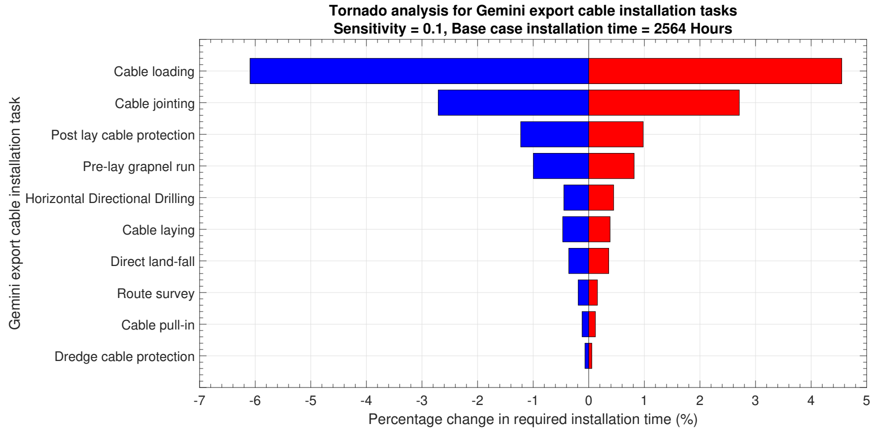


Figure 5.3: Tornado diagram showcasing the influence of installation task on the total time required for the Gemini export cable installation

Impact per cable section on the time required for installation

The final sensitivity study was aimed at investigating the impact per cable section on the time required for the *Marine Installation Plan*.

The approach for quantifying the impact of a cable section on the total time required was by factoring a 10 % change in the loading time required. The loading time was chosen as the installation task representing the impact of a cable section due to its weight-age on its installation as compared to the other tasks. The result is shown in Figure 5.4.

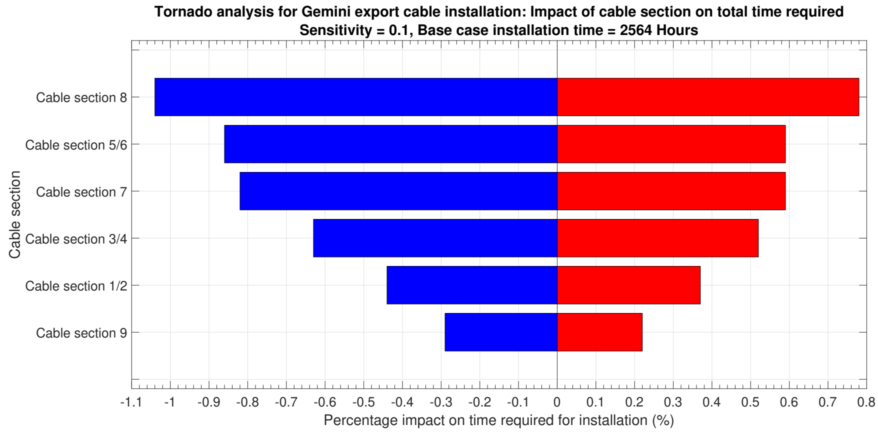


Figure 5.4: Tornado diagram showcasing the impact of a cable section on the total time required for installation

The result indicates a trend where the length of the cable section is proportional to its impact on the total time for installation. A conclusion that can be drawn from this observation is that the MIP can be optimized to schedule the installation of longer cable sections in time periods where the likelihood of observing favourable weather windows is higher.

Percentage delay in installation due to changes in the cable layer operating constraint

Multiple simulations were run to assess the impact of the cable layer constraint on the installation. The cable laying vessel, which is modelled based on the Nexus has a cable carrying capacity of 5000 t [17]. Based on this carrying capacity the RAO of the vessel was assumed to be 0.6. The design limit wave height of the cable laying vessel is 3 m [23]. A 10 % margin was assumed as the wave height operational limit for the laying chute resulting in a range of (2.97-3 m). The percentage delay associated with this margin was minimal.

5.2.8. Weather window designation strategy

The concept of weather window and its equation was given in Chapter 3. The approach for designating the weather window for each installation task has been based on the time required (captured in Table 5.5), and process uncertainties defined in Table 5.4. The process uncertainties have been assigned as the contingency factor for each installation task.

This means that the weather window per installation task has been assigned as the base time required added to the additional time required if the installation task was executed at the lower possible range in the uncertainty margin defined.

5.3. Marine Installation Program model results and reflection

The simulation results of the MIP modelled in Section 5.2 are presented alongside the method statement plan. This is followed by a reflection on the results.

5.3.1. Summary of the Marine Installation Program model results

Figure 5.5a shows the MIP plan constructed as per the method statement information. The second column shows the total time allotted to the installation of each power cable. The yellow bars indicate the distribution of months suitable for the installation activities. The MIP implementation results in Figure 5.5b, are based on observations made in the Gantt chart shown in Figure 5.1. This showcases the outcome of the method statement plan implemented in real-life. The total time taken for installation is assumed to be 6480 hours due to the confidentiality of more detailed information on the project's execution. The simulation results are depicted in Figure 5.5c. The installation time taken per cable section was obtained by simulation with the model inputs described in Section 5.2, under the influence of a deterministic weather data set. The total time taken for simulation of the entire installation scenario including weather delays and the supportive installation activities is 4070 hours (March 14 2015- August 30 2015). A detailed account of the simulation results is given in Appendix A, Figure A.4.

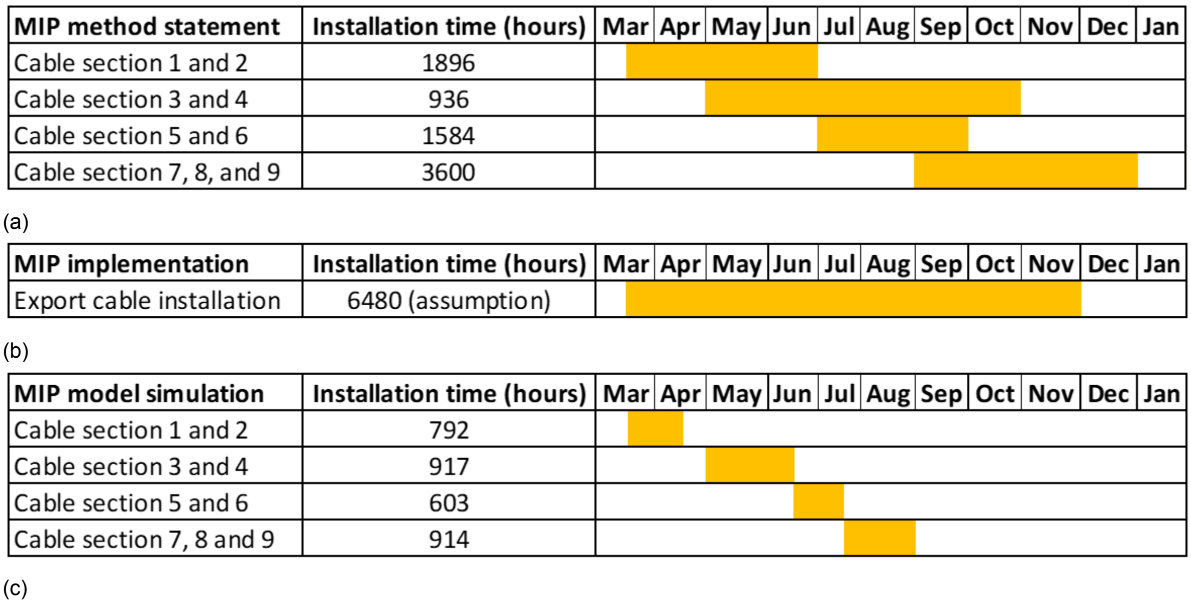


Figure 5.5: A summary of the method statement plan (Figure 5.5a), the real life execution of the MIP (Figure 5.5b), and the model outcome (Figure 5.5c))

The MIP was planned for a period between March and January. On implementation, the export cable installation was complete by November. The reason behind this is presumed to be twofold. Firstly, due to changes or optimization steps that may have modified the *Marine Installation Program plan*. The method statement was formulated in 2012 and there are no indications as to whether it was a finalized version of the installation plan. Secondly, due to the incidence of favourable weather forecasts that may have decreased the wait time for some of the marine engineering tasks.

5.3.2. Reflection on the Marine Installation Program model

The validity of the MIP model built for Gemini can not be determined at the end of this case study. The model simulation results can not be validated against the implementation of the method (Figure 5.5b) due to the unavailability of specific installation information such as the time taken per cable section and the process flow.

The focus of the reflection on the model will be on its differences and limitations when it comes to describing the method statement plan. The outcome of this discussion is identifying the points of improvement for accurately modelling future cases. The factors that impact the results produced by the model, which shed light on its limitations can be summarized as follows:

Assumption of a perfect supply chain

The supply chain for the power cables from the cable manufacturer to the installation contractor was assumed to be perfect as explained in Chapter 3, Section 3.5). In reality delays are probable and the designation of time for the MIP also takes it into account. The MIP model simulation results do not factor this possibility into account.

Quality of asset and installation task inputs

The inputs used for the model comprised of a combination of data from the method statement and guess values based on the understanding built on the power cable installation tasks and assets. The reliability of the guess values can not be ascertained. The quality of the inputs is a determinant on the reliability of the simulation accuracy. The learned outcome from this reflection is that for future modelling scenarios, the acquisition of a more detailed data pertaining to the assets and installation rates is key for an accurate simulation of power cable installation case study.

Installation process flow assumptions

The process flow for installation used in the model assumed that each cable installation task is structured in a fixed sequence depending on the method of installation. This may not be true in real life. Installation processes can be executed in parallel or with an overlap. The range of the overlap between burial and laying is not known as no information is available on it. Similarly, the installation of power cables can take place simultaneously. In the model the installation of cables was also assumed to take place sequentially.

Worker shift patterns and non-work periods

The worker patterns are unknown and were assumed to be 24 hour shifts throughout the installation project with no holidays. In the method statement, a non work period between the month of July to August was defined. This was not implemented into the model and therefore its consequences on the installation time taken is unknown.

Weather window calculation methods for the laying process

The weather window determination for the laying process in reality is not as straightforward as defined in the model. According to [7], laying windows are defined over a route in parts. For a simultaneous lay burial installation method a single continuous weather window is required.

On the other-hand for post-lay burial installation, shorter installation weather windows are required. The method by which these weather windows are defined and the logic behind their calculations is unknown. The presumption is that the weather window calculation pattern is dependent on the route properties or in other words the slack distribution over the route, which may not always be constant in practice. In this model, the slack variation was assumed to be minimal over the route and each lay task was assumed to be performed in a single continuous weather window.

Impact of the marine engineering activities

It is hard to identify to what extent and what proportion of time and resources are consumed by the other marine engineering activities in the installation plan compared to the cable installation tasks. The modelling of the HDDs and assumptions for the crossings are simplistic and do not capture the scale of the activity accurately. A more accurate breakdown of marine engineering activities as well as their composition is useful for modelling future case studies.

6

Conclusion and recommendations

This chapter presents the conclusions and recommendations of the thesis. Section 6.1 highlights the key conclusions produced from this study, and section 6.2 lists the recommendations based on this study for the future.

6.1. Conclusions

This report documents the steps taken to model the installation of power cables for offshore wind farms using a discrete event simulation based logistics model. The research question and sub-questions of this thesis are:

"How can the processes and strategies used for power cable installation for offshore wind farms be modelled and analysed using a logistics model"

- What are the stages, variables, constraints, and assets involved in offshore wind power cable installation?
- How can installation processes be captured, modelled and simulated in a logistics framework?
- What are the factors that impact the installation of power cable installation and how can they be incorporated into the model?
- How can the model be applied to a real case study for simulation and validation?

The conclusions per research question are captured in the following sections.

6.1.1. Main research conclusion

The main research question is addressed in this section. The goal behind the implementation of a logistics model for power cable installation is to study an installation plan's time and resource effectiveness. A literature review on power cable installation is made to build the framework for defining the installation processes in the model. Next, the UWISE ML language is used to define the processes in a discrete event simulation environment on ECN Install. Model input uncertainties are specified and their impacts on an installation program are analysed through a sensitivity study. Finally, a historical case study is constructed and analysed using the model.

6.1.2. Elements of power cable installation

Firstly an understanding of the composition of a power cable installation project is built through a literature study. The project's stages, processes, assets, installation methods, and influencing weather parameters are identified. The processes involved in power cable installation are listed along with their key characteristics. The main assets are cable layers which are chosen based on the water depth, and cable protection equipment which are selected based on the burial depth requirements. Installation methods stem from different sequences of processes. The most important weather parameter impacting a cable installation plan are incident waves. The outcome of this literature study is the construction of a decision logic where the choices made in a Marine Installation Program are connected to the cable route properties. The key conclusions can be summed up as:

- The most important stage for modelling is the Marine Installation Program where an installation schedule is finalized for implementation.
- Six processes define power cable installation.
- The installation of a power cable is centered around the cable layer.
- The relationship between the Route Engineering stage and the Marine Installation Program stage is important to understand for the model.
- The decision tree captures all documented power cable installation methods.

6.1.3. Capturing and modelling the installation processes

The complexity of power cable installation requires dynamic modelling principles for accurate calculations. This notion is first introduced in order to highlight how the limitations of using a logistics model can be overcome. The reason dynamic modelling is used for power cable installation is mainly because it captures the slack for cable laying accurately. Accurate slack estimation is a determinant for the time required for the laying operation. Dynamic models capture this accurately by mathematical modelling the forces exerted on a cable under its different contact configurations over the sea-bed surface. A logistic model represents installation processes as a function of input rates, therefore its ability to estimate the time required for installation activities such as cable laying, can be improved by integrating some dynamic modelling principles such as slack calculation. A simplified approach for estimating the input lay rate is set for the logistics model where the relationship between slack, vessel speed and cable payout rate is assumed. Besides the incorporation of dynamic model principles, the logistic model's base assumptions are set. The process flow per installation method is designated based on the decision logic developed at the end of the literature study. The conclusions at the end of this section are:

- Dynamic modelling of power cable installation is used most commonly for accuracy. The most important transferable property identified from a dynamic model to a logistics model for describing installation accurately is the slack calculation method.
- UWISE ML provides a robust set of actions for defining power cable installation processes.
- The model base assumptions such as the sea-bed morphology being constant, and that all installation tasks are executed in a non-parallel order do not mirror reality. These have been set for simplicity of mapping the process on ECN Install.

6.1.4. Factors impacting power cable installation

Once the installation processes and their flow orders are defined in the model, the effect of input uncertainties is studied. Uncertainties are defined as the set of input values and ranges in the model that originate from installation processes, asset operational constraints, and installation strategies used in a Marine Installation Program. Process uncertainties are identified by noting the input requirements per installation task and then designating the probable range based on physical principles or model assumptions that govern the behaviour of the task. Asset constraint uncertainties are defined based on the possible changes in the operating conditions of an installation asset such as a cable layer. Finally, installation strategies cover a broad set of decision making changes that are likely for a MIP. Once these uncertainties are defined, their impact on the sensitivity of an MIP is studied by setting a simple cable installation scenario. The key findings of this stage of the thesis are:

- The process uncertainty definition for cable laying has a clear structure because the physics of cable laying are understood and available more clearly.
- The assumption for the objective of cable loading to be minimizing the incidence of synchronization errors was taken due the lack of information available on its dynamics.
- Based on the estimations used in this thesis, a MIP is most sensitive to cable loading.
- The asset constraint uncertainty was focused on understanding the impact of a cable layer's RAO on its limiting wave height range. The higher the range the higher the chances of finding weather windows.

- Installation uncertainties are circumstantial to a given cable installation project.

6.1.5. Application of the model for historical case study

The last step in the study is the implementation of the defined model principles and input uncertainties by constructing a historical case study. The export cable installation of Gemini is chosen due to the availability of its MIP documentation. In total, the installation processes of 9 power cables are modelled sequentially and the weather windows are assigned based on the uncertainty margins. Simulations of the case yielded results whose validity could not be ascertained against the MIP implemented. A reflection on the modelling approach is made to identify points of improvement for future case studies. The case study conclusions are:

- The results of the Gemini case study could not be validated against the real events however the quality of results is variable with better inputs of the actual vessels from the project. These are confidential, therefore the usefulness of this conclusion is as a recommendation for future case studies.
- Worker shift patterns are unknown. The assumption that they are 24 hour work periods can be a source of erroneous results.
- The simplification of other marine engineering activities in a MIP can lead to difficulty in identifying whether their impact on the time required for installation is higher than the installation tasks themselves.
- Knowing the weather window calculation strategy for the laying process can improve the realism of the model.

6.2. Recommendations

With the work done this thesis and its conclusions, the following recommendations are set for the future.

- **MIP optimization:** The scope for understanding what the optimization strategies are for a Marine Installation Program was not explored in this thesis. The model developed thus-far requires optimization and this can form a new research question.
- **MIP cost modelling:** The cost modelling of installation activities in a case study based on accurately available day rates of vessels and equipment is recommended for future studies. Cost structure estimations were identified from books and reports [22][4], however no clear figures were available for analysis using the model framework.
- **Integration of more dynamic modelling principles to improve model inputs:** In this thesis, the dynamics of cable laying were integrated into the model to improve the quality of inputs. An example of adding more dynamic principles can be the incorporation of sea-bed morphological changes on the MIP at the time of its implementation.
- **Simulations with different installation strategy uncertainties:** Simulations considering different installation strategies such as the crew working patterns were not implemented in this thesis due to the lack of information. Future simulations can be set up upon the availability of such information.

A

Gemini export cable installation

A.1. Model data

Figure A.1 shows the coordinates used for the cable route.

Parameter	Name	X-coordinate	Y-coordinate	UTM Zone
Unit		m	m	
Format	text	number	number	text
	Landfall	354582.43	5925657.82	32U
	Floater	354220.65	5925850.11	32U
	Joint nine km	346609.69	5930037.92	32U
	Joint fifteen km	343327.50	5935130.72	32U
	End HDD sixteen km	342858.61	5935858.27	32U
	Trench end point	329699.15	5938294.46	32U
	Joint thirty seven km	326572.18	5940344.29	32U
	Joint sixty five km	317440.93	5967151.93	32U
	OSS Buitengaats	306292.98	5991672.54	32U
	OSS Zee energie	296221.15	5991632.29	32U

Figure A.1: Coordinates used for cable route way points.

Figure A.2 shows the installation asset inputs used for Gemini.

Parameter	Name	X-coordinate	Y-coordinate	UTM Zone
Unit		m	m	
Format	text	number	number	text
	Landfall	354582.43	5925657.82	32U
	Floater	354220.65	5925850.11	32U
	Joint nine km	346609.69	5930037.92	32U
	Joint fifteen km	343327.50	5935130.72	32U
	End HDD sixteen km	342858.61	5935858.27	32U
	Trench end point	329699.15	5938294.46	32U
	Joint thirty seven km	326572.18	5940344.29	32U
	Joint sixty five km	317440.93	5967151.93	32U
	OSS Buitengaats	306292.98	5991672.54	32U
	OSS Zee energie	296221.15	5991632.29	32U

Figure A.2: Installation asset inputs for Gemini.

Figure A.3 shows the MIP model for the Gemini export cable.

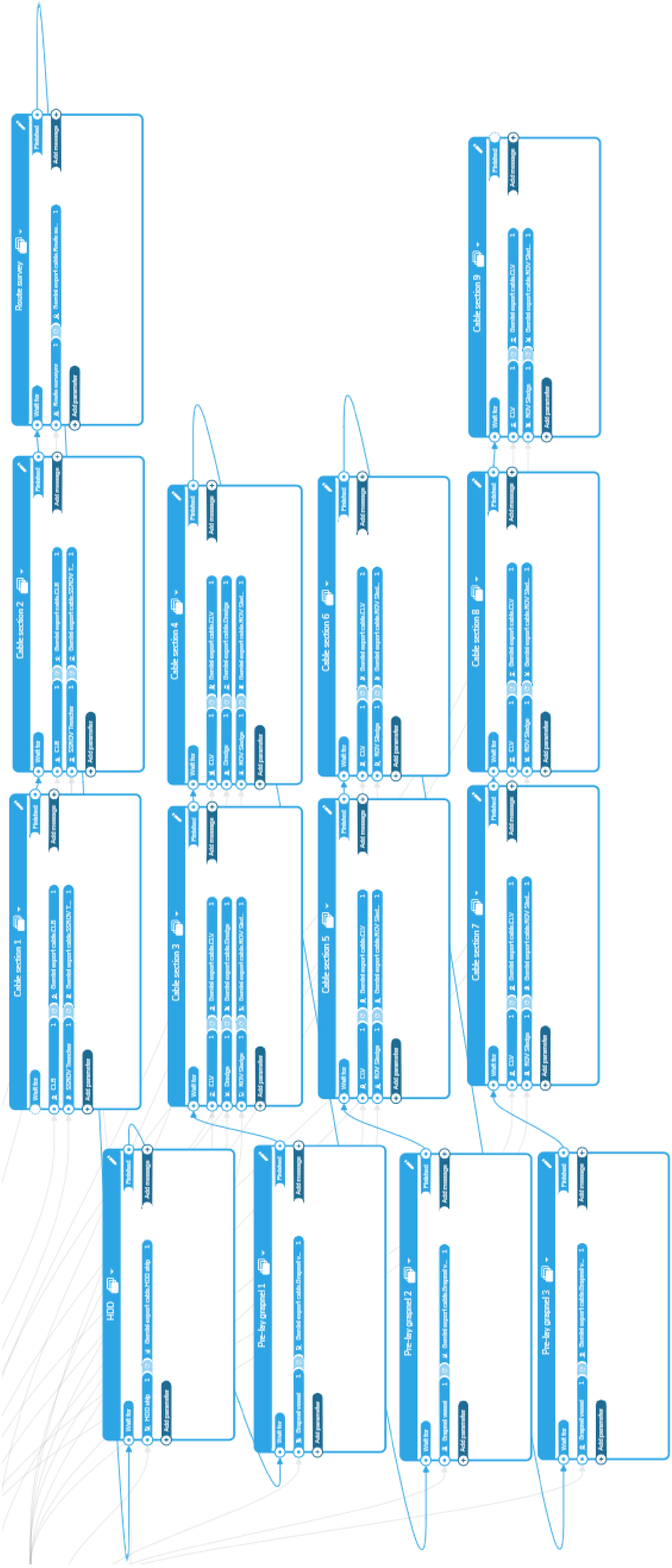


Figure A.3: Construction of the Gemini export cable MIP process on ECN Install.

A.2. Simulation results

Figure A.4 shows the MIP model weather driven simulation result overview.

Key Simulation Results	Unit	Value
Starting weather year		2014
Start of simulation	[date]	2014-05-14T00:00:00
End of process	[date]	2015-08-30T14:27:21
Process target date	[date]	2016-01-01T00:00:00
End of simulation	[date]	2017-05-13T00:00:00

Figure A.4: Results of the weather driven simulation.

The detailed weather driven simulation results are provided in the following pages.

UWISE ML Block	Action Type	Start Time	Total Duration	Core Duration	Permits Delay	Weather Delay	Resource Delay	Idle Time	End Time
		[date]	[h]	[h]	[h]	[h]	[h]	[h]	[date]
Full Scenario		2014-05-14T00:00:00	11,401.08	2,564.63	0.00	1,540.45	7,296.00	0.00	2015-09-01T01:04:41
Core base case		2014-05-14T00:00:00	11,401.08	2,564.63	0.00	1,540.45	7,296.00	0.00	2015-09-01T01:04:41
Cable section 1		2015-03-14T00:00:00	537.89	241.41	0.00	296.48	0.00	0.00	2015-04-05T09:53:10
Cable section 2		2015-03-14T00:00:00	1,116.95	241.41	0.00	337.65	0.00	537.89	2015-04-29T12:56:43
Cable section 3		2015-03-14T00:00:00	1,622.57	223.93	0.00	101.39	0.00	1,297.25	2015-05-20T14:34:07
Cable section 4		2015-03-14T00:00:00	1,934.73	223.93	0.00	88.23	0.00	1,622.57	2015-06-02T14:43:57
Cable section 1.Load cable to layer	Work	2015-03-14T00:00:00	136.84	73.00	0.00	63.84	0.00	0.00	2015-03-19T16:50:14
Cable section 5		2015-03-14T00:00:00	2,541.75	287.15	0.00	192.87	0.00	2,061.73	2015-06-27T21:44:53
Cable section 6		2015-03-14T00:00:00	2,950.95	287.15	0.00	122.05	0.00	2,541.75	2015-07-14T22:57:09
Cable section 7		2015-03-14T00:00:00	3,335.76	222.96	0.00	0.00	0.00	3,112.80	2015-07-30T23:45:39
Cable section 1.Shore pull-in (total)		2015-03-14T00:00:00	306.72	24.00	0.00	0.00	0.00	282.72	2015-03-26T18:43:16
Cable section 8		2015-03-14T00:00:00	3,987.46	279.69	0.00	372.01	0.00	3,335.76	2015-08-27T03:27:32
Cable section 9		2015-03-14T00:00:00	4,105.08	117.62	0.00	0.00	0.00	3,987.46	2015-09-01T01:04:41
HDD		2015-03-14T00:00:00	1,280.00	109.52	0.00	0.00	0.00	1,170.48	2015-05-06T07:59:45
Pre-lay grapnel 1		2015-03-14T00:00:00	1,297.25	17.26	0.00	0.00	0.00	1,280.00	2015-05-07T01:15:07
Pre-lay grapnel 2		2015-03-14T00:00:00	2,061.73	112.44	0.00	14.56	0.00	1,934.73	2015-06-07T21:43:35
Pre-lay grapnel 3		2015-03-14T00:00:00	3,112.80	146.64	0.00	15.21	0.00	2,950.95	2015-07-21T16:48:14
Route survey		2015-03-14T00:00:00	1,170.48	53.53	0.00	0.00	0.00	1,116.95	2015-05-01T18:28:40
Cable section 1.Transit to landfall offshore point	Transit	2015-03-19T16:50:14	141.88	0.41	0.00	141.48	0.00	0.00	2015-03-25T14:43:16
Cable section 1.Float export cable to shore pull-in	Work	2015-03-25T14:43:16	4.00	4.00	0.00	0.00	0.00	0.00	2015-03-25T18:43:16
Cable section 1.Shore pull-in	Work	2015-03-25T18:43:16	24.00	24.00	0.00	0.00	0.00	0.00	2015-03-26T18:43:16
Cable section 1.Joint to onshore cable	Work	2015-03-26T18:43:16	20.00	20.00	0.00	0.00	0.00	0.00	2015-03-27T14:43:16
Cable section 1.Lay till joint	Cable Laying	2015-03-27T14:43:16	59.47	7.95	0.00	51.52	0.00	0.00	2015-03-30T02:11:40
Cable section 1.Install final joint	Work	2015-03-30T02:11:40	80.00	80.00	0.00	0.00	0.00	0.00	2015-04-02T10:11:40
Cable section 1.Transit to port after lay	Transit	2015-04-02T10:11:40	1.52	1.52	0.00	0.00	0.00	0.00	2015-04-02T11:42:54
Cable section 1.Load SSROV trecher to Pontoon	Work	2015-04-02T11:42:54	3.00	3.00	0.00	0.00	0.00	0.00	2015-04-02T14:42:54
Cable section 1.Transit SSROV to installation route	Transit	2015-04-02T14:42:54	0.09	0.09	0.00	0.00	0.00	0.00	2015-04-02T14:48:06
Cable section 1.Trench-bury cable till joint	Cable Laying	2015-04-02T14:48:06	66.26	26.63	0.00	39.64	0.00	0.00	2015-04-05T09:03:59
Cable section 1.Transit to port after trench-bury	Transit	2015-04-05T09:03:59	0.82	0.82	0.00	0.00	0.00	0.00	2015-04-05T09:53:10
Cable section 2.Load cable to layer	Work	2015-04-05T09:53:10	317.22	73.00	0.00	244.22	0.00	0.00	2015-04-18T15:06:19
Cable section 2.Transit to landfall offshore point	Transit	2015-04-18T15:06:19	93.84	0.41	0.00	93.43	0.00	0.00	2015-04-22T12:56:33
Cable section 2.Float export cable to shore pull-in	Work	2015-04-22T12:56:33	4.00	4.00	0.00	0.00	0.00	0.00	2015-04-22T16:56:33
Cable section 2.Shore pull-in	Work	2015-04-22T16:56:33	24.00	24.00	0.00	0.00	0.00	0.00	2015-04-23T16:56:33
Cable section 2.Joint to onshore cable	Work	2015-04-23T16:56:33	20.00	20.00	0.00	0.00	0.00	0.00	2015-04-24T12:56:33
Cable section 2.Lay till joint	Cable Laying	2015-04-24T12:56:33	7.95	7.95	0.00	0.00	0.00	0.00	2015-04-24T20:53:33
Cable section 2.Install final joint	Work	2015-04-24T20:53:33	80.00	80.00	0.00	0.00	0.00	0.00	2015-04-28T04:53:33
Cable section 2.Transit to port after lay	Transit	2015-04-28T04:53:33	1.52	1.52	0.00	0.00	0.00	0.00	2015-04-28T06:24:46
Cable section 2.Load SSROV trecher toPontoon	Work	2015-04-28T06:24:46	3.00	3.00	0.00	0.00	0.00	0.00	2015-04-28T09:24:46

Cable section 2.Transit SSROV to installation route	Transit	2015-04-28T09:24:46	0.09	0.09	0.00	0.00	0.00	0.00	2015-04-28T09:29:58
Cable section 2.Trench-bury cable till joint	Cable Laying	2015-04-28T09:29:58	26.63	26.63	0.00	0.00	0.00	0.00	2015-04-29T12:07:32
Cable section 2.Transit to port after trench-bury	Transit	2015-04-29T12:07:32	0.82	0.82	0.00	0.00	0.00	0.00	2015-04-29T12:56:43
Route survey.Move to start	Transit	2015-04-29T12:56:43	1.89	1.89	0.00	0.00	0.00	0.00	2015-04-29T14:49:51
Route survey.Move 2	Transit	2015-04-29T14:49:51	8.86	8.86	0.00	0.00	0.00	0.00	2015-04-29T23:41:35
Route survey.Move 3	Transit	2015-04-29T23:41:35	14.30	14.30	0.00	0.00	0.00	0.00	2015-04-30T13:59:46
Route survey.Move 4	Transit	2015-04-30T13:59:46	13.60	13.60	0.00	0.00	0.00	0.00	2015-05-01T03:36:01
Route survey.Move 5	Transit	2015-05-01T03:36:01	5.09	5.09	0.00	0.00	0.00	0.00	2015-05-01T08:41:12
Route survey.Return	Transit	2015-05-01T08:41:12	9.79	9.79	0.00	0.00	0.00	0.00	2015-05-01T18:28:40
HDD.Move to HDD point	Transit	2015-05-01T18:28:40	0.76	0.76	0.00	0.00	0.00	0.00	2015-05-01T19:14:12
HDD.Prepare HDD	Work	2015-05-01T19:14:12	108.00	108.00	0.00	0.00	0.00	0.00	2015-05-06T07:14:12
HDD.Return to port	Transit	2015-05-06T07:14:12	0.76	0.76	0.00	0.00	0.00	0.00	2015-05-06T07:59:45
Pre-lay grapnel 1.Move to grapnel-run location	Transit	2015-05-06T07:59:45	1.42	1.42	0.00	0.00	0.00	0.00	2015-05-06T09:24:40
Pre-lay grapnel 1.Grapnel run	Cable Laying	2015-05-06T09:24:40	7.21	7.21	0.00	0.00	0.00	0.00	2015-05-06T16:37:26
Pre-lay grapnel 1.Grapnel run repeat	Cable Laying	2015-05-06T16:37:26	7.21	7.21	0.00	0.00	0.00	0.00	2015-05-06T23:50:12
Pre-lay grapnel 1.Return after grapnel run	Transit	2015-05-06T23:50:12	1.42	1.42	0.00	0.00	0.00	0.00	2015-05-07T01:15:07
Cable section 3.Transit to trench	Transit	2015-05-07T01:15:07	0.76	0.76	0.00	0.00	0.00	0.00	2015-05-07T02:00:40
Cable section 3.Trench	Cable Laying	2015-05-07T02:00:40	4.97	4.97	0.00	0.00	0.00	0.00	2015-05-07T06:58:39
Cable section 3.Transit to port after trench	Transit	2015-05-07T06:58:39	1.36	1.36	0.00	0.00	0.00	0.00	2015-05-07T08:20:10
Cable section 3.Load cable to layer	Work	2015-05-07T08:20:10	207.39	106.00	0.00	101.39	0.00	0.00	2015-05-15T23:43:23
Cable section 3.Transit to cable route	Transit	2015-05-15T23:43:23	0.76	0.76	0.00	0.00	0.00	0.00	2015-05-16T00:28:59
Cable section 3.Lay from 15 km to 37 km	Cable Laying	2015-05-16T00:28:59	12.01	12.01	0.00	0.00	0.00	0.00	2015-05-16T12:29:36
Cable section 3.Install joint at 37 km	Work	2015-05-16T12:29:36	80.00	80.00	0.00	0.00	0.00	0.00	2015-05-19T20:29:36
Cable section 3.Transit to port after lay	Transit	2015-05-19T20:29:36	1.51	1.51	0.00	0.00	0.00	0.00	2015-05-19T21:59:58
Cable section 3.Transit to back-fill	Transit	2015-05-19T21:59:58	0.76	0.76	0.00	0.00	0.00	0.00	2015-05-19T22:45:31
Cable section 3.Back-fill	Cable Laying	2015-05-19T22:45:31	4.97	4.97	0.00	0.00	0.00	0.00	2015-05-20T03:43:30
Cable section 3.Transit to port after back-fill	Transit	2015-05-20T03:43:30	1.36	1.36	0.00	0.00	0.00	0.00	2015-05-20T05:05:01
Cable section 3.Transit to trench-bury point	Transit	2015-05-20T05:05:01	1.42	1.42	0.00	0.00	0.00	0.00	2015-05-20T06:29:57
Cable section 3.Trench-bury	Cable Laying	2015-05-20T06:29:57	6.49	6.49	0.00	0.00	0.00	0.00	2015-05-20T12:59:26
Cable section 3.Transit to port after trench-bury	Transit	2015-05-20T12:59:26	1.58	1.58	0.00	0.00	0.00	0.00	2015-05-20T14:34:07
Cable section 4.Install joint at 37 km (total)		2015-05-20T14:34:07	294.09	80.00	0.00	88.23	0.00	125.85	2015-06-01T20:39:25
Cable section 4.Transit to trench	Transit	2015-05-20T14:34:07	0.76	0.76	0.00	0.00	0.00	0.00	2015-05-20T15:19:40
Cable section 4.Trench	Cable Laying	2015-05-20T15:19:40	4.97	4.97	0.00	0.00	0.00	0.00	2015-05-20T20:17:39
Cable section 4.Transit to port after trench	Transit	2015-05-20T20:17:39	1.36	1.36	0.00	0.00	0.00	0.00	2015-05-20T21:39:10
Cable section 4.Load cable to layer	Work	2015-05-20T21:39:10	106.00	106.00	0.00	0.00	0.00	0.00	2015-05-25T07:39:10
Cable section 4.Transit to cable route	Transit	2015-05-25T07:39:10	0.76	0.76	0.00	0.00	0.00	0.00	2015-05-25T08:24:47
Cable section 4.Lay from 15 km to 37 km	Cable Laying	2015-05-25T08:24:47	12.01	12.01	0.00	0.00	0.00	0.00	2015-05-25T20:25:23
Cable section 4.Install joint at 37 km	Work	2015-05-29T12:39:25	80.00	80.00	0.00	0.00	0.00	0.00	2015-06-01T20:39:25
Cable section 4.Transit to port after lay	Transit	2015-06-01T20:39:25	1.51	1.51	0.00	0.00	0.00	0.00	2015-06-01T22:09:48
Cable section 4.Transit to back-fill	Transit	2015-06-01T22:09:48	0.76	0.76	0.00	0.00	0.00	0.00	2015-06-01T22:55:20

Cable section 4.Back-fill	Cable Laying	2015-06-01T22:55:20	4.97	4.97	0.00	0.00	0.00	0.00	2015-06-02T03:53:20
Cable section 4.Transit to port after back-fill	Transit	2015-06-02T03:53:20	1.36	1.36	0.00	0.00	0.00	0.00	2015-06-02T05:14:51
Cable section 4.Transit to trench-bury point	Transit	2015-06-02T05:14:51	1.42	1.42	0.00	0.00	0.00	0.00	2015-06-02T06:39:47
Cable section 4.Trench-bury	Cable Laying	2015-06-02T06:39:47	6.49	6.49	0.00	0.00	0.00	0.00	2015-06-02T13:09:16
Cable section 4.Transit to port after trench-bury	Transit	2015-06-02T13:09:16	1.58	1.58	0.00	0.00	0.00	0.00	2015-06-02T14:43:57
Pre-lay grapnel 2.Move to grapnel-run location	Transit	2015-06-02T14:43:57	1.58	1.58	0.00	0.00	0.00	0.00	2015-06-02T16:18:38
Pre-lay grapnel 2.Grapnel run	Cable Laying	2015-06-02T16:18:38	54.64	54.64	0.00	0.00	0.00	0.00	2015-06-04T22:57:01
Pre-lay grapnel 2.Grapnel run repeat	Cable Laying	2015-06-04T22:57:01	69.20	54.64	0.00	14.56	0.00	0.00	2015-06-07T20:08:54
Pre-lay grapnel 2.Return after grapnel run	Transit	2015-06-07T20:08:54	1.58	1.58	0.00	0.00	0.00	0.00	2015-06-07T21:43:35
Cable section 5.Load cable to layer	Work	2015-06-07T21:43:35	134.00	134.00	0.00	0.00	0.00	0.00	2015-06-13T11:43:35
Cable section 5.Transit to cable route	Transit	2015-06-13T11:43:35	1.51	1.51	0.00	0.00	0.00	0.00	2015-06-13T13:13:57
Cable section 5.Lay	Cable Laying	2015-06-13T13:13:57	31.92	15.74	0.00	16.18	0.00	0.00	2015-06-14T21:08:58
Cable section 5.Install joint at 63 km	Work	2015-06-14T21:08:58	256.69	80.00	0.00	176.69	0.00	0.00	2015-06-25T13:50:26
Cable section 5.Transit to port after lay	Transit	2015-06-25T13:50:26	2.54	2.54	0.00	0.00	0.00	0.00	2015-06-25T16:22:42
Cable section 5.Transit to cable route for trench-bury	Transit	2015-06-25T16:22:42	1.58	1.58	0.00	0.00	0.00	0.00	2015-06-25T17:57:22
Cable section 5.Trench-bury	Cable Laying	2015-06-25T17:57:22	49.18	49.18	0.00	0.00	0.00	0.00	2015-06-27T19:07:55
Cable section 5.Transit to port after trench-bury	Transit	2015-06-27T19:07:55	2.62	2.62	0.00	0.00	0.00	0.00	2015-06-27T21:44:53
Cable section 6.Load cable to layer	Work	2015-06-27T21:44:53	134.00	134.00	0.00	0.00	0.00	0.00	2015-07-03T11:44:53
Cable section 6.Transit to cable route	Transit	2015-07-03T11:44:53	3.22	1.51	0.00	1.72	0.00	0.00	2015-07-03T14:58:23
Cable section 6.Lay	Cable Laying	2015-07-03T14:58:23	15.74	15.74	0.00	0.00	0.00	0.00	2015-07-04T06:42:33
Cable section 6.Install joint at 63 km	Work	2015-07-04T06:42:33	200.34	80.00	0.00	120.34	0.00	0.00	2015-07-12T15:02:42
Cable section 6.Transit to port after lay	Transit	2015-07-12T15:02:42	2.54	2.54	0.00	0.00	0.00	0.00	2015-07-12T17:34:57
Cable section 6.Transit to cable route for trench-bury	Transit	2015-07-12T17:34:57	1.58	1.58	0.00	0.00	0.00	0.00	2015-07-12T19:09:38
Cable section 6.Trench-bury	Cable Laying	2015-07-12T19:09:38	49.18	49.18	0.00	0.00	0.00	0.00	2015-07-14T20:20:11
Cable section 6.Transit to port after trench-bury	Transit	2015-07-14T20:20:11	2.62	2.62	0.00	0.00	0.00	0.00	2015-07-14T22:57:09
Pre-lay grapnel 3.Move to grapnel-run location	Transit	2015-07-14T22:57:09	2.62	2.62	0.00	0.00	0.00	0.00	2015-07-15T01:34:07
Pre-lay grapnel 3.Grapnel run	Cable Laying	2015-07-15T01:34:07	57.38	53.32	0.00	4.06	0.00	0.00	2015-07-17T10:56:40
Pre-lay grapnel 3.Grapnel run repeat	Cable Laying	2015-07-17T10:56:40	19.48	19.48	0.00	0.00	0.00	0.00	2015-07-18T06:25:15
Pre-lay grapnel 3.Grapnel run repeat 2	Cable Laying	2015-07-18T06:25:15	79.77	68.61	0.00	11.15	0.00	0.00	2015-07-21T14:11:17
Pre-lay grapnel 3.Return after grapnel run	Transit	2015-07-21T14:11:17	2.62	2.62	0.00	0.00	0.00	0.00	2015-07-21T16:48:14
Cable section 7.Load cable to layer	Work	2015-07-21T16:48:14	131.00	131.00	0.00	0.00	0.00	0.00	2015-07-27T03:48:14
Cable section 7.Transit to OSS Buitengaats	Transit	2015-07-27T03:48:14	3.67	3.67	0.00	0.00	0.00	0.00	2015-07-27T07:28:29
Cable section 7.Pull-in	Work	2015-07-27T07:28:29	16.00	16.00	0.00	0.00	0.00	0.00	2015-07-27T23:28:29
Cable section 7.Lay	Cable Laying	2015-07-27T23:28:29	15.36	15.36	0.00	0.00	0.00	0.00	2015-07-28T14:49:51
Cable section 7.Transit to port after lay	Transit	2015-07-28T14:49:51	2.54	2.54	0.00	0.00	0.00	0.00	2015-07-28T17:22:07
Cable section 7.Transit to cable route for trench-bury	Transit	2015-07-28T17:22:07	2.62	2.62	0.00	0.00	0.00	0.00	2015-07-28T19:59:04
Cable section 7.Trench-bury	Cable Laying	2015-07-28T19:59:04	47.99	47.99	0.00	0.00	0.00	0.00	2015-07-30T19:58:18
Cable section 7.Transit to port after trench-bury	Transit	2015-07-30T19:58:18	3.79	3.79	0.00	0.00	0.00	0.00	2015-07-30T23:45:39
Cable section 8.Load cable to layer	Work	2015-07-30T23:45:39	169.00	169.00	0.00	0.00	0.00	0.00	2015-08-07T00:45:39
Cable section 8.Transit to OSS Zee-energie	Transit	2015-08-07T00:45:39	3.95	3.95	0.00	0.00	0.00	0.00	2015-08-07T04:42:32

Cable section 8.Pull-in	Work	2015-08-07T04:42:32	16.00	16.00	0.00	0.00	0.00	0.00	2015-08-07T20:42:32
Cable section 8.Lay	Cable Laying	2015-08-07T20:42:32	19.76	19.76	0.00	0.00	0.00	0.00	2015-08-08T16:28:09
Cable section 8.Transit to port after lay	Transit	2015-08-08T16:28:09	2.54	2.54	0.00	0.00	0.00	0.00	2015-08-08T19:00:25
Cable section 8.Transit to cable route for trench-bury	Transit	2015-08-08T19:00:25	2.62	2.62	0.00	0.00	0.00	0.00	2015-08-08T21:37:22
Cable section 8.Trench-bury	Cable Laying	2015-08-08T21:37:22	433.76	61.75	0.00	372.01	0.00	0.00	2015-08-26T23:23:08
Cable section 8.Transit to port after trench-bury	Transit	2015-08-26T23:23:08	4.07	4.07	0.00	0.00	0.00	0.00	2015-08-27T03:27:32
Cable section 9.Load cable to layer	Work	2015-08-27T03:27:32	47.00	47.00	0.00	0.00	0.00	0.00	2015-08-29T02:27:32
Cable section 9.Transit to OSS-Buitengaats	Transit	2015-08-29T02:27:32	3.67	3.67	0.00	0.00	0.00	0.00	2015-08-29T06:07:47
Cable section 9.Pull in OSS-Buitengaats	Work	2015-08-29T06:07:47	16.00	16.00	0.00	0.00	0.00	0.00	2015-08-29T22:07:47
Cable section 9.Lay	Cable Laying	2015-08-29T22:07:47	5.61	5.61	0.00	0.00	0.00	0.00	2015-08-30T03:44:20
Cable section 9.Pull-in OSS Zee-energie	Work	2015-08-30T03:44:20	16.00	16.00	0.00	0.00	0.00	0.00	2015-08-30T19:44:20
Cable section 9.Transit to port after lay	Transit	2015-08-30T19:44:20	3.95	3.95	0.00	0.00	0.00	0.00	2015-08-30T23:41:13
Cable section 9.Transit to cable route for trench-bury	Transit	2015-08-30T23:41:13	3.79	3.79	0.00	0.00	0.00	0.00	2015-08-31T03:28:33
Cable section 9.Trench-bury	Cable Laying	2015-08-31T03:28:33	17.53	17.53	0.00	0.00	0.00	0.00	2015-08-31T21:00:16
Cable section 9.Transit to port after trench-bury	Transit	2015-08-31T21:00:16	4.07	4.07	0.00	0.00	0.00	0.00	2015-09-01T01:04:41

References

[1] 4Coffshore. Submarine power cable losses totalling over 350 million in claims, 2015. URL https://www.4coffshore.com/news.

[2] 8-13.nl. Gemini offshore wind farm, 2020. URL https://www.geminiwindpark.nl/.

[3] Zhao Bo and Ye Yincan. *Installation of the Submarine Optical Cable*. 2018. ISBN 9780128134764. doi: 10.1016/B978-0-12-813475-7.00006-0.

[4] BVG Associates. A Guide to an Offshore Wind Farm Updated and extended. *Published on behalf of The Crown Estate and the Offshore Renewable Energy Catapult*, (January):1–70, 2019. ISSN 1751-4223. URL http://www.thecrownestate.co.uk/guide{_}to{_}offshore{_}windfarm.pdf.

[5] Deltares. JIP CALM, 2019. URL https://www.offshore-energy.biz/keep-calm-and-reduce-cable-failures/.

[6] DHI. Hourly time series weather data used for ECN Install, 2019. URL https://www.metocean-on-demand.com/.

[7] DNVGL. Subsea power cables in shallow water. (March), 2016. URL www.dnvgl.com.

[8] STX Europe. Offshore Cable Installation - Lillgrund. Technical Report January, Vattenfall, 2009. URL https://www.osti.gov/etdeweb/servlets/purl/979750.

[9] John Horne and Raynald Leconte. Marine and maintenance (from inception to end of life). *Undersea Fiber Communication Systems: Second Edition*, pages 605–649, 2016. doi: 10.1016/B978-0-12-804269-4.00017-9.

[10] Mark J Kaiser and B Snyder. Offshore wind energy installation and decommissioning cost estimation in the U.S. outer continental shelf. (November):340, 2010.

[11] Georgios Katsouris and Andrew Marina. Cost Modelling of Floating Wind Farms. (March): 36, 2016. ISSN 0197-3533. URL http://questfwe.com/wp-content/uploads/2018/02/Cost-Modeling-of-Floating-Wind-Farms-ECN-2016.pdf.

[12] Vigney Kumar. Optimization of Offshore Wind Farm Installation Procedure With a Targeted Finish Date. page 91, 2017. URL https://repository.tudelft.nl/islandora/object/uuid{%}3A14461c46-90a3-44b8-8b64-ac6dae303f88?collection=education.

[13] Ludwig Freytag. Gemini: Shallow water power cable installation, 2015. URL https://www.ludwig-freytag.de/tagu-en/qualification/referencedetails.php?we{_}objectID=1081.

[14] Makailay. Dynamics of power cable laying, 2014. URL https://www.makai.com/cable-software/makailay/.

[15] Richard E. Nance. A history of discrete event simulation programming languages, 1993. ISSN 1558-1160. URL https://vtechworks.lib.vt.edu/bitstream/handle/10919/19854/TR-93-21.pdf?sequence=3{&}isAllowed=y.

[16] DEME Offshore. Offshore wind installation equipment data, 2020. URL https://www.deme-group.com/technologies/living-stone.

[17] Van Oord. Cable-laying vessel Nexus, 2020. URL https://www.vanoord.com/activities/cable-laying-vessel.

[18] Simon Powles. Time taken for the installation of a new joint for an offshore windfarm, 2016. URL https://www.4coffshore.com/news/power-csl-unveil-new-cable-joint-nid4000.html.

[19] Maksym Semenyuk. Offshore Wind Farm Installation Planning. Decision-support tool for the analysis of new installation concepts. page 150, 2019.

[20] Offshore Standard. DNV-OS-H101 Marine Operations , General. (October 2011):1–55, 2019.

[21] Y. Tekle Muhabie, P. Rigo, M. Cepeda, M. de Almeida D'Agosto, and J. D. Caprace. A discrete-event simulation approach to evaluate the effect of stochastic parameters on offshore wind farms assembly strategies. *Ocean Engineering*, 149(June 2016):279–290, 2018. ISSN 00298018. doi: 10.1016/j.oceaneng.2017.12.018. URL https://doi.org/10.1016/j.oceaneng.2017.12.018.

[22] Kurt E Thomsen. *OFFSHORE WIND OFFSHORE WIND to Successful Offshore Wind Farm Installation*. 2012. ISBN 9780123859365. doi: 10.1016/B978-0-12-385936-5.00019-9. URL https://www.elsevier.com/books/offshore-wind/thomsen/978-0-12-410422-8.

[23] Typhoon Offshore B V. Outline Method Statement Submarine Export cable installation. Technical report, 2012.

[24] Van Oord. Gemini project gantt chart, 2018. URL https://www.vanoord.com/projects.

[25] Vlasblom. Chapter 2: Trailing suction hopper dredger, 2007. URL https://dredging.org/documents/ceda/downloads/vlasblom2-trailing{_}suction{_}hopper{_}dredger.pdf.

[26] Yuanhui Wang, Xinqian Bian, Xiaoyun Zhang, and Wenbo Xie. A study on the influence of cable tension on the movement of cable laying ship. *MTS/IEEE Seattle, OCEANS 2010*, pages 1–8, 2010. doi: 10.1109/OCEANS.2010.5664404.

[27] Frank D E Wild, Wessel Bakker, and D N V Gl. JIP CABLE LIFETIME MONITORING. 2018.

[28] Clym Stock Williams. UWISE ML Training course presentation. Technical report, 2019.

[29] Thomas Worzyk. *Submarine power cables: Design, Installation, Repair, Environmental Aspects*. Springer, 2009. ISBN 9783642012693. URL https://link.springer.com/book/10.1007/978-3-642-01270-9{#}about.

[30] E. E. Zajac. Dynamics and Kinematics of the Laying and Recovery of Submarine Cable. page 80, 1957. URL https://ia800301.us.archive.org/33/items/bstj36-5-1129/bstj36-5-1129.pdf.