University of Liège – Faculty of applied sciences
Academic year 2013-2014

Optimization of the installation process of offshore wind turbines

Optimisation du processus de montage
des éoliennes offshore

Travail de fin d'études réalisé en vue de l'obtention du grade de
Master Ingénieur Civil des constructions
par Julie Desemberg

Jury members:
Supervisor: Prof. P. Rigo
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Objectifs

Ce travail de fin d'étude concerne l'analyse du processus de montage des éoliennes offshore. Les séquences de construction auxquelles nous nous sommes intéressés sont les suivantes : le transport des composants entre les fournisseurs et le port, le pré-assemblage réalisé au port, le transport des composants vers le site offshore et enfin, l'installation des éoliennes sur le site offshore.

Le premier objectif fixé est la réalisation d'un état de l'art expliquant le marché de l'éolien offshore, les différents composants d'un tel parc éolien, les différentes méthodes de construction, les bateaux utilisés pour le transport et l'installation et enfin, les ports impliqués durant la phase de construction.

Le second objectif est la réalisation de simulations concernant un projet spécifique en faisant varier différents paramètres. L'objectif étant d'identifier l'influence de ces différents paramètres sur le temps de construction. Ces simulations sont réalisées avec le logiciel EOSIM développé au sein du département ANAST de l'Université de Liège. Ce logiciel permet de simuler les étapes de construction, c'est-à-dire la chaîne logistique, d'un parc éolien offshore en tenant compte de données météorologiques réelles (vitesses de vent et hauteurs de vague).

Le dernier objectif consiste en la comparaison de deux techniques de montage : celle où le rotor est pré-assemblé avec ses trois pâles sur le site d'assemblage onshore et, celle où seulement deux pâles sont assemblées onshore et la troisième est montée en mer.

Ce travail permet donc de se familiariser avec le domaine très spécifique qu'est la construction d'éoliennes offshore. De plus, la réalisation de simulations est abordée. Celles-ci sont effectuées dans le but d'évaluer des temps de construction et de réaliser des choix entre différentes options.

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SUMMARY

Title: Optimization of the installation process of offshore wind turbines
Author: Julie Desemberg
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This master thesis concerns the analysis of the installation process of offshore wind turbines. This analysis could be realized thanks to the software "EOSIM" developed in department ANAST of the University of Liège. This software uses discrete event simulation (D.E.S.) in order to simulate the construction steps. The construction of an offshore wind farm depends on several weather conditions. The software allows the evaluation of the risk linked to the weather data, by using real weather data of various years.

In this work, we will first present the offshore wind sector, explaining the offshore wind market, the different components of an offshore wind farm, the different installation strategies, the vessels used for transport and installation and the ports which are involved during the construction phase.

Secondly, we will analyse the influence of various parameters on a specific project by running simulations of the construction thanks to the previously mentioned software. The influence of the following parameters on the lead time is studied: the distances, the speeds, the number of turbines and the meteorological limits of the different operations (wave heights and wind speeds).

Finally, we compare two assembly scenarios, once again by realizing simulations of wind farm construction.

In the first method, the rotor is preassembled with its three blades onshore and installed as a whole.

While, in the second method, the rotor is preassembled onshore with only two blades and the third blade being installed when the rotor is assembled on the turbine.

In this work, the critical parameters that should be adapted in order to optimize the duration of construction of the project are identified. Moreover, the comparison of the two assembly scenarios shows that dependence on the project, an appropriate choice of the assembly method allows savings of time.

RÉSUMÉ

Titre : Optimisation du processus de montage des éoliennes offshore
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Année académique 2013-2014

Ce travail de fin d'études concerne l'analyse du processus de montage des éoliennes offshore. Cette analyse a pu être réalisée grâce au logiciel « EOSIM » développé au sein du département ANAST de l'Université de Liège. Ce logiciel utilise la simulation d'événements discrets (D.E.S.) afin de simuler les différentes étapes de construction. La construction d'un parc offshore dépend fortement des conditions météorologiques. Le logiciel utilisé permet d'évaluer le risque lié à ces données météo en utilisant les données réelles de plusieurs années.

Dans ce travail, nous présentons d'abord de façon générale le domaine de l'éolien offshore en expliquant le marché de l'éolien offshore, les différents composants d'un parc éolien offshore, les différentes stratégies d'installation, les bateaux employés pour le transport et l'installation et les ports impliqués dans la construction.

Dans un second temps, nous réalisons une analyse de l'influence de différents paramètres sur un projet spécifique en réalisant des simulations de construction à l'aide du logiciel précédemment mentionné. L'influence des paramètres suivants sur le temps de construction est étudiée : les distances, les vitesses, le nombre d'éoliennes et les limites météorologiques des différentes opérations (hauteurs de vague et vitesses de vent).

Finalement, nous comparons deux méthodes d'assemblage à nouveau en réalisant des simulations de construction. Dans la première méthode, le rotor est préassemblé avec ses trois pâles onshore et installé en entier. Dans la deuxième technique, le rotor est préassemblé avec seulement deux pâles et la troisième pâle est montée une fois que le rotor est installé sur l'éolienne.

Dans ce travail, les paramètres qu'il convient d'adapter en priorité pour optimiser le temps de construction du projet sont identifiés. De plus, la comparaison entre les deux méthodes d'assemblage montre que selon le projet, un choix approprié de stratégie d'assemblage permet de réaliser des économies de temps.

Acknowledgement

This master thesis was a four month work and it could be achieved thanks to the help of many people.

I first want to thank my supervisor Professor P. Rigo for his availability and advices. I would also like to thank Mrs. Fiona Buckley for her comments and ideas about my work. Moreover, I would like to thank Professor L. Courard and Professor M. Cools for accepting to be members of my jury.

I am also thankful to Mr. C. Petcu for taking the time to respond to my questions and for having read this report. I want to thank Mr. Y. Tekle for helping me with the problems I encountered with the software.

Lastly, I would like to thank Mrs. Gladys Brocard for having read this report.

Finally, I thank all my family and friends for their support not only during this thesis, but during all my studies.

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CHAPTER 1 INTRODUCTION

The offshore wind sector is a growing market expected to expand quite extensively over next years. Europe is the current leader of this market and should benefit its first mover advantage by exporting its technologies around the world.

However the construction of an offshore wind farm is far more complicated than the construction of an onshore one. Indeed, the components are bigger and the construction steps are very dependent on the weather conditions. Moreover, offshore wind turbines need specific substructures.

This master thesis concerns the analysis of the installation process of offshore wind turbines. This analysis could be realized thanks to a software called “EOSIM”, developed in department ANAST of the University of Liège. This software uses discrete event simulation in order to simulate the following construction steps of an offshore wind farm: the transport of the components from the supplier to the harbour, the pre-assembly realized at the onshore site, the transport of the components to the offshore site and finally, the installation of the turbines on the offshore site. In order to assess the risk linked to weather conditions, the software uses real data of various years.

In this report, we will first present the offshore wind sector, thanks to a state of the art explaining the offshore wind market, the different components of an offshore wind farm, the different installation strategies, the vessels used for transport and installation and the harbours which are involved during the construction phase.

Afterwards, we will make an analysis of the parameters of a specific project. This analysis could be realized thanks to the previously described software. The parameters we varied are the following ones: distances, speeds, number of wind turbines and workability limits. These limits are necessary because they fix the value of the weather data (wave heights and wind speeds) above which an operation cannot be realized.

Finally, we will compare two installation strategies once again thanks to simulations realized with the software.

In the first one, the rotor is preassembled with its three blades on the onshore site.

In the second one, called the bunny ear method, the rotor is preassembled onshore with only two blades while the third blade is installed on the offshore site, in an independent fashion.

The realization of this type of analysis on a real project can help the user choose between different options of construction which involve different installation strategies or vessels.

CHAPTER 2 STATE OF THE ART

This state of the art presents the offshore wind power market and the technics currently used for the construction of an offshore wind farm.

Europe is the leader in the offshore wind power market and it is expected that during next years, it will benefit of its first mover advantage thanks to the expansion of the offshore wind market in the rest of the world.

The construction of an offshore wind farm is far more complicated than the construction of an onshore one. The substructures used in an offshore farm benefit from the experience of oil and gas industry which has been using these technologies for years. The components of an offshore wind turbine are bigger than the ones used for an onshore wind turbine. The important size of these components can create transport problems. Electrical infrastructure is also more difficult than for the onshore. Indeed, far offshore farms need an offshore substation. Moreover, in order to connect the farm to the shore, long subsea cables are needed.

A standard installation strategy does not currently exist to construct offshore wind farms. Various options exist: use of feeder vessels, use of a mobilization port… The choice of a strategy obviously depends on the cost and the lead time. There are also various loading approaches related to whether or not the turbine components are preassembled onshore.

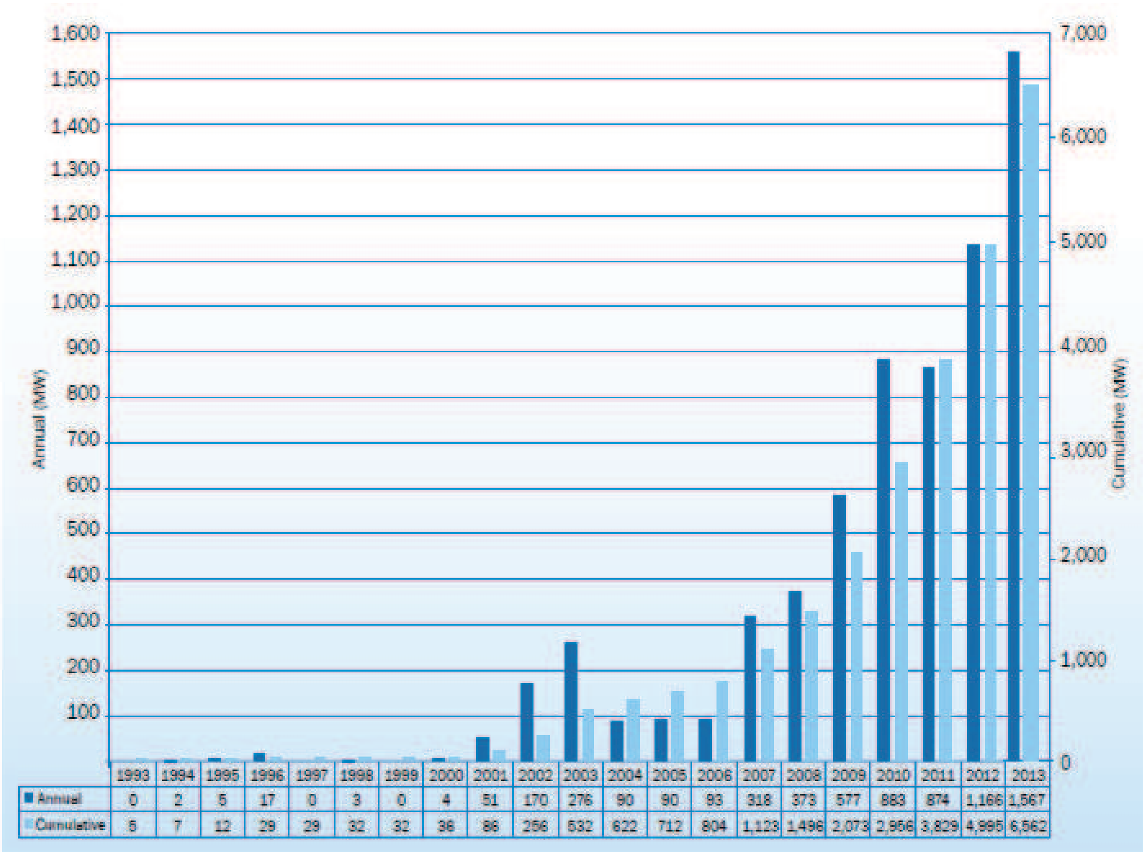
1 OFFSHORE WIND POWER MARKET

1.1 HISTORY

The first offshore wind farm was built in 1991 in Denmark at Vindeby. The project was composed by 11 turbines with a total capacity of 4.95MW. The location of the project was at 1.8km of the Danish coast and at a depth ranging between 2m and 4m [4COFFSHORE].

Until 2001, the development of the offshore wind market was irregular and was composed of some isolated projects in Denmark and Germany. The turbines remained under the capacity of 1MW. The year 2001 was marked by the Middelgrunden project in Denmark which was the first “utility-scale” project with 20 turbines and a total capacity of 40MW [THE WINDPOWER].

As we can see in Figure 1, since 2001, the offshore capacity has increased significantly. The share of the offshore wind capacity in the total wind capacity has grown too.



	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Annual	0	2	5	17	0	3	0	4	51	170	276	90	90	93	318	373	577	883	874	1,166	1,567
Cumulative	5	7	12	29	29	32	32	36	86	256	532	622	712	804	1,123	1,496	2,073	2,956	3,829	4,995	6,562

Figure 1: Cumulative and annual offshore wind capacity installed[1]

[1] E.W.E.A., *The European offshore wind industry-key trends and statistics 2013*, January 2014, p.10

1.2 *CURRENT SITUATION IN EUROPE*

With a total installed capacity of 6 562MW [E.W.E.A., 2014] at the end of 2013, Europe is the current leader in the offshore wind power market. Currently, Europe owns 69 offshore wind farms and a total of 2080 offshore wind turbines [E.W.E.A., 2014].

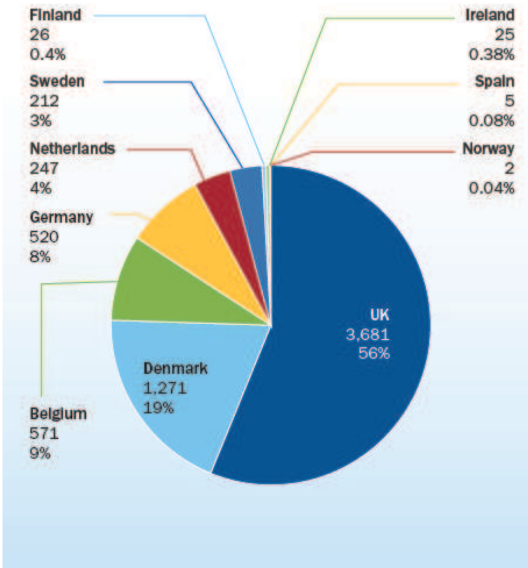


Figure 2: Repartition of the installed offshore wind capacity[2]

As we can see in Figure 2, UK has the most important installed capacity of Europe with 3681MW [E.W.E.A, 2014]. In second position, we have Denmark and then, Belgium. The countries close to the Mediterranean Sea are not well represented in the offshore wind market. Indeed, most wind farms are situated in the North Sea, the Baltic Sea and the Atlantic Ocean. This can easily be explained by the fact that the Mediterranean Sea is too deep. The construction of deep water wind farms will be one of next years' big challenges. The map showed in Figure 3 confirms the facts presented above.

[2] E.W.E.A., *The European offshore wind industry-key trends and statistics 2013,* January 2014, p.11

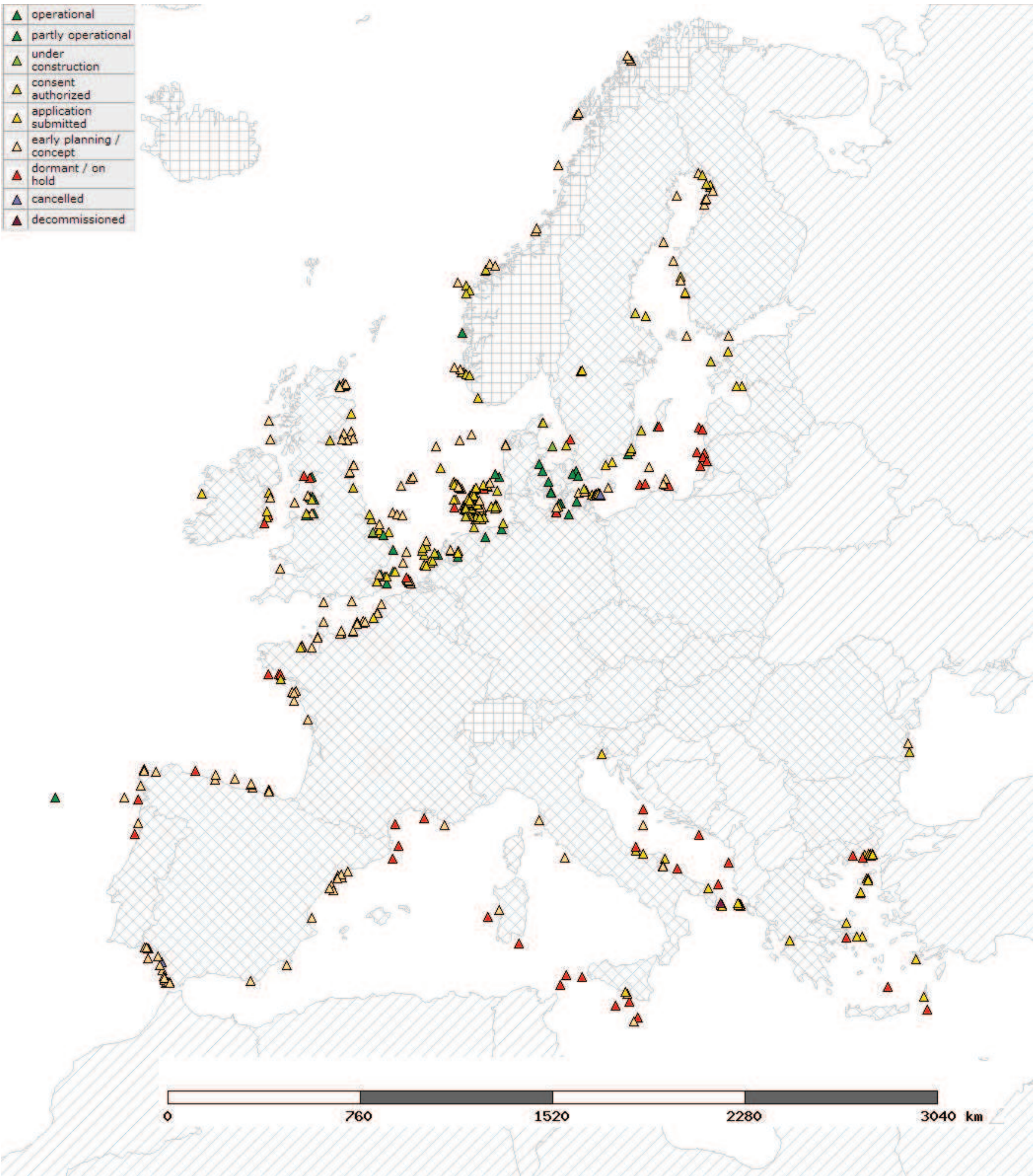


Figure 3: European wind farms (2011)[3]

1.3 PERSPECTIVES

The European Union has already fixed several objectives for 2020 and further for 2030.

1.3.1 2020

The targets of the wind energy sector for 2020 are [E.W.E.A., September 2013]:

- 15-17% of energy from wind energy;
- 520 000 jobs in Europe;

[3] ORECCA, Map of the offshore renewable plants, http://map.rse-web.it/orecca/map.phtml

- 342 Mt of CO_2 avoided;
- 26.6 billions of investment in 2020.

More specifically, we can expect an offshore installed capacity of 40 GW covering between 4% and 4.2% of the European electricity consumption. We can also expect one quarter of the wind energy to come from the offshore wind sector. This way, the offshore wind market should avoid the emission of 102 Mt of CO_2 [E.W.E.A., 2011]. The expected evolution of offshore capacities between 2011 and 2020 is presented in Figure 4.

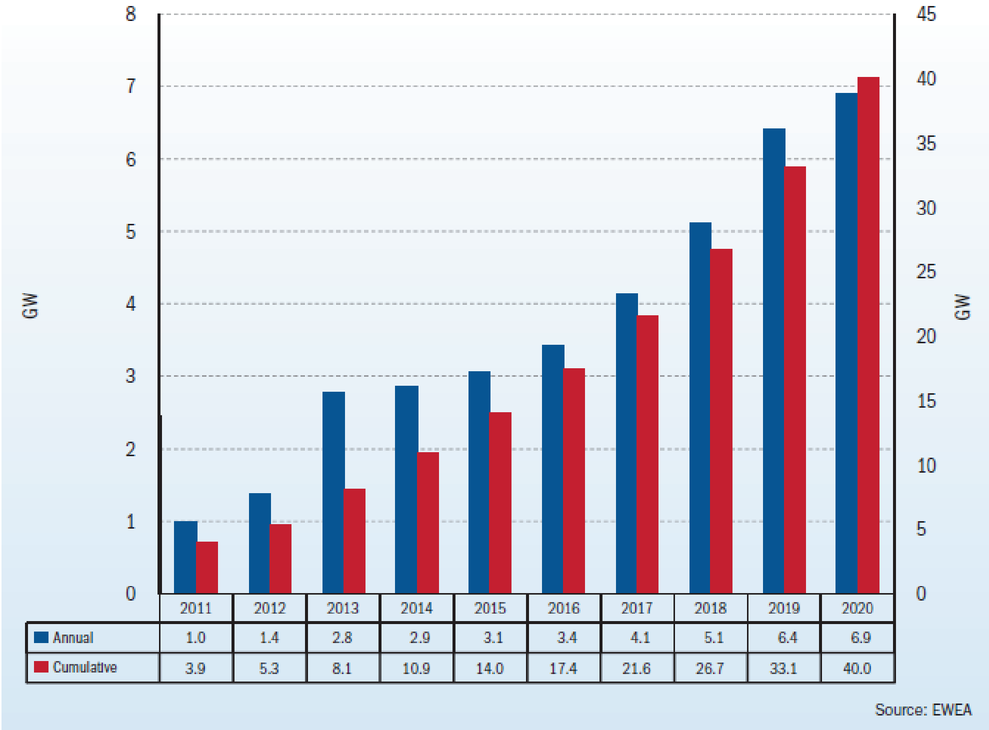


Figure 4: Annual and cumulative expected offshore wind capacities[4]

1.3.2 2030

The targets of the wind energy sector for 2030 are still under discussion. The objectives should be close to the following ones [E.W.E.A., September 2013]:

- 28.5% of European electricity from wind energy;
- 795 000 jobs in Europe;
- 646Mt of CO2 avoided;
- 25.3 billions of investment.

More specifically, we can expect an installed capacity of 150GW in 2030. Offshore wind energy should produce 13.9% of European energy consumption. Offshore wind farms will produce half of the European wind electricity in 2030 as we can see in Figure 5. In 2030, the offshore wind power should avoid 315Mt CO_2 [E.W.E.A. 2011].

[4] E.W.E.A., *Wind in our sails,* 2011, p.19

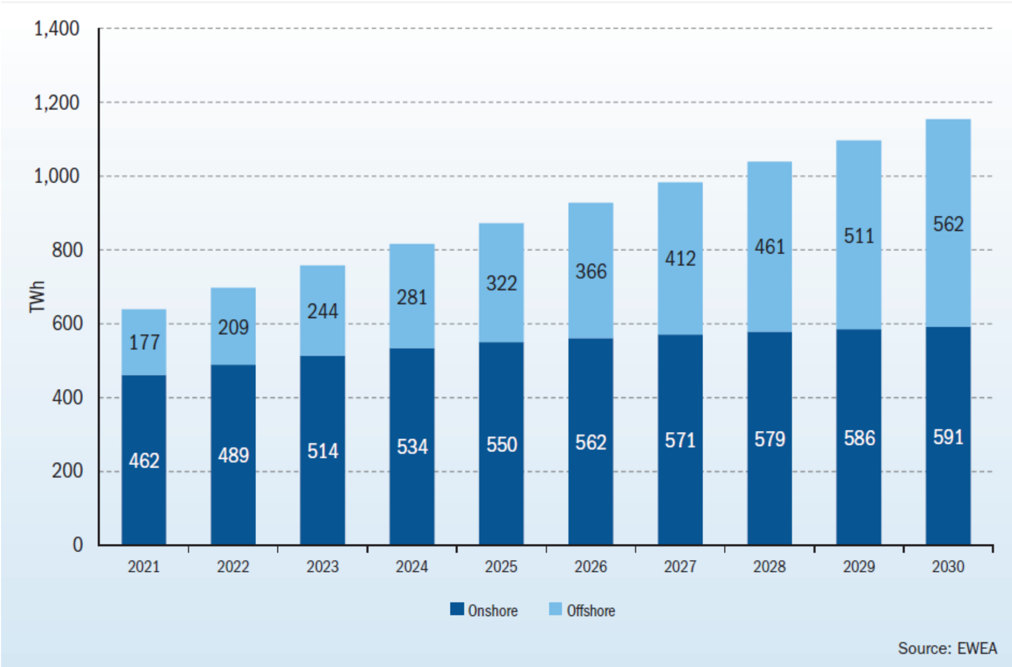


Figure 5: Wind electricity production[5]

1.4 SITUATION IN THE REST OF THE WORLD

1.4.1 Global wind capacity

The repartition of installed capacity is showed in Figure 6.

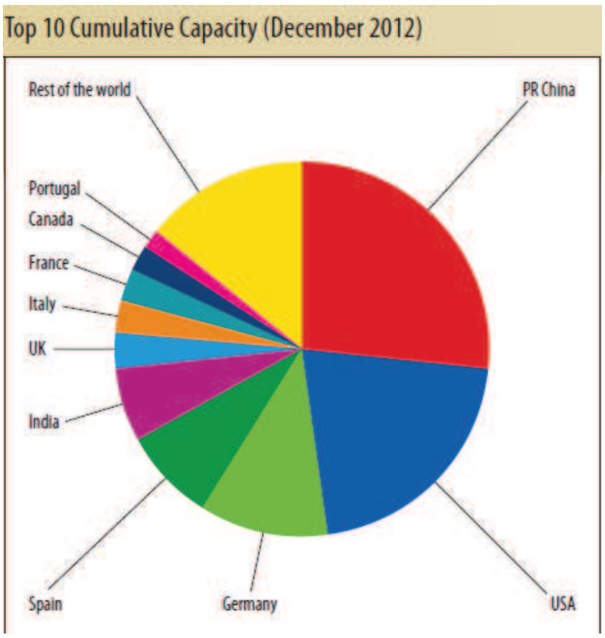


Figure 6: Top ten cumulative capacity (2012)[6]

As we can see in Figure 6, China is the current leader in the wind power market with a total capacity of 75.324MW (26.7%) in 2012 [G.W.E.C., 2012]. As presented in Figure 7, the world total capacity is 282.587MW [G.W.E.C., 2012].

[5] E.W.E.A., *Wind in our sails,* 2011, p.24

[6] G.W.E.C., *Global wind report-Annual market update 2012,* 2012, p.10

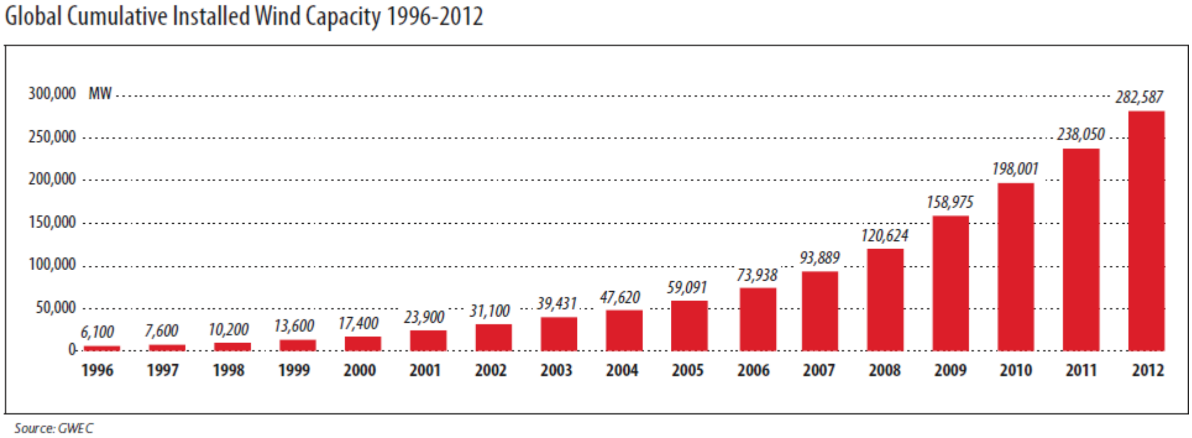


Figure 7: Evolution of the global cumulative installed wind capacity[7]

1.4.2 Global offshore wind capacity

Today, offshore wind energy represents 2% of the global installed wind capacity around the world [G.W.E.C., 2012]. 90% of offshore capacity is located in Europe [G.W.E.C., 2012]. The rest of the projects are mostly situated in China. Other countries such as the United States, Japan, Korea, Canada, Taiwan and India seem to be interested in this technology.

Global offshore wind power in the end of 2012

	2012 (MW)	Cumulative (MW)
UK	854	2,947.9
Denmark	46.8	921
China	127	389.6
Belgium	185	379.5
Germany	80	280.3
Netherland	0	246.8
Sweden	0	163.7
Finland	0	26.3
Japan	0.1	25.3
Ireland	0	25.2
Korea	3	5
Norway	0	2.3
Portugal	0	2
Total	1,296	5,415

Figure 8: Global offshore wind capacity (2012)[8]

As we can see in Figure 8, the United Kingdom is the world leader with a total installed capacity of 2947.9MW in 2012 [G.W.E.C., 2012]. The first country located out of Europe is China with a capacity of 389.6MW in 2012 [G.W.E.C., 2012]. According to this, Europe could use its leader position to export its knowledge around the world.

[7] G.W.E.C., *Global wind report-Annual market update 2012,* 2012, p.13
[8] G.W.E.C., *Global wind report-Annual market update 2012,* 2012, p.40

China

Most projects are located in inter-tidal zones. Its target is to reach 30GW of offshore wind capacity by 2020 [G.W.E.C., 2012]. The main problem is the lack of coordination between the different governmental associations which slows down the progress.

Taiwan

The Taiwanese objective is to reach 3GW of offshore wind capacity by 2030 [G.W.E.C., 2012].

Japan

As an island, the Japanese offshore potential is very high (estimated at 1573GW) [G.W.E.C., 2012]. Due to the Fukushima disaster, Japan is currently very interested by new sources of energy such as offshore wind. Japan has some offshore on-going projects and is currently testing new types of foundations such as floating foundations. The development of floating technologies is very important in Japan because of the high water depth (200m deep close to the coast).

South Korea

South Korea has ambitious objectives. The government plans an installed offshore capacity of 1.5GW by 2019. Local governments are also planning offshore projects (4.5GW). These offshore projects are ambitious to complete the target of 11% energy produced from renewable sources by 2030. Many well-known Korean companies are interested in the offshore market such as Samsung, Doosan, Daewoo and Hyundai [G.W.E.C., 2012].

United States

Currently, there are no commercial-scale offshore projects in operation or in construction in the United Sates. However, eleven projects counting for a total of 3824MW are currently in development [NAVIGANT CONSULTED INC., 2013]. Some projects are federal projects, while others are states' projects. All of them are located on the East coast.

2 COMPONENTS OF AN OFFSHORE WIND FARM

2.1 SUBSTRUCTURES

Many types of substructures exist. All these types can be divided in two categories: floating and non-floating substructures (or classic substructures). The type of foundation depends on the wind speed, the water depth, the wave height and the size and weight of the wind turbine. As we can see in Figure 9, monopiles are the most popular substructures (76%).

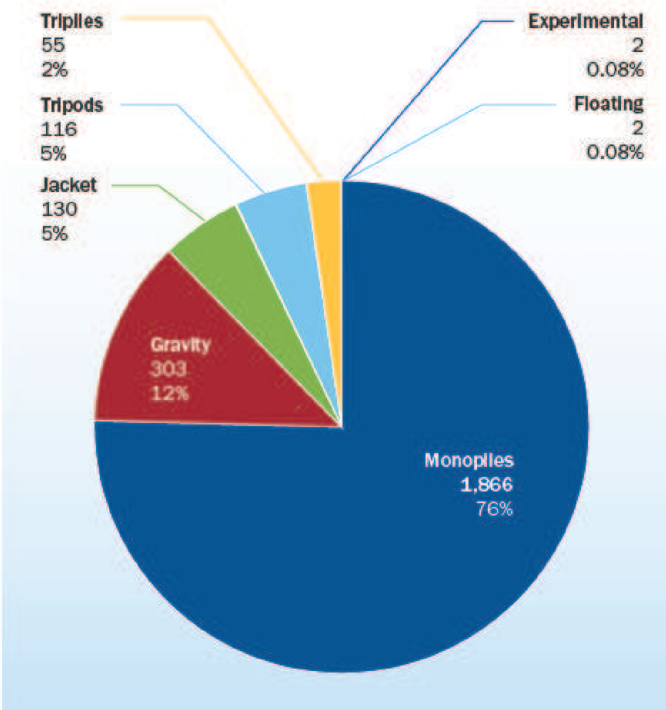


Figure 9: Repartition of substructure types(2013)[9]

In Figure 10 and Figure 11, we can see the types of foundations and their water depth limits.

[9] E.W.E.A., *The European offshore wind industry-key trends and statistics 2013,* January 2014, p.13

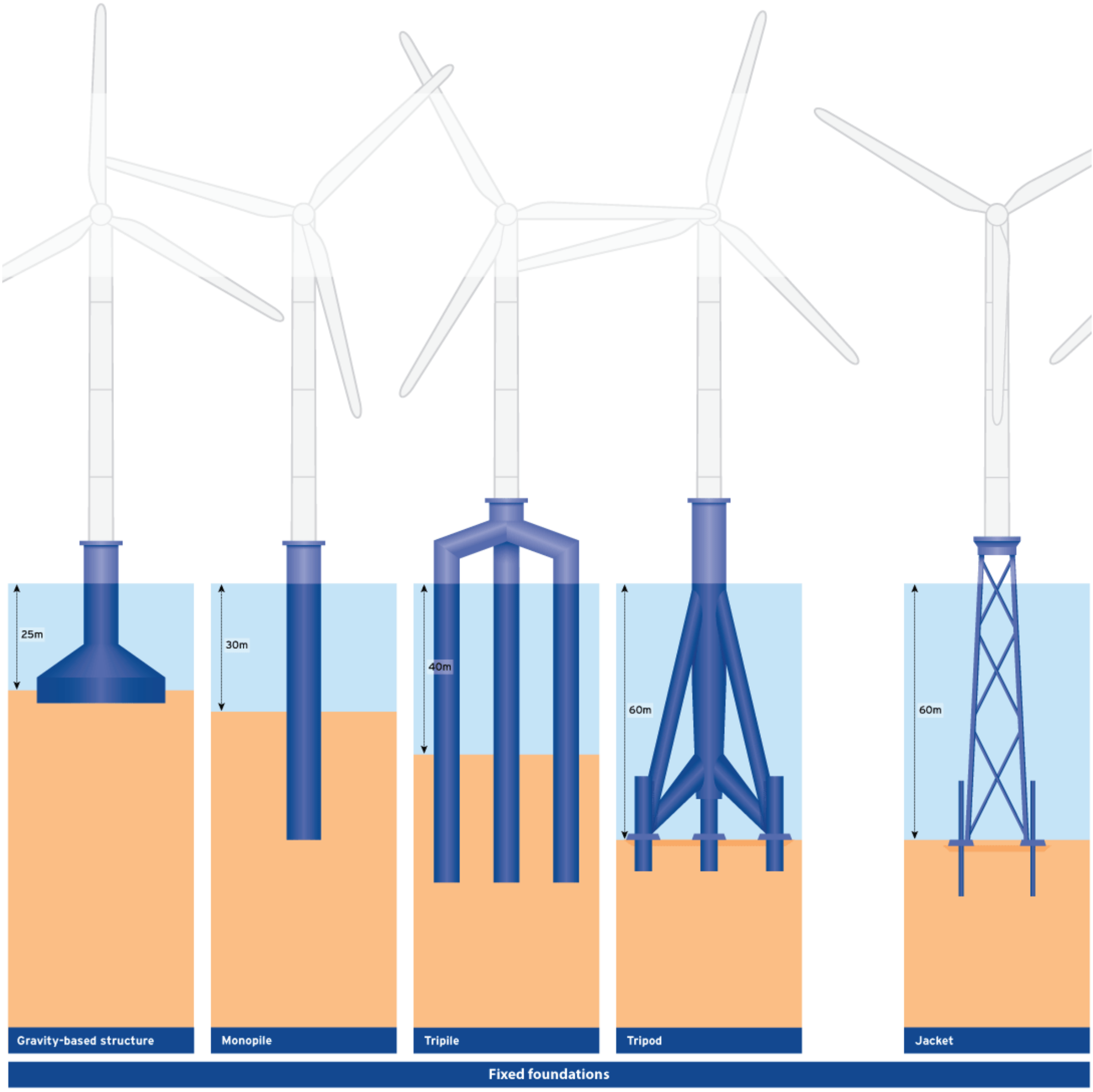


Figure 10: Types of classic substructures[10]

[10] Windpower offshore, Foundations types and depth limits-Alternative solutions, http://www.windpoweroffshore.com/article/1210054/foundations-types-depth-limits---alternative-solutions

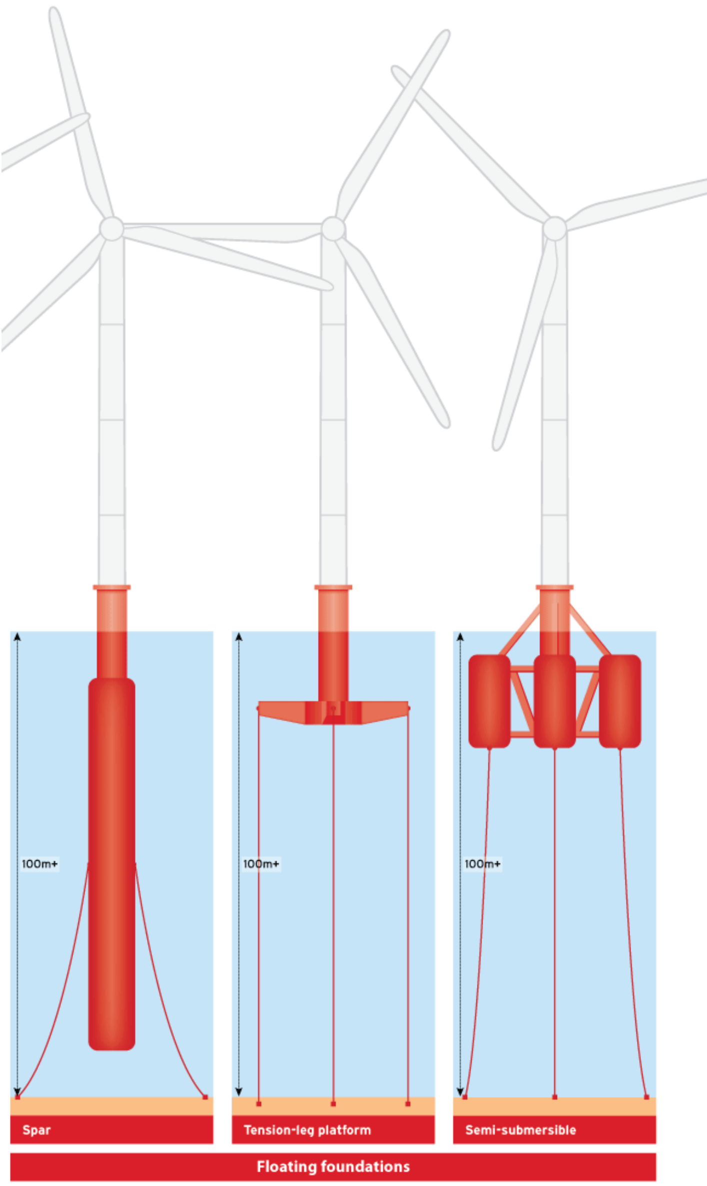


Figure 11: Floating substructures[11]

2.1.1 Classic substructures

Classic substructures are the only ones currently used in large-scale offshore wind projects. The main types are:

- Monopile foundation
- Gravity-based structure
- Jacket foundation
- Tripod foundation
- Tri-pile foundation

[11] Windpower offshore, Foundations types and depth limits-Alternative solutions, http://www.windpoweroffshore.com/article/1210054/foundations-types-depth-limits---alternative-solutions

Monopiles

Monopile foundations are the most popular substructures (76%). Monopiles are usually cylindrical steel tubes embedded into the sea bed. Their diameter and thickness depend on the water depth and the wind turbine. The monopile foundation is linked to the wind turbine by a transition piece (Figure 12). This type of foundation isn't efficient in high water depth (more than 25m). Developments are made to create new monopiles stable in higher water depth thanks to an extra-large diameter. Thanks to its simplicity this type of foundation is the first choice when the project complexity isn't too high.

Actually, the limit of diameter is around 6m, but this limit should increase due to the researches realized in extra-large monopiles. The maximum weight is around 1000t.

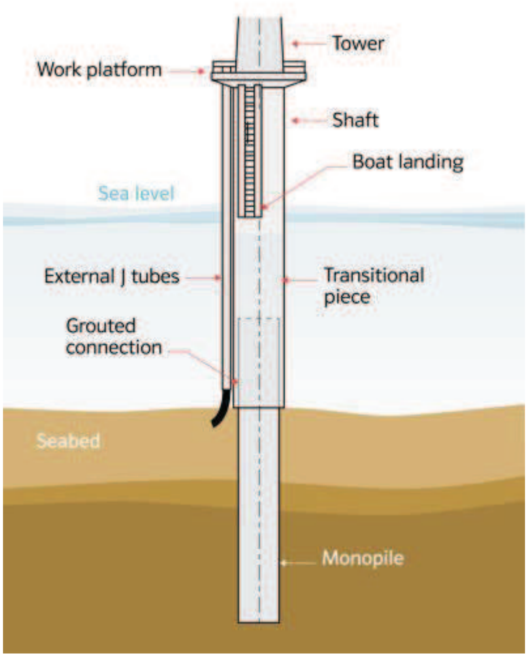


Figure 12: Monopile foundation[12]

Three ways exist in order to embed the monopile:

- Hammering: the monopile can be embedded with a hydraulic hammer (Figure 13). The inconvenience is that this technique produces a lot of noise. This noise can harm fish or sea animals. New techniques must be found to mitigate this noise.

[12] Eon energy, Offshore elements, https://www.eonenergy.com/About-eon/our-company/generation/planning-for-the-future/wind/offshore/Rampion/project-information/offshore-elements

Figure 13: Hydraulic hammer+monopile[13]

- Vibration: monopiles can also be installed by vibrating hammers (Figure 14). This technique is faster and produces less noise than the hydraulic hammer.

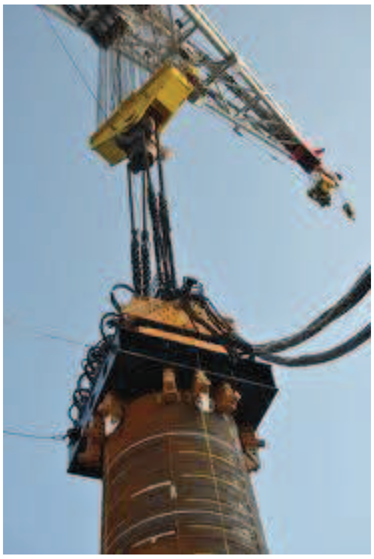


Figure 14: Vibrating hammer[14]

- Drilling: drilled monopile foundations are in development. The goals are to reduce the noise and the costs. The drilled monopiles are made of concrete and developments are made to avoid the use of a transition piece. The installation method is presented in Figure 15.

[13]Offshore technology, MENCK specialty hydraulic hammers, http://www.offshore-technology.com/contractors/dredging/menck/
[14] Offshorewind, Germany : modular vibrating of monopiles for offshore wind farm Riffgat, http://www.offshorewind.biz/2012/06/26/germany-modular-vibrating-of-monopiles-for-offshore-wind-farm-riffgat/

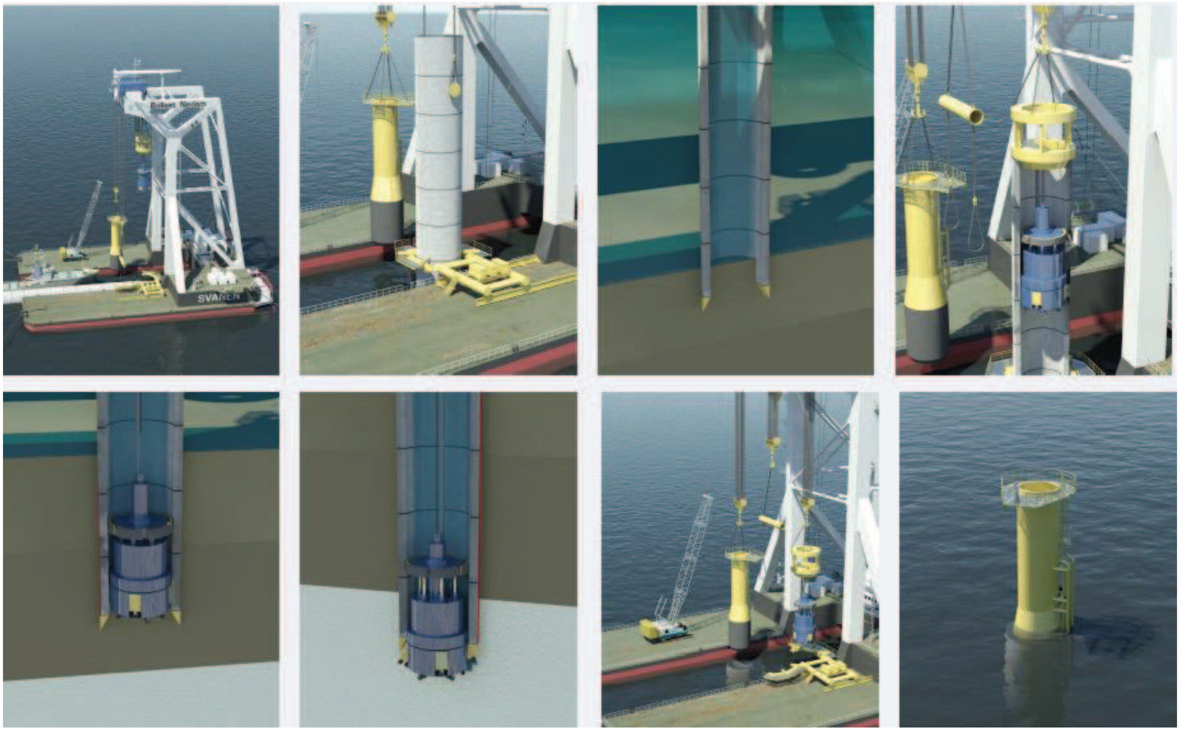


Figure 15: Installation method of a drilled monopile[15]

Gravity based foundations

The stability is ensured by dead loads which weigh down the structure. Gravity based foundations are composed of reinforced concrete cylinders or cones constructed in building yards and transported on site. Once installed on site the caissons are filled with sand, rock, concrete or iron depending on the conditions. The size of a gravity based foundation mainly depends on the turbine capacity, the water depth and the weather conditions. Currently, this type of substructure is mainly used up to 30 meters deep. Gravity based substructures require an extraspace in the harbour, some large vessels and an intensive man work. Moreover, it is logistically complex. This type of foundation is mainly used when the ballast is available at a low cost.

Construction and installation steps are the following ones:

- Construction of the concrete cones in building yards (Figure 16).
- Preparation of the sea bed level thanks to dredging and the installation of the foundation layer.
- Transport onshore of the gravity based foundation. On the Thornton Bank project this was realized thanks to self propelled modular trailers [KENNETH PEIRE, HENDRIK NONNEMAN AND ERIC BOSSCHEM, 2009].
- Lifting and transport offshore. On the Thornton Bank project, the transport offshore was realized with a shearleg cranebarge and the gravity based foundation was lowered below the water table [KENNETH PEIRE, HENDRIK NONNEMAN AND ERIC BOSSCHEM, 2009] (cfr Figure 16).

[15] MAARTEN VAN DER VEEN; EDWIN VAN DE BRUG; MARCEL VAN BERGEN; DOLF ELSEVIER VAN GRIETHUYSEN; KLAAS ADELAAR; JURJAN BLOKLAND, *Drilled monopile foundations: environmental friendly, structural robust and cost efficient,* December 2011, Ballast Nedam Offshore, p.1

- Installation of the gravity base foundation.
- Backfill of the foundation pit.
- Infill of the gravity base foundation.
- Installation of the scour protection.

Figure 16: Construction and transport of the gravity based foundations on the Thornton Bank project[16]

Jacket foundation

The jacket foundation is a space frame structure made up of several steel piles. This type of foundation is used in deeper locations. The objective of a space frame structure is to minimize the weight. In jacket substructures, the load is situated further from the axis. This position of the load allows material savings. Firstly, the jacket foundation was used in the oil and gas industry. This type of foundation is likely to be more used in the offshore wind industry in the coming years as projects are going further from shore. The substructure is fixed to the ground thanks to piles. The high cost of manufacture and assembly is compensated by the material savings in high water depths. The cost is expected to decrease during next years thanks to the development of an automated production.

Construction and installation steps are the following ones [GEERT DEWAELE, 2012]:

- Sea bed preparations.
- Transport and unloading of piles on the jack-up platform.
- Positioning of the piles in the holes of the piling frame (if used) and hammering (Figure 17). The piling frame is used to accelerate the installation of piles.
- Assembly of jackets, pile stoppers and midsection.
- Transport of jacket foundations (Figure 18).
- Jacket installation (Figure 18).
- Achievements of the grouting between jacket legs and piles.

[16] C-POWER, Photo gallery phase 1, http://www.c-power.be/photo-gallery-phase-1

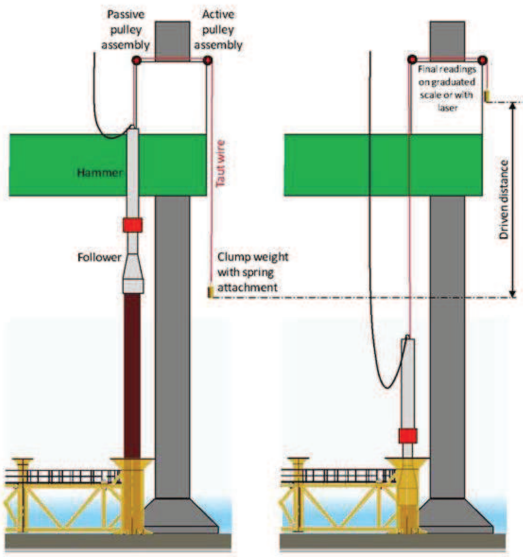


Figure 17: Hammering of piles[17]

Figure 18: Transport and installation of the jacket[18]

Tripod foundation

As the jacket foundation, the tripod foundation is a space frame substructure. The tripod is composed of three steel piles as legs and a central steel shaft attached to the turbine tower. The piles diameter ranges between 2m and 3m and the distance between the piles is between 20m and 40m [E.W.E.A., 2011]. The size of this substructure is influenced by the turbine capacity, the water depth and the weather conditions. Usually, this type of foundations can be employed in water depths from 20m until 50m [E.W.E.A., 2011].

[17] C-POWER, *Jackets*, http://www.c-power.be/jackets
[18] C-POWER, *Jackets*, http://www.c-power.be/jackets

The steps followed for the installation of a tripod foundation are similar to the ones followed for the jacket installation. Here are the steps followed in the global tech 1 project for the installation of the tripods [LUTZ SIEMERS, CLAUS BIEGER, 2013]:

- sea bed preparations;
- loading of piles and tripods;
- transfer to offshore site;
- installation of the tripod;
- installation of three piles;
- grouting.

Figure 19: Tripods loading, transfer and installation

[19]

Tri-pile foundation

Once again, the tri-pile foundation is a space frame foundation which consists of three piles connected to each other thanks to a transition piece. This transition piece is located up to the water level. The tri-pile foundation has already been employed in BARD 1 offshore project situated in the North Sea at a water depth of 40 m. The tripile foundation can be employed for projects with water depths between 25m and 50m [BARD]. This system is light and compact. It can already be manufactured in series by a company active in the offshore domain (Bard). In order to adapt to the site's conditions, the piles height and thickness can be modified. This way, the transition piece doesn't have to change and can be easily produced in series.

The construction steps are the following ones:

- sea bed preparations;
- loading of piles;

[19] LUTZ SIEMERS, CLAUS BIEGER, *Global Tech 1 offshore wind farm installation process*, September 2013, Hochtief Solutions AG

- transfer to the offshore site;
- installation of piles thanks to a guiding frame;
- loading of the transition piece;
- transfer of the transition piece;
- installation of the transition piece (Figure 19);
- grouting with a special cement.

Piles and transition pieces can be transferred at the same time depending on the boat.

Figure 20: Installation of the transition piece of the tri-pile foundation at BARD 1 offshore[20]

2.1.2 Floating substructures

As the offshore wind projects are moving further from shore, in deeper waters (Figure 21), floating substructures are a key challenge for the next years.

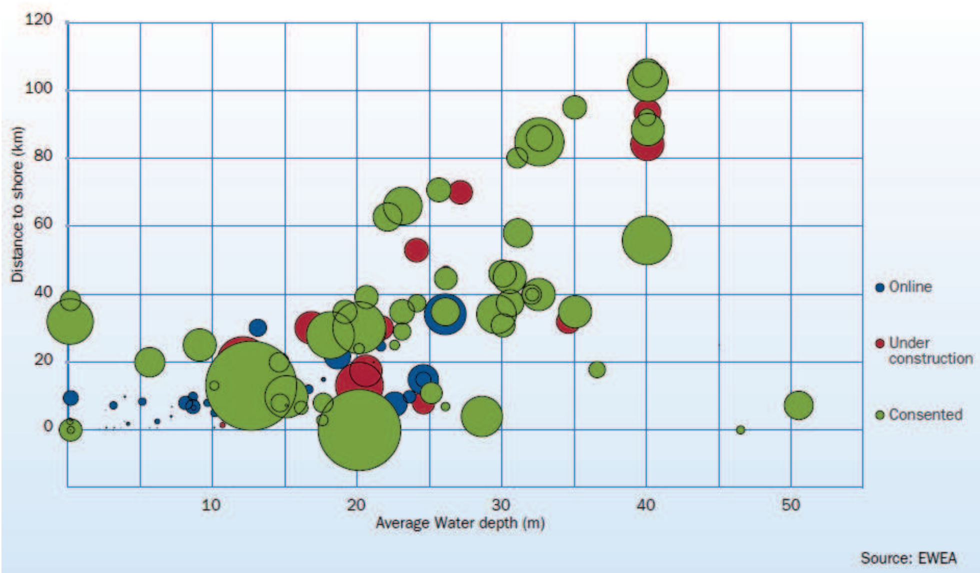


Figure 21: Water depth and distance of offshore projects[21]

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[20] Renewable energy world.com, 5-MW BARD Near-shore Wind Turbine Erected in Germany, http://www.renewableenergyworld.com/rea/images/5-mw-bard-near-shore-wind-turbine-erected-in-germany-54098/48320

We can see in Figure 21 that consented and under construction projects are going further from shore and in deeper waters. In 2012, the average water depth of online offshore farms was 22m and the average distance from shore was 29 km [E.W.E.A., July 2013]. These two values should increase significantly during next years as the current trend suggests it.

Another trend is the increase of the turbine's size. Deep offshore solutions will have to take this trend into account.

These solutions such as floating substructures will allow unlocking the Mediterranean market, the Atlantic market and the deep North Sea market. The most important challenge will take place in the Mediterranean Sea as there is currently no offshore wind farm in this sea due to the high water depth.

Another advantage of floating substructures is that they allow an easy decommissioning. Moreover as they are usually assembled in sheltered waters and then towed out to site, they don't require any expensive vessel.

The steps followed in order to develop full-scale offshore wind farms with floating substructures are the following ones [E.W.E.A., July 2013]:

- research and development with modelling tools;
- demonstration thanks to numerical demonstrations and some experiments;
- pilot which is a down-scaled model;
- prototype which is a full-scaled model;
- pre-production with a small amount of installed floating turbines;
- serial production which is the final stage.

Currently, the most advanced projects of floating substructures are at the prototype stage.

In order to develop floating substructures, the offshore wind sector had to adapt existing technologies from the oil and gas industry. The three main concepts are the followings:

- spar Buoy;
- tension Leg Platform;
- semi-submersible.

Spar Buoy

There are currently no large scale wind farms using the spar buoy technology, but there is already a full scale prototype of wind turbine: the Hywind project developed by Statoil. One "Hywind turbine" is currently tested in Norway. There are also other projects using this technology such as the "Kabashima project" in Japan.

The spar buoy is composed of a cylindrical buoy and ballast. The ballast is used to lower the center of gravity. Indeed the lower parts are heavy and the upper parts are light. This way, the center of buoyancy is higher than the center of gravity and the stability of the turbine is ensured.

[21] E.W.E.A., *Deep water The next step for offshore wind energy,* July 2013

This buoy is linked to the ground thanks to anchoring cables. The anchoring system allows this floating substructure to be used between 120m and 700m [HENRIK STIESDAL, 2009].

The construction steps are not similar to the ones followed by the construction of a wind turbine with a classic substructure. Indeed, the wind turbine and its floating foundation are assembled in sheltered waters and then, they are towed to its final location.

The construction steps followed for the Hywind project were the following ones [STATOIL]:

- Construction of the substructure.
- The substructure is towed horizontally to the assembly site situated in sheltered waters (Figure 22).
- The substructure is straightened up and moored in the assembly site.
- Then, the substructure is ballasted.
- The middle tower is assembled.
- The nacelle and the upper tower are assembled together onshore and then, transported to the harbour to be assembled to the middle tower and the substructure.
- The rotor and the three blades are assembled onshore and then, transported and assembled to the rest.
- The assembled turbine is towed vertically to field.
- Finally, the turbine is installed and moored in the offshore site.

Figure 22: substructure tow[22]

Tension Leg Platform

The tension leg platform (TLP) is a very buoyant structure semi-submerged. The structure is held semi-submerged thanks to mooring lines anchored in the sea bed. Holding the structure semi-submerged increases the buoyancy and the stability. The TLP can be used in water depths bigger than 50m [E.W.E.A., 2013].

The first floating test turbine was composed of a tension leg platform. It was a 75% size pilot wind turbine installed in Italy and called Blue-H [BLUE-H].

[22] BUKSÉR OG BERGING, Recent projects, http://www.bube.no/Who-We-Are/Recent-Projects/, p. 14

The construction steps are similar to the ones presented for the spar buoy. The turbine and its substructure are assembled at yard and then, towed out to the offshore site thanks to a stabilizing floater (Figure 23). The stabilizing floater consists in cylindrical buoys and a steal frame that prevents the structure to pitch [SCLAVOUNOS P.D., LEE S., DIPIETRO J, POTENZA G., CARAMUSCIO P., DE MICHELE G, 2010]. Once on site, the substructure is connected to gravity anchors and then the mooring lines are pretensioned by removing water ballast from the buoy.

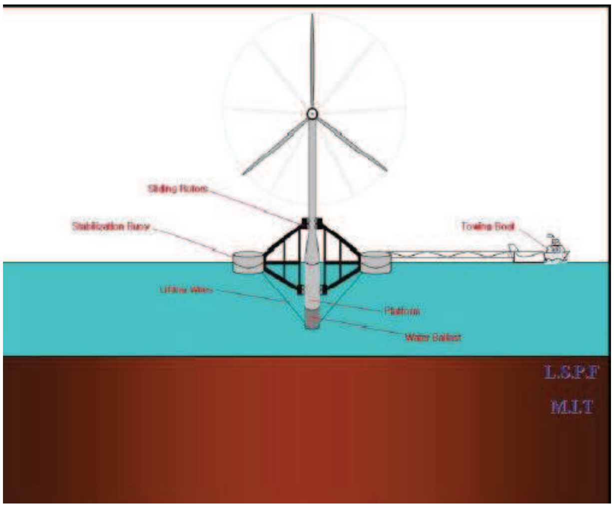

Figure 23: Stabilizing floater[23]

Semi-submersible

The semi-submersible substructure combines the principles of the two first options (spar-buoy and tension leg platform) with the addition of a semi-submersible substructure.

A full-scaled prototype of this type of substructure already exists and was developed by "Principle Power". Its name is WindFloat. The full-scaled prototype was realized in 2011 off the Portugal coast. The semi-submersible substructure is composed of three columns which increase the dynamic stability. This system is combining ballast and anchored mooring lines. The mooring lines of the WindFloat turbines are composed of classical components such as chain and polyester lines. The WindFloat turbine can be used in water depths higher than 40m[Principle Power].

The steps are similar to the ones followed for the two other floating substructures. However, in the case of the WindFloat prototype, the assembly of the substructure and the tower was realized on site in a dry dock. The dock was then flooded. This technology is already used in the ship construction sector.

[23] SCLAVOUNOS P.D., LEE S., DIPIETRO J.(Massachusetts Institute of technology), POTENZA G., CARAMUSCIO P., DE MICHELE G. (ENEL Ingegneria e Innovazione Spa), *Floating offshore wind turbines: tensión leg platform and taught leg buoy concepts supporting 3-5MW wind turbines,* European Wind Energy Conference EWEC 2010, Warsaw, Poland 20-23April 2010, p.2

The steps presented here are the steps followed for the installation of the WindFloat prototype [Principle Power]:

- installation of the columns in a dry dock;
- final assembly of the trust in the dry dock;
- tower, nacelle, hub and blades installation still in the dry dock;
- flooding of the dock;
- loading-out the turbine thanks to tugs;
- towing out of the turbine to the offshore site (Figure 24);
- installation on site and connection of the mooring lines to the preinstalled anchors.

Figure 24: Towing out of WindFloat[24]

2.2 *THE TURBINE'S COMPONENTS*

The main turbine's components are the following ones:

- the blades;
- the hub;
- the nacelle;
- the tower sections.

[24] Principle Power, http://www.principlepowerinc.com/images/PrinciplePowerWindFloatBrochure.pdf, WindFloat Brochure

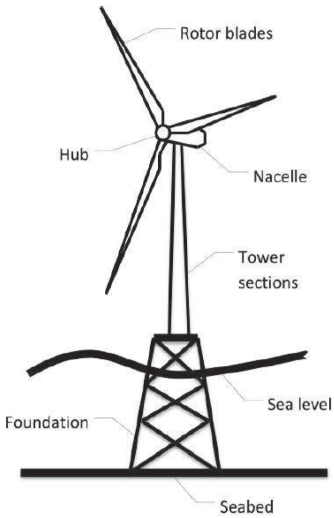

Figure 25: Main turbine's components[25]

2.2.1 The blades

Most offshore turbines' rotors are composed of 3 blades, but researches are currently made by some companies to develop 2 bladed offshore turbines.

The blades are connected to the nacelle via a hub.

Most blades are currently made of composite materials such as fibreglass, epoxy resins, carbon fibres or polyester resins [BVG ASSOCIATES].

The diameter of a 5MW offshore turbine is around 120m and the blade is around 5m wide. The blade of such a turbine has a weight between 15T and 25T [BVG ASSOCIATES].

The blades' shape is a compromise between the best aerodynamic shape (low thickness) and the best structural shape (high thickness). The blades' shape is defined by key parameters: the chord (perimeter of the aerofoil cross-section), the thickness, the twist (angular rotation of aerofoil) and the position of the aerodynamic center. Blades are not only designed to extreme loadings, but also to fatigue as they are submitted to cyclically varying aerodynamic loads and reversing gravity loading.

There are different types of blades. In the first one, two shells are assembled around a central spar. In the second one, structural elements are incorporated between the shells and connected by glass fiber shear webs.

A lightning protection system has to be incorporated to the wind turbine as lightning can cause critical damages.

During last years, the rotor diameter has increased a lot (Figure 26). This is logical as the rotor diameter increases with the rotor swept area which is linked to the rated capacity.

[25] J-D. CAPRACE, C. PETCU, M.VELARDE, P. RIGO, *Toward a risk based simulation for the erection of an offshore windmill park,* 2012, Proceeding of the 11th International Conference on Computer Applications and Information Technology in the Maritime Industries, p.3

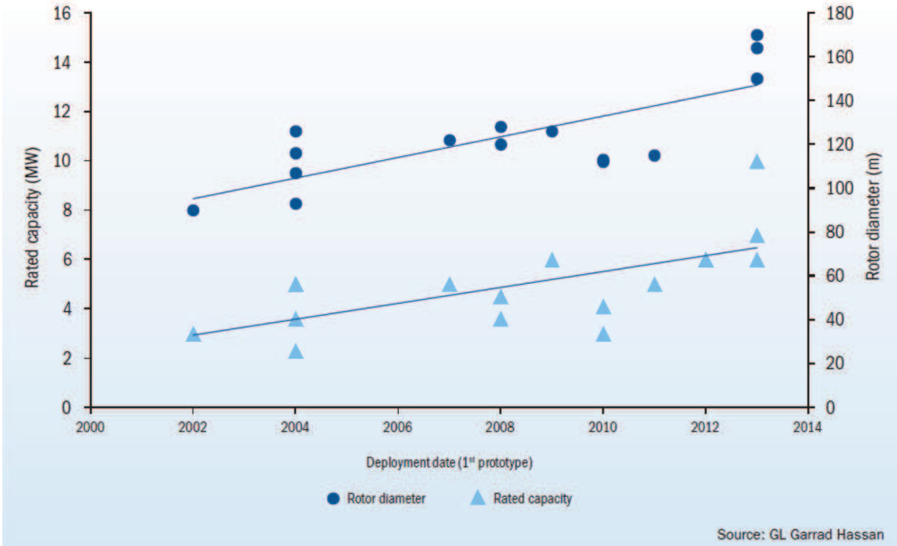

Figure 26: Evolution of the rotor diameter[26]

In twelve years, the rotor diameter has increased from less than 100m until more than 160m. As the rotor diameter increases, transportation can become a problem. New solutions have to be found to adapt to this new situation. It is likely that blades' manufacturer will install their production facilities closer to sea in order to allow an easy transport of these big components.

2.2.2 The hub

The hub is the piece that makes the connection between the blades and the turbine drive train. The hub is made of SG iron (also called ductile iron). Its mass is between 30T and 40T [BVG ASSOCIATES]. The hub also contains the pitch system and the support for the blade bearing. Its shape is nearly spherical.

2.2.3 The nacelle

The nacelle has two main functions:

- Supporting the rotor;
- Converting the rotational energy into 3 phase AC electrical energy.

Here are typical dimensions: 10-15mx4mx4m. Its weight is between 150T and 300T [BVG ASSOCIATES]. The combination of the rotor and the nacelle is very heavy and it can cause problems of stability.

The nacelle contains mechanical and electromechanical elements. The main goal of these elements is to convert mechanical energy into electrical energy. These elements include the gearbox, the generator, the yaw system, and the cooling system.

2.2.4 Tower sections

The tower sections are composed of steel tubular elements. The tower is rigidified by circular and longitudinal stiffeners. Towers are mostly composed of two sections called upper and lower tower. The sea is a hard environment. This is why a protection against corrosion must be provided.

[26] E.W.E.A., *Wind in our sails,* 2011

The objective of the tower is to transfer the top loads to the substructure. The tower also contains some electrical and control equipments. It must also provide an access to the nacelle.

The height of the tower of modern offshore wind turbines is around 80m. Its weight is around 200T-400T. The top diameter (4-5m, for a 5MW wind turbine) is smaller than the base diameter (~6m, for a 5MW wind turbine) [BVG ASSOCIATES].

The tower is dimensioned to resist to fatigue, extreme loads and also to respect natural frequencies requirements.

2.3 *ELECTRICAL INFRASTRUCTURE*

Two main options currently exist for the electrical infrastructure:

- An onshore substation
- An offshore substation

In order to develop this chapter we used a report of 2011 of the European Wind Energy Association[27].

2.3.1 Onshore substation

This option was the one used in early projects and is still the one used in close to shore projects. The connection to shore is realized at medium voltage (MV). The connections between turbines are also realized at medium voltage (~33kV).

In the onshore station, current is transformed into higher voltages (150kV) for the local distribution system.

The turbine generation voltage is of 690V. An incorporated transformer and switchgear allow it to pass to medium voltage (~33kV).

Subsea cable technology at medium voltage already existed before the first offshore wind farms. A subsea cable is composed of 3 phase conductors and an optical fiber communications cable. All these cables are contained in a single external covering.

2.3.2 Offshore substation

In the case of large and far from shore wind farms, an offshore substation can be used to avoid the use of a large number of cables. Indeed a medium voltage cable can export 30-40MW at its maximum. High voltage cables can export more power with a smaller number of cables and smaller electrical losses.

The equipment present in an offshore substation is the same as onshore, but with more environmental protections.

An offshore substation is a major risk for the energy production. It explains why redundancy is used in such stations. In order to provide this redundancy, two transformers and two export cables can be used.

[27] E.W.E.A., *Wind in our sails,* 2011

Offshore substation is beneficiating from the experience from the oil and gas industry. First, the foundation is constructed. Then, the top structure containing all the electrical equipments is built on shore. Finally, this top structure is transported to the site, installed on the foundation and connected to the cables. The installation of the top structure and its foundation requires very expensive and large vessels and cranes which have a low availability.

In this system, the cables in the wind farm, between the turbines, are medium voltage cables. However the export cables are high voltage cables as a transformer is present on the offshore substation.

It can be difficult to find a vessel with all the technology needed for the installation of the HV cable on a long distance at a high depth.

2.3.3 Bottlenecks of the supply chain

We can identify two main bottlenecks: the production of the large transformer(s) present in the substation and the production of the high voltage cables.

For large transformers, there can be until three years delay.

It is expected that during next years, high voltage cables demand will be superior to the production. This is why additional capacity has to be already developed.

2.3.4 Trends

We can identify two main trends:

- Use of High voltage direct current (HVDC) instead of High voltage alternating current (HVAC). Big advances have been made in the HVDC technology and there are still developments. For large and far from shore wind farms, this technology seems to be an advantage for subsea power transmission. There might be a potential for multi-terminal capability.
- Higher voltages for connection between turbines. The array cables seem to evolve from 33kV to 45-60kV. This trend could be explained by the fact that a single 33kV cable can only transmit 30-40MW.

3 Construction of an offshore wind farm

The life of an offshore wind farm can be divided into 4 steps with different ports and vessels needs:

- Development: need of vessels to carry out the surveys.
- Construction: need of vessels to install the components.
- Operation: need of passenger boats to transport technicians and need of vessels to make the repairs (depending on the importance of these repairs).
- Decommissioning: need of vessels close to the ones used during the construction phase.

In this section, we are mainly going to talk about the development and construction phases. Indeed, the developments made in this report concern the construction phase. This is why we are not going to address the operation and maintenance phase and the decommissioning phase.

3.1 *INSTALLATION STRATEGIES*

In the construction phase, two main types of vessels can be used: feeder vessels and installation vessels. The first ones are used between a port and the construction site to transport the different pieces and once on the wind farm, the pieces are transferred from the feeder vessel to an installation vessel. The objective of an installation vessel is to assemble and install different elements of a wind turbine or its foundation. Transferring pieces from a feeder vessel to an installation vessel takes more time than transferring these pieces onshore. However, feeder vessels allow a better degree of utilization of installation vessels as they are only used for the installation of the turbines and its foundations. Feeder vessels can be an advantage if the distance between the port and the offshore site is high.

We can also distinguish two main types of ports: manufacturing or mobilization ports. A mobilization port is used when parts are not directly transported from manufacturing ports to the offshore site.

By combining these two vessels and these ports strategies, we have four main installation strategies resumed in Figure 27.

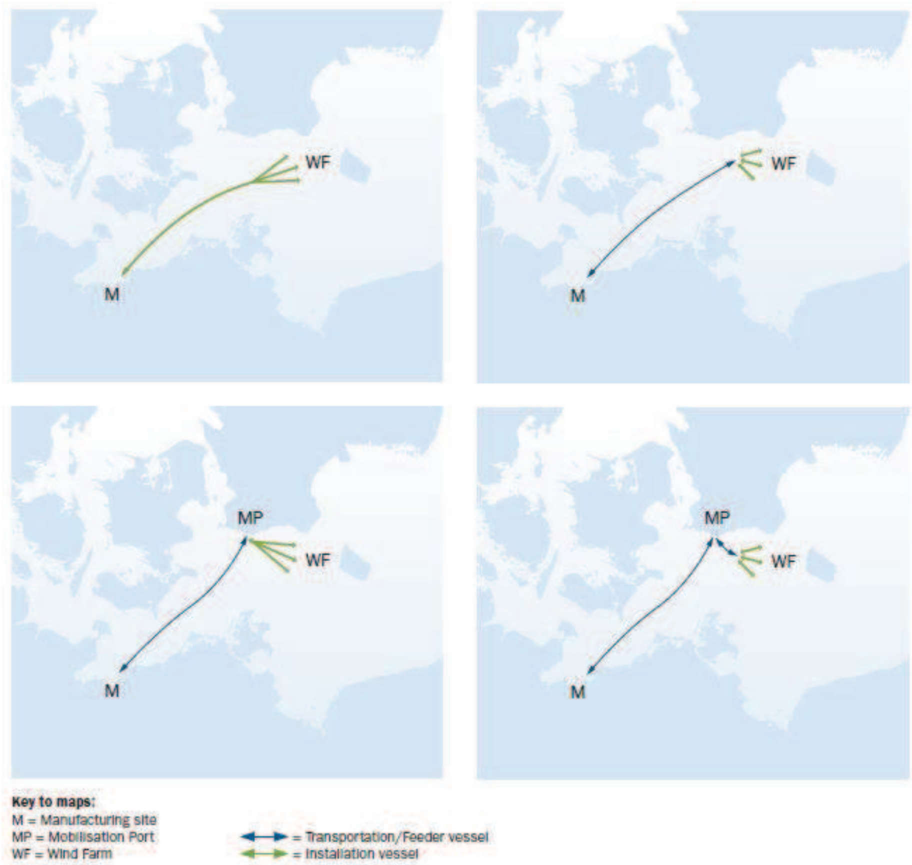

Figure 27: Installation strategies[28]

[28] E.W.E.A., *Wind in our sails,* 2011, p.86

3.2 *VESSELS*

3.2.1 Development phase

During the development, vessels are needed to carry out various surveys: for example, environmental or geotechnical surveys. These geotechnical surveys need a stable platform and a low-specialized jack-up vessel is generally used. The development phase also includes the meteorological mast installation which can also be made with a low-spec jack-up.

3.2.2 Construction phase

This phase requires the highest number of vessels. In this section, we are mainly going to talk about the installation vessels even if low specialized vessels are also used during the construction phase to transport equipment and personnel. There are two main types of installation vessels: the ones that were built exclusively for the offshore wind industry and the ones that come from others sectors such as the oil and gas industry.

In order to select an installation vessel, various characteristics are analyzed: the vessel's performances, its cost, its lift capacity, its precision of lifting, its dimensions, its meteorological limitations (wind speed and wave height) and its availability.

Installation vessels are used to carry out various operations:

- installation of foundations;
- installation of wind turbine's components;
- repairs;
- installation of export cables and inter-array cables;
- installation of substation foundations and topsides.

The graph below presents an analysis of the installation vessels supply and demand for the next decade in the offshore wind sector.

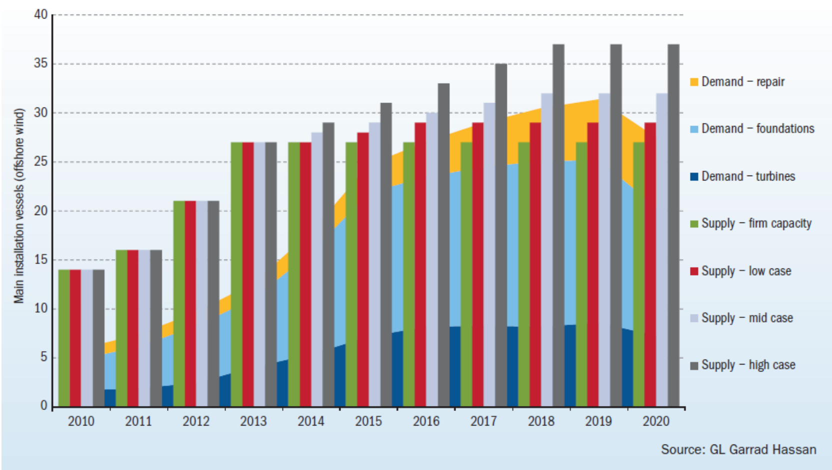

Figure 28: Installation vessels supply and demand for the next decade in the wind energy sector[29]

[29] E.W.E.A., *Wind in our sails,* 2011, p. 77

In Figure 28, four cases are analyzed for the supply:

- Firm capacity: existing vessels dedicated to the offshore wind sector+ under construction vessels+ under contract vessels+ vessels from other industries (example: oil and gas industry).
- Low case: Firm capacity+ 2 new vessels dedicated to the offshore wind sector by 2015.
- Mid case: Firm capacity+ 5 new vessels dedicated to the offshore wind sector by 2020.
- High case: Firm capacity+ 10 new vessels dedicated to the offshore wind sector by 2020.

The mid case is the most likely to happen.

We can see, in Figure 28, that supply is higher than demand until 2015, except for the cables laying vessels (not indicated in the graph). From 2015 to 2020, some shortages appear. The lead time for a new vessel is between 24 and 36 months.

We can distinguish different types of installation vessels (Figure 29):

- **The jack-up vessels and barges**. These vessels can execute the most roles in the wind farm construction. They have a high stability due to the fact that they lift themselves above water level thanks to the lowering of their legs into the sea bed. This high stability is very important for lifting operations. Its high stability is the reason why it still highly dominates the turbines' installation. In small projects, only one jack-up is used for all tasks. The current trend is to have bigger projects. In this type of projects, various installation vessels are used and are more specialized. The difference between vessels and barges is that the first ones are self-propelled and the second ones not.
- **Leg-stabilized crane vessel.** Two boats of this type exist and they are owned by "A2 Sea". This type of boats was mainly used for the installation of wind turbines in early projects, in shallower sites. They were first standard vessels that were then adapted for the installation of offshore wind turbines. Due to the fact that they were first standard vessels, they have a good hydrodynamic hull form which allows them to make rapid and cheap transits. They can be used in water depths up to 24m [E.W.E.A., 2011]. As offshore wind projects are more and more situated in deeper waters, these two boats have a limited future in the offshore wind turbines installation.
- **DP2 heavy lift cargo.** This type of vessel is composed of a cargo vessel with heavy lift cranes. This type of boat is fast, cheap and has a heavy lift capacity. They can be used as feeder vessels as wind farms are going further from shore. Offshore transfers are possible even in rough sea conditions. This type of vessel is not stable enough to install wind turbine's components.
- **Semi-submersible heavy lift vessel.** This type of vessel was first developed by the oil and gas industry. The hull can be flooded in order to increase the deadweight and decrease highly the effect of waves. After ballasting, this type of boat is motionless except for the highest waves. Its main inconvenient is its very expensive cost.
- **Shearleg crane barge.** This type of barge corresponds to a dumb barge with a very heavy-lift configuration. The lifting frame is attached to the deck. This type of barge is mainly used for heavy-lifting in sheltered waters. However, it can also be used in deeper waters, far from shore, but it is very dependent on meteorological conditions.

- **Floating dumb barge with crane.** It is the cheapest boat. As it has a low stability, it can not operate as a main installation vessel. It can play the role of a feeder vessel or a lot of other small roles.
- **Cable laying vessels.** They can lay export cables or array cables. They are equipped with turntables of important size to stock the cables, cable guiding sheaves, equipment for trenching. Most of them are equipped with dynamic positioning systems (DP) to hold their position even in rough conditions.

Figure 29: Vessels types[30]

[30] **Excalibur :** 4C Offshore, http://www.4coffshore.com/windfarms/vessel-excalibur-(formerly-the-wijslift-6,-hubinsel-6)-vid10.html , Excalibur
SeaPower: 4C Offshore, http://www.4coffshore.com/windfarms/vessel-sea-power-vid39.html , SeaPower
Jumbo Javelin: 4C Offshore, http://www.4coffshore.com/windfarms/vessel-jumbo-javelin-vid57.html , Jumbo Javelin
Thialf: 4C Offshore, http://www.4coffshore.com/windfarms/vessel-thialf-vid45.html, Thialf
Rambiz: 4C Offshore, http://www.4coffshore.com/windfarms/vessel-rambiz-vid34.html, Rambiz
Haven Seaforth: 4C Offshore, http://www.4coffshore.com/windfarms/vessel-haven-seaforth-vid616.html, Haven Seaforth
Sea Spider: Schottel, http://www.schottel.de/marine-propulsion/stt-transverse-thruster/references/references-detail/?tx_schottel_pi1%5Bproduct%5D=8&tx_schottel_pi1%5Bpointer%5D=4&tx_schottel_pi1%5Breference%5D=97&cHash=97c146f3d15fc283bade9ab30f67113f, Sea Spider

3.3 PORTS

Ports requirements depend on the role played by the port: manufacturing or mobilization port. The requirements also depend on the vessels dimensions and the dimensions, the weight and the number of wind farm elements. These parameters will also define the port infrastructure needed.

The different port requirements concern [E.W.E.A., 2011]:

- the quay length;
- the weight that the quay can support;
- the possibility to jack up next to the quay side;
- the availability of cranes;
- the roll-on roll-off capability;
- the availability of facilities during the whole construction phase;
- the water depth in the port;
- the possibility to transport the rotor in the waterway depending on the rotor size (150-200m);
- the area of storage;
- the possession of permits for 24/7 labour in the port;
- the availability of information technology, service providers and security services;
- the completion of safety, environmental and health standard rules for the wind industry.

Ports are also used by the offshore wind sector during the operation and maintenance phase, but during this phase, there are less requirements.

In annex-A, we can see a list of ports that were used in the past or that are likely to be used in future for the offshore wind construction.

3.4 LOADING METHODS

We can distinguish six different loading approaches presented in Figure 30.

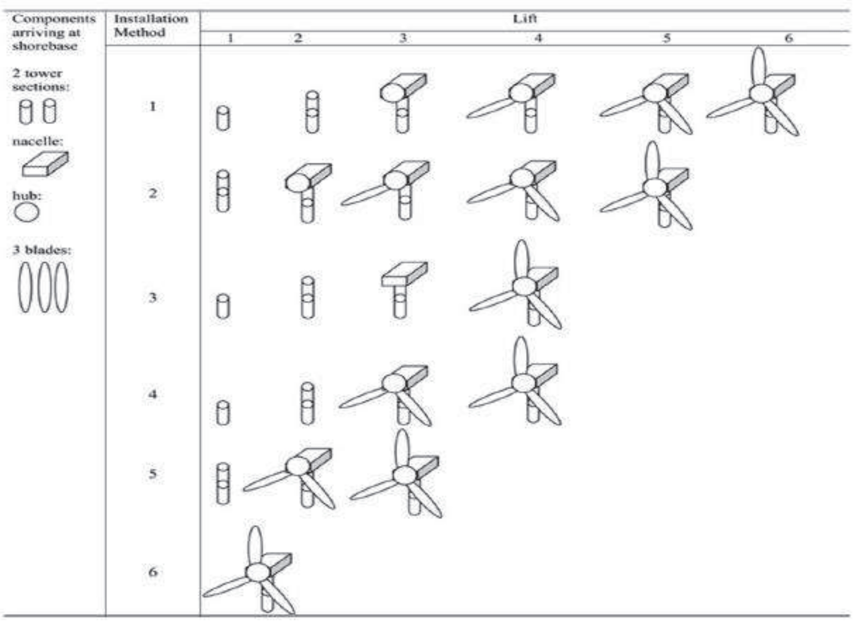

Figure 30: Loading approaches[31]

In the first one, all the elements are loaded separately. In the second one, the only difference is that the tower is preassembled at harbour.

In the third one, the rotor is fully assembled at harbour and the entire rotor is loaded on the ship.

The fourth one is called the “bunny” version. The rotor is pre-assembled with only two pales. The third pale is loaded separately and assembled to the rest of the rotor once on site. The fifth one is the bunny version but the tower is preassembled at harbour.

In the sixth one, a fully assembled wind turbine is loaded and transported. Due to different reasons such as the availability of vessels capable of transporting fully assembled turbines, the sixth method is not yet used at a commercial scale.

- [31] KAISER M. J., SNYDER B.F., *Offshore wind energy cost modeling: installation and decommissioning,* 2012, Springer, p.75

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CHAPTER 3 PRESENTATION OF EOSIM

The program I used to realize my master thesis is called "Eosim". This software is developed at the University of Liège in the ANAST department by C. Petcu and Y. Tekle Muhabie with the supervision of Prof. P. Rigo. The development was made in collaboration with "Tractebel Engineering".

As we already noted in the previous chapter, it is much more difficult to construct an offshore wind farm than an onshore one. Indeed, construction steps are more dependent on weather conditions. The use of a software simulating the installation of an offshore wind farm can help to assess the risk linked to meteorological conditions.

In order to calculate the duration for each construction step and finally the total lead time, the software uses real weather data of various years.

1 INSTALLATION STRATEGY

The installation strategy currently taken into account in the software is the one described in Figure 31.

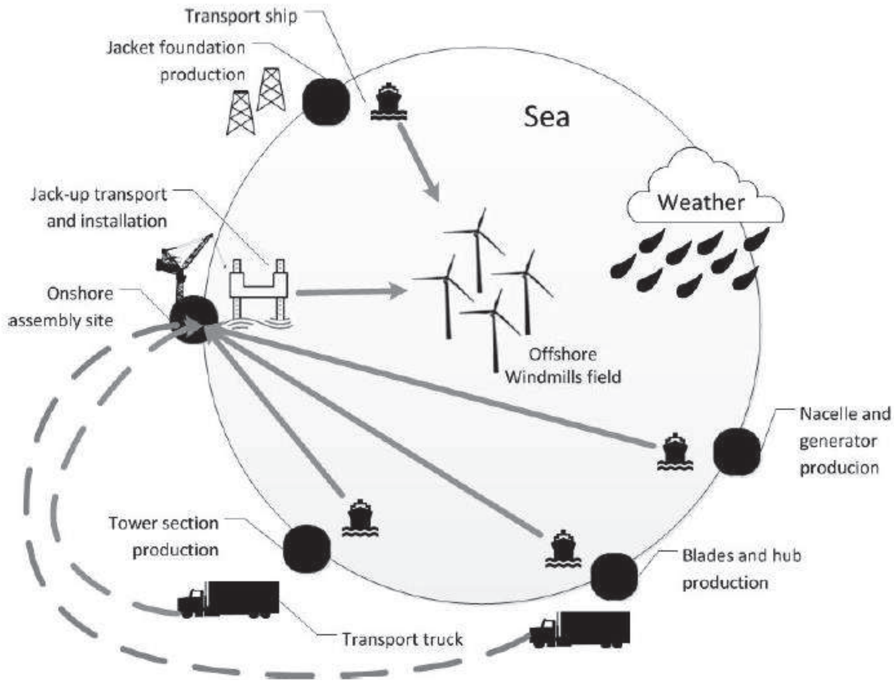

Figure 31: Installation strategy[32]

We can see that there are four main operations: the piling phase, the jacket phase, the transport of the turbines components and the installation of the turbines components.

Piles are transported with a transport ship directly from their manufacturing site until the offshore wind farm. Once on the offshore site, they are transferred from the transport ship to an installation vessel in order to be driven.

Jackets are transported from their manufacturing site directly to the offshore site thanks to the installation vessel. Once on site, they are installed and grouted.

In this strategy, all turbines components are transported to an assembly site thanks to transport ships or trucks. In the model, the logistic steps are simplified. We assume that all turbines components are produced on the same site and carried with a transport ship.

Once on the assembly site, pieces are preassembled and loaded on an installation vessel. The vessel transports the components to the offshore wind farm. First the lower and upper tower sections are installed on top of the already installed jacket foundation. Secondly the nacelle is linked to the tower. Finally, the rotor components (blades) are assembled to the rest of the wind turbine.

[32] J-D. CAPRACE, C. PETCU, M.VELARDE, P. RIGO, *Toward a risk based simulation for the erection of an offshore windmill park,* 2012, Proceeding of the 11th International Conference on Computer Applications and Information Technology in the Maritime Industries., p. 5

Thanks to small modifications of the program it is easy to simulate other installation strategies. However, in this report, we decided to use only this installation strategy as it was the one already implemented.

2 Loading approaches

Two loading approaches are implemented in the software.

In the first loading approach, the installation steps for the turbines components are the following ones:

- preassembly of the rotor with its three blades at the assembly site;
- parts loading;
- waiting for a time window with good weather at port;
- transporting turbine parts;
- waiting for a time window with good weather at the offshore site;
- lower tower section erection;
- waiting for a time window with good weather at the offshore site;
- upper tower and nacelle erection;
- waiting for a time window with good weather at the offshore site;
- rotor installation.

The second loading approach is called the bunny ear method. The installation steps are the following ones:

- preassembly of the rotor with two blades;
- parts loading;
- waiting for a time window with good weather at port;
- transporting turbine parts;
- waiting for a time window with good weather at the offshore site;
- lower tower section erection;
- waiting for a time window with good weather at the offshore site;
- upper tower section and nacelle erection;
- waiting for a time window with good weather at the offshore site;
- installation of the preassembled rotor;
- waiting for a time window with good weather conditions;
- installation of the third blade.

3 Weather data

The program takes into account real weather data. The simulations can then be run for various starting years. The program gives the lead time for each starting year. The results can then be exploited to plan the construction steps of a future project. The only condition in order to obtain these results is to have the real weather data of the previous years at the location of the project.

The weather has an important influence on offshore operations. For each offshore operation there are limits of wind speed or/and wave height. If the wind speed or the wave height is too high, the operation can't be made. The assembly is then delayed due to the weather conditions.

The construction of a wind farm must be a continuous process for as long as possible as the equipment used is very expensive. The discontinuity of the construction is due to the weather conditions.

The program can be used to compare the delays of different scenarios in order to find the most appropriate construction scenario.

In the specific project studied in this report, measurements were available for the last decade with a time step of 10 minutes for the wind speeds and 30 minutes for the wave heights. Three different measurements were available: the average wind speed at a first altitude in m/s, the average wind speed at a second altitude in m/s, the average wave height in m.

4 RISK BASED SIMULATION

The objective of the risk based simulation is to evaluate the risk of the strategic decision linked to the construction of an offshore wind farm before its construction.

4.1 DISCRETE EVENT SIMULATION

Discrete simulation is likely to be more and more used in production planning. The program used here in order to develop the software is “PlantSimulation” developed by “Siemens”.

In a discrete event simulation, only points in time are taken into account. For example, in the simulation of a particular step, we are only interested in the start and finish times. In the program used, there are different material flow objects. Once an element enters such an object, the program calculates the time it takes to exit it. Finally, the program makes a list of the important events (start and finish times of each operation).

The program allows the user to define specific process rules for each object. For example, the loading of the turbines components on the jack-up vessel is represented by a material flow object of type “singleproc”. A “singleproc” object is composed of a single station that processes parts. An element enters the object, is processed and leaves the object. The object contains information about the method used to load the components. Each part (element) also contains information such as its dimensions. The model contains data about the resources.

A simulation can then give a feedback about the interaction between human resources, material resources, transport, and equipment. Simulation results can be used in order to manage the surface, the transport, hazards and to identify bottlenecks. Such an analysis will help to increase the productivity, to identify the source of problems or to choose between different options.

However, discrete event simulation still has some limitations. The procedures realized in reality cannot be defined in detail, as they are very complex. Some assumptions or omissions have to be made.

4.2 *METHODOLOGY*

The workflow of the simulation is represented in Figure 32.

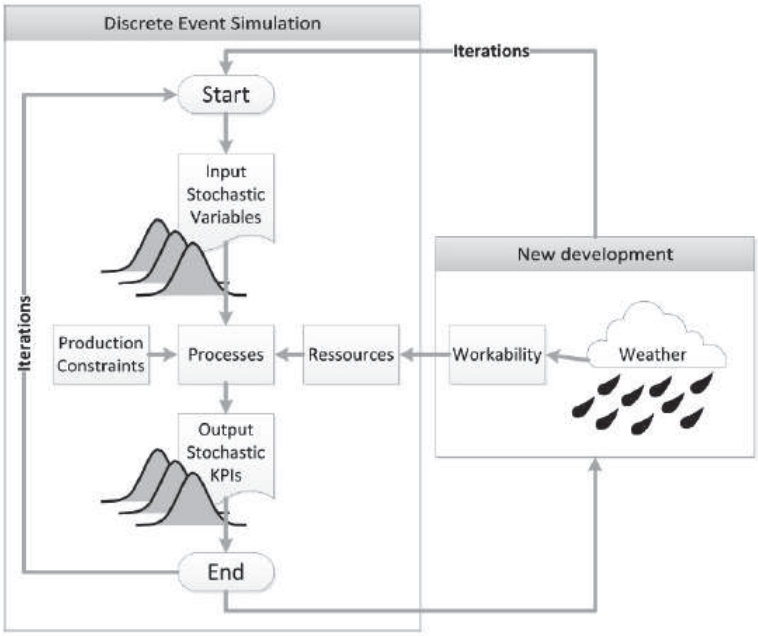

Figure 32: Workflow of the risk based simulation[33]

First, the weather data are collected and completed.

Then, the workability is found. This parameter tells if it is possible to realize an operation. It verifies if the wind speed limits or the wave height limits are not exceeded. Thanks to the "workability", it is possible to find the time window available for the realization of an operation. In other words, the time window is the interval of time during which meteorological data are smaller than the limits (wave heights and wind speeds). An example of the workability calculation is given in Figure 33 for the jackets installation. The wind speed limit for this operation is 12m/s at the two altitudes and the wave height limit is 0.75m. The workability parameter is equal to 0 if the operation can't be realized due to the weather conditions and 1 if it can. We can see that after 4/01/2006 14:30, the operation can't be realized because the wave height is too high.

[33] EOSIM, Methodology, http://www.offshorewindsimulation.org/?q=node/15

Date	Wave height [m]	Wind speed 1 [m/s]	Wind speed 2 [m/s]	Workability
4/01/2006 13:40	0.68	10.17113016	10.18184789	1
4/01/2006 13:50	0.7	10.72845236	10.86778291	1
4/01/2006 14:00	0.71	10.39620259	10.5248154	1
4/01/2006 14:10	0.74	10.55696861	10.68558142	1
4/01/2006 14:20	0.78	10.58912181	11.03926666	0
4/01/2006 14:30	0.81	9.260122716	9.442324205	0
4/01/2006 14:40	0.86	9.59237249	9.624525694	0
4/01/2006 14:50	0.91	9.549501551	9.645961163	0
4/01/2006 15:00	0.96	8.381268477	8.659929577	0
4/01/2006 15:10	0.96	8.777824658	9.260122716	0
4/01/2006 15:20	0.96	8.584905435	8.885002004	0

Figure 33: Workability

Then, we have to impose the stochastic input data. Indeed, it is applied to some processes such as loading times or duration of the rotor assembly. Instead of giving a constant loading time, we give the mean loading time and the standard deviation of a normal distribution. The same is done for the rotor assembly duration.

For example, for the loading time of the jacket foundations, the parameters of the normal distribution are the following ones:

$$\mu = 3600 seconds$$

$$\sigma = 540 seconds$$

Then, by using the next formula[34], we can represent the probability density (Figure 34).

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-\frac{(x-\mu)^2}{2\sigma^2})$$

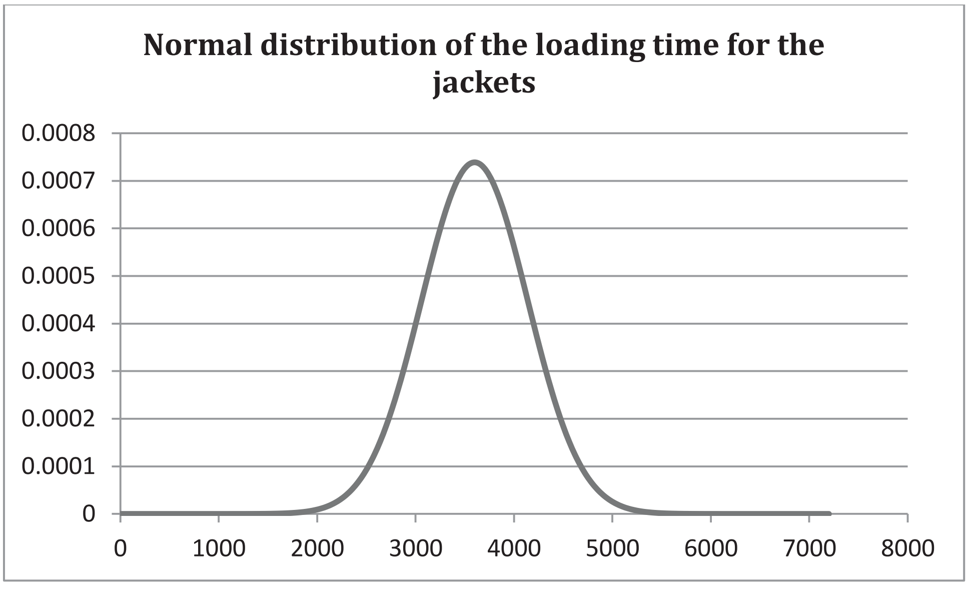

Figure 34: Normal distribution of the loading time for the jackets

[34] Tecnomatix Plant Simulation help

In addition to these stochastic input variables, some parameters have to be defined before the simulation such as the number of piles per jacket, the number of jackets and of turbines components. It is also important to set the characteristics of the vessels used and the various distances of the project.

For each construction step, the production constraints and the necessary resources have to be defined. An example of this is the assembly of the rotor with its three blades. The production constraint is that this step can't begin before the three blades and the hub are available and the necessary resource is a crane with high loading capacity.

Once launched, the model will simulate the logistical chain of the project.

Finally, the simulation will give the user results, such as diagrams showing lead times or, charts showing the distribution of process durations. It is also possible to calculate the percentages of working against waiting.

Thanks to this program, it is also easy to calculate the cost as all the durations of each step are given. However, the program does not currently calculate the cost as they have to be provided by companies and are most of the time confidential.

5 INTERFACE

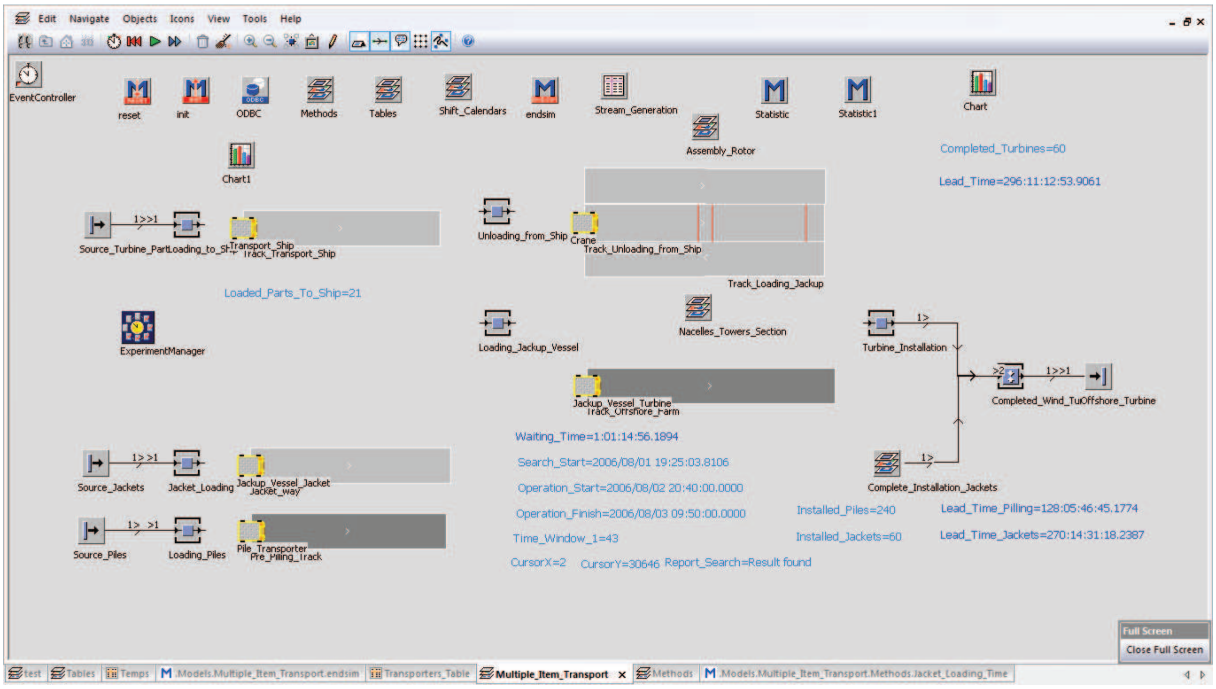

Figure 35: Interface

The interface (Figure 35) allows the user to see the evolution of the construction. The simulation begins at the left of the screen with the sources of turbines components, jackets and piles and it ends at the right of the screen where all the components are assembled.

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6.2 *WEB SITES*

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6.3 *OTHERS*

- Tecnomatix Plant Simulation help

CHAPTER 4 IMPROVEMENTS MADE TO THE SOFTWARE

In order to obtain the results presented further, we first had to modify some methods in the software as the first ones weren't like predicted.

Thanks to the results I first obtained, I could identify some imperfections in the software. Once an imperfection found, we talked about it with the two developers of the software,. C. Petcu and Y. Tekle, in order to find a solution. Then, they implemented the best solution.

In this chapter, I decided to explain two main improvements we made.

The first improvement is in relation to the condition that chooses if it is better to take one or two jackets at a certain moment.

The second one concerns the way of calculating the available time window. First, all the time windows were calculated at the beginning of the simulation. Then, we decided to compute them during the simulation. This takes more time, but the results obtained are closer to reality.

1 DECISION RELATED TO THE JACKETS NUMBER

1.1 BEFORE IMPROVEMENTS

1.1.1 Methodology

In the model used, the jack-up vessel for the jackets installation and transport can carry one or two jackets depending on the weather conditions and the available time window. Indeed, the choice of one or two jackets depends on which is the fastest option. The steps followed in the case of a trip with one or two jackets are described below.

Figure 36: Steps followed for the installation of the jackets

The condition that chose if it was better to take one or two compared the waiting time at the offshore site for the installation of the second jacket to the double amount of the transport time. The transport time is the time needed to go from the harbour to the offshore site or the contrary.

1.1.2 Results

The results we obtained before improvements are showed in Figure 37. The transport time showed in the figure is the time needed to go from the harbour to the offshore site. The reference situation is for 150km which was the distance between the source of the jackets and the offshore site in a specific project.

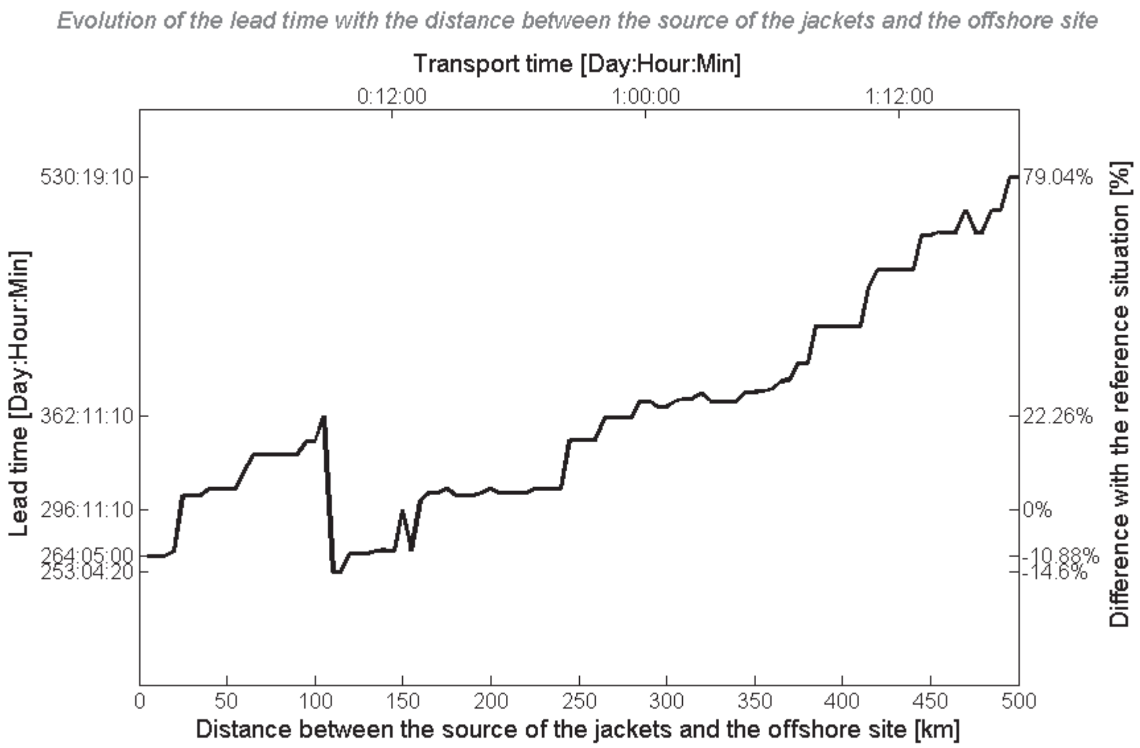


Figure 37: Evolution of the lead time with the distance between the source of the jackets and the offshore site before improvements related to the choice about the number of jackets transported

As we can see in Figure 37, there is an important gap between 110km and 115km with a difference of 109 days in the lead time. Before and after the gap, the evolution is nearly linear.

1.2 IDENTIFICATION OF THE PROBLEM

While trying to find the reason of the two nearly parallel linear evolutions linked by a gap in Figure 37, we realized that before the gap the jackets were mainly transported one by one and after the gap two by two.

The condition first used to choose if we should transport one or two jackets was not optimal at that very moment. Indeed, the objective of this condition was to choose the number of jackets transported that took the less time. We can obviously see that it would have been more interesting to take mostly two jackets at the beginning of the graph in order to minimize the lead time.

The problem was that this condition didn't take into account the waiting time at the harbour before the installation of the second jacket (step 9 in Figure 36 in the case of a transport of one jacket.)

1.3 Improvements

1.3.1 Modifications

The improvement was to use the waiting time at the harbour in the condition. Instead of comparing the waiting time at the offshore site before the installation of the second turbine with the double of the transport time, we compare: the addition of the double of the transport time (steps 7 and 10 in Figure 36 in the case of the transport of one jacket) and the waiting time at the harbour (step 9 in Figure 36 in the case of the transport of one jacket) with the waiting time at the offshore site (step 7 in Figure 36 in the case of the transport of two jackets).

1.3.2 Results

We can see in Figure 39 that after the improvement of the condition, we don't have a gap anymore. This figure is presented in the next section. This section concerns the way of computing the time window as there were still some necessary improvements.

2 Way of computing the time window

2.1 Before improvements

2.1.1 Methodology

All the time windows were computed at the beginning of the simulation. Knowing the workability and the time window needed for an operation, it was then possible to know the time windows at which the operation could be realized.

Figure 38 explains how the time windows for an operation were found assuming that the operation needed a time window of 30 minutes to be realized. The time windows are represented by 1 and when there is no time window, there is a 0.

Date	Workability	Time window	
4/01/2006 13:40	1	1	First available time window
4/01/2006 13:50	1	1	
4/01/2006 14:00	1	1	
4/01/2006 14:10	1	1	Second available time window
4/01/2006 14:20	1	1	
4/01/2006 14:30	1	1	
4/01/2006 14:40	1	0	
4/01/2006 14:50	1	0	
4/01/2006 15:00	0	0	
4/01/2006 15:10	0	0	
4/01/2006 15:20	0	0	

Figure 38: way of computing the time window before improvements

2.1.2 Results

The results we obtained before improvements are showed in Figure 39.

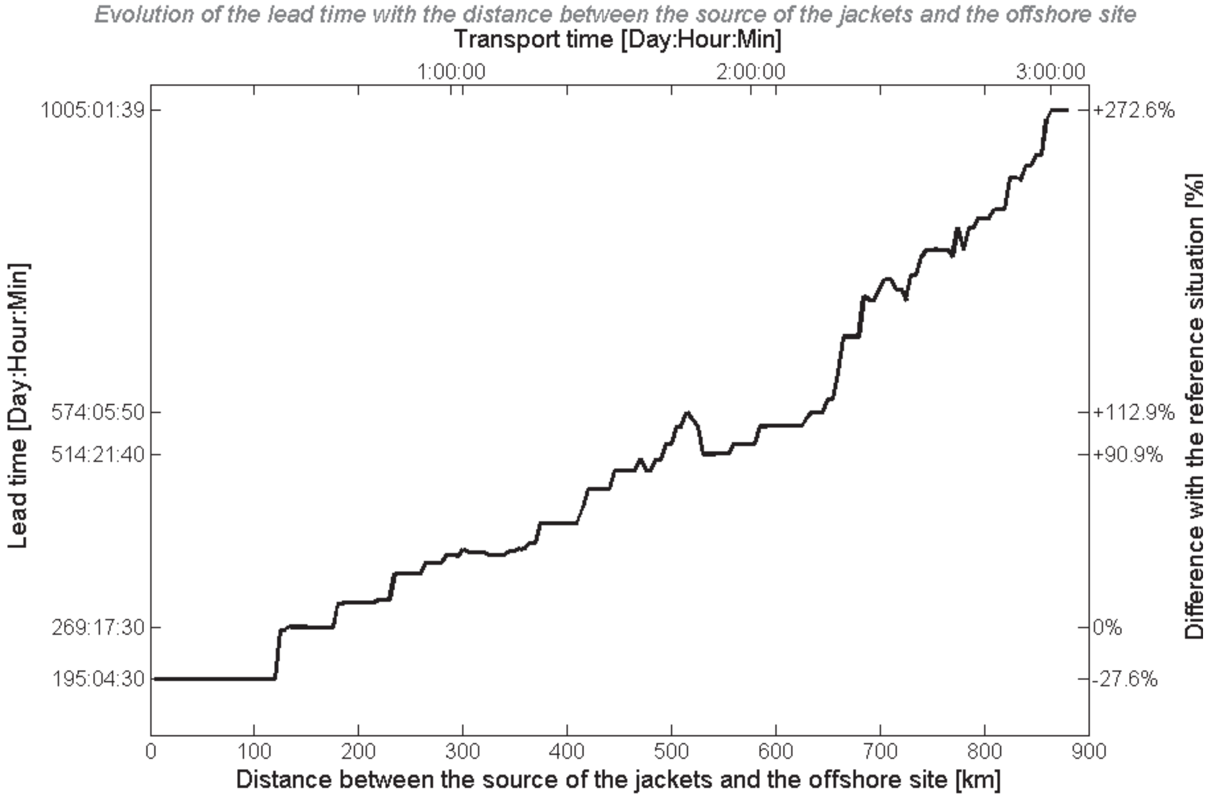


Figure 39: Evolution of the lead time with the distance between the source of the jackets and the offshore site before improvements about the computing of the time window

Once again, we can see ups and downs. The biggest gap is of 60 days between 515km and 530km. This gap is illogical because it means that if the offshore site is 15km closer to the jackets source, the construction will last 60 days more.

2.2 Identification of the problem

The problem was the way of computing the window. We are going to use an example to explain it. If the distance is bigger, the time window needed to transport the jackets is longer. In order to explain the problem, we are going to associate time windows to two distances. The time windows used in the example are not realistic. In reality transport times are longer, but we are going to use small time windows to simplify the problem.

Distances	10km	15km
Time windows needed	50 min	70min

We are going to assume the workability case presented in Figure 40. The workability is the same for both distances, but we can see that the time windows are different.

Date	Workability	Time window distance 20km		Time window distance 30km	
4/01/2006 13:40	1	1	First available time window	1	First available time window
4/01/2006 13:50	1	1		1	
4/01/2006 14:00	1	1		1	
4/01/2006 14:10	1	1		1	
4/01/2006 14:20	1	1		1	
4/01/2006 14:30	1	1	Second available time window	1	
4/01/2006 14:40	1	1		1	
4/01/2006 14:50	1	1		1	Second available time window
4/01/2006 15:00	1	1		1	
4/01/2006 15:10	1	1		1	
4/01/2006 15:20	1	0		1	
4/01/2006 15:30	1	0		1	
4/01/2006 15:40	1	0		1	
4/01/2006 15:50	1	0		1	
4/01/2006 16:00	0	0		0	
4/01/2006 16:10	0	0		0	
4/01/2006 16:15	1	1	Third available time window	0	
4/01/2006 16:30	1	1		0	
4/01/2006 16:40	1	1		0	
4/01/2006 16:50	1	1		0	
4/01/2006 17:00	1	1		0	

Figure 40: Way of computing of the time windows before improvements

We assume that the operation can start at the same moment for the two distances: 4/01/2006 14:40. We can see in Figure 1 that with a distance of 10 km, the next time window available starts on 4/01/2006 16:15. With a distance of 15km, the next time window starts on 4/01/2006 14:50. We can see that with this method the operation will end sooner even if the distance is bigger.

2.3 IMPROVEMENTS

2.3.1 Modifications

Instead of computing the time window in advance (at the beginning of the simulation), we compute it at the moment the operation can start. This operation takes more time than the previous method as the time windows have to be searched not only once but at each starting point of the operation.

2.3.2 Results

After this improvement and other small ones, we reduced significantly the ups and downs. There are still small downs due to an inconvenient of the simulations we already highlighted. Indeed, it is impossible to reproduce exactly the reality as some assumptions have to be made during the realization of the model. The results obtained are presented in the chapter "analysis of parameters".

CHAPTER 5 ANALYSIS OF PARAMETERS

In this chapter, we are going to analyze the influence of various parameters on the lead time (total duration of construction) of a real project composed of 60 turbines.

In order to realize this analysis, we first had to run different simulations. Running one simulation takes around 10 minutes and we need many of those in order to make one graph. After getting the results, we had to post process them. First we transferred the results from excel to matlab. We then had to change the format of the results in a format that matlab can exploit. Finally we could make the graphs.

We chose to exploit the results in Matlab and not in the “experiment manager” tool present in Plant Simulation for various reasons.

Firstly, the experiment manager doesn’t allow us to register all the simulations’ steps corresponding to each value of a parameter in different files. These results are important to understand the graphs and they allow us to realize Gantt charts. Moreover, Matlab has more options to plot the graphs.

All the simulations presented below are realized with the same beginning date: 1rst of April 2006. Moreover, they were all done with the assumption that the jacket installation vessel transports 2 jackets per each trip and that the piles vessel transports 8 piles per trip. We didn’t use the condition presented in the previous chapter that chooses whether or not the jackets vessel should transport 1 or 2 jackets. We will analyze later the influence of this condition.

This chapter only concerns the fully assembled rotor strategy. The analysis of the bunny ear method will be presented in the next chapter.

1 DISTANCES

To analyze the influence of the distance, we decided to vary various distances (Figure 41):

- DISTANCE 1: The distance covered by the transport ship for the transport of the turbines components (tower sections, nacelle, hub, blades) from the source(s) until the onshore assembly site.
- DISTANCE 2: The distance covered by the jack-up vessel for the transport of the jackets.
- DISTANCE 3: The distance covered by the jack-up vessel for the turbines components installation.
- DISTANCE 4: The distance covered by the transport ship for the transport of the piles from their source to the offshore site. Once on the offshore site, the piles are transferred to an installation vessel (jack-up vessel).

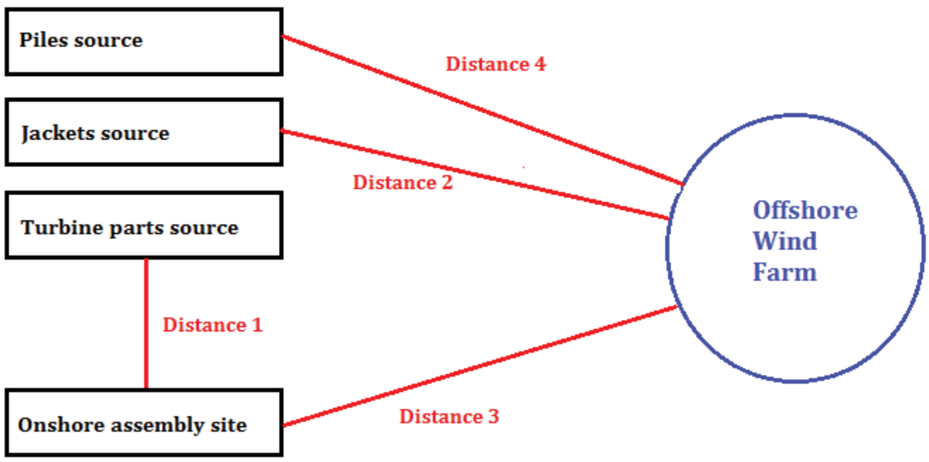


Figure 41: Various distances

The reference situation is the following one:

Distance 1 [km]	Distance 2 [km]	Distance 3 [km]	Distance 4 [km]	Lead time [Day:Hour: Min]
500	150	75	150	**217:06:42**

1.1 DISTANCE 1

Distance 1 is covered directly by a transport ship. The average speed of the transport ship is 12km/h and the transport can be realized if the wind speed is smaller than 17m/s and the wave height is smaller than 2m.

In Figure 42, we can see the evolution of the lead time with distance 1. In order to obtain the graph below, we had to run 100 simulations. Distance 1 varies from 5km until 995km with a step of 10km. On the graph, the transport time is the time required by the ship to cover distance 1.

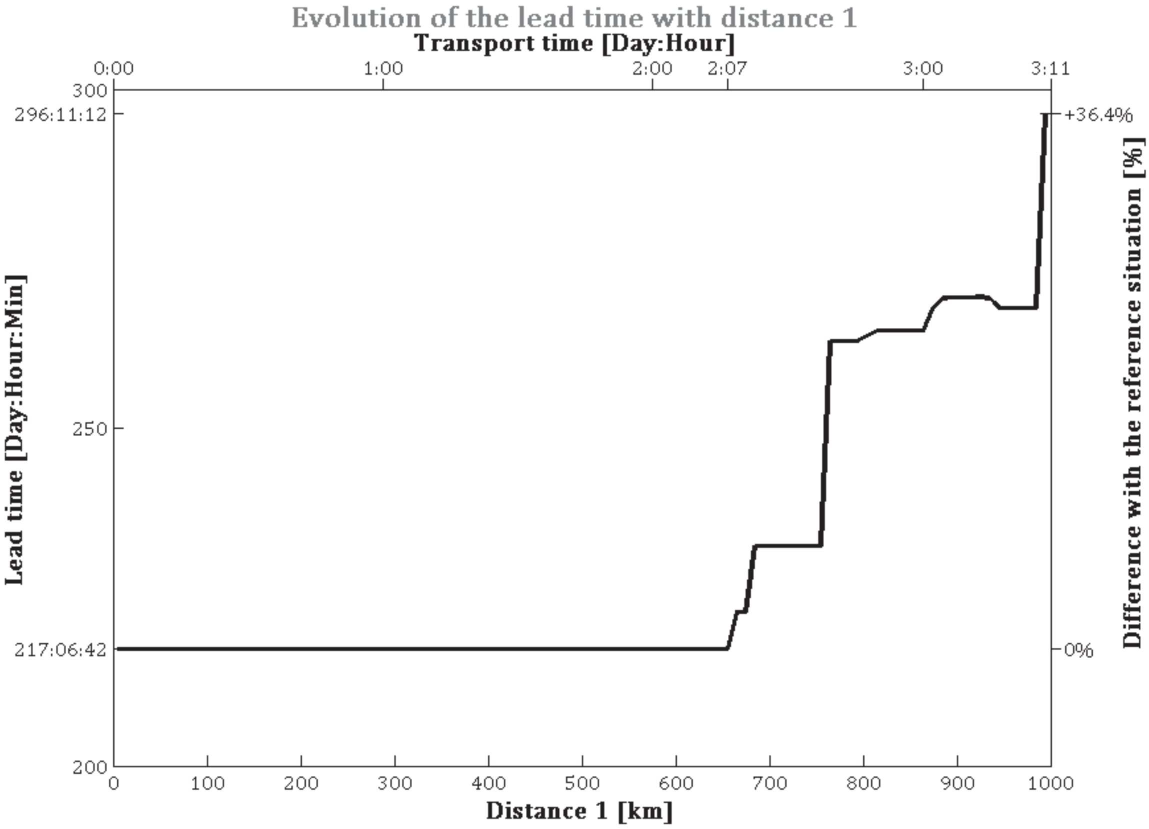


Figure 42: Evolution of the lead time with distance 1

As we can see in the graph above (Figure 42), distance 1 doesn't have any influence until 655km (2 days and 7 hours of transport time). From 655km until 995 km, the lead time is growing with leaps due to the weather conditions and the time window. Indeed, as the distance increases, the transport time increases also. Moreover, the longer the transport time, the longer the necessary time window. It is harder to find a big time window with good weather conditions compared to a small one.

We are now going to analyze the Gantt charts for distance 1 equal to 5 and 655km in order to understand why the lead time is constant between these two distances (Figure 43 and Figure 44). We can see in these two Gantt charts that the total lead time from 5km until 655km is not impacted by the components transport, but by the end of the jacket phase. Indeed, even if the components are on the assembly site. They can't be installed before the corresponding jacket is installed.

Figure 43: Gantt chart for distance 1=5km

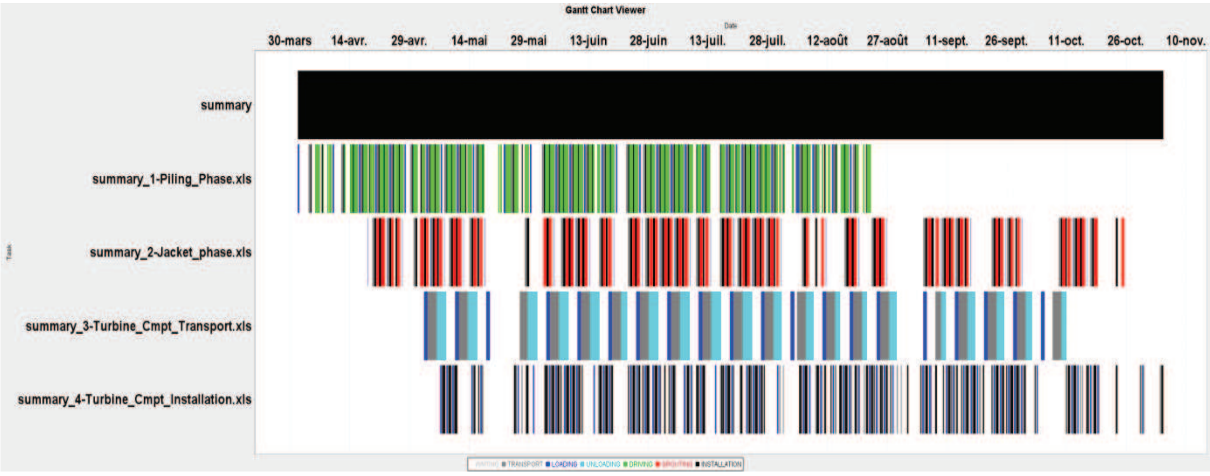


Figure 44: Gantt chart for distance 1=655km

In Figure 45, we can see the Gantt chart for distance 1 equal to 995km. For this case, even if the jackets are installed, the installation of the components can't be realized before the components are transported on the assembly site. As the distance between the source of the components and the harbour is big (995km), their transport delays their installation. The three Gantt charts presented in this section are showed in full size in annex-B.

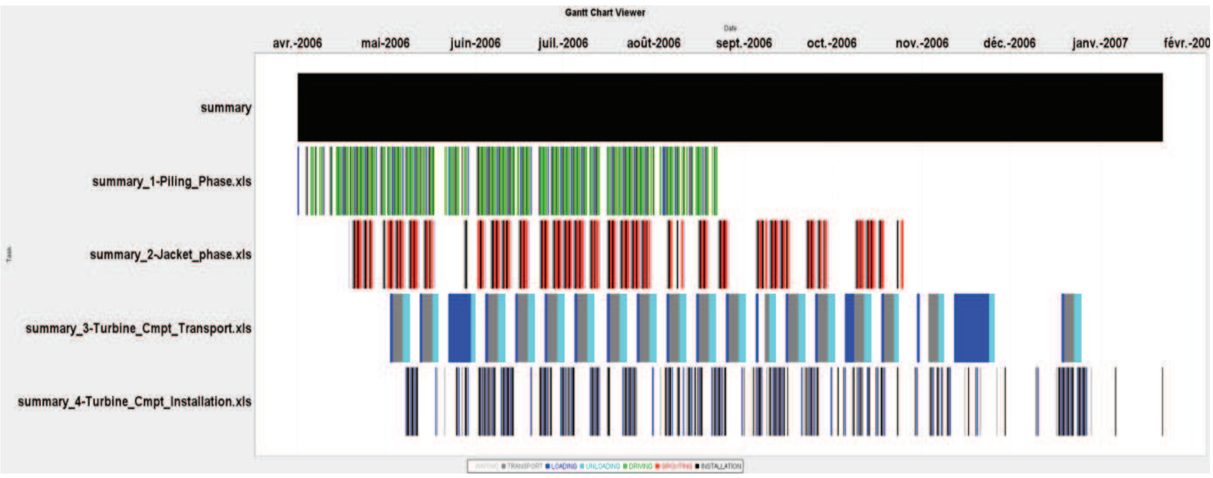


Figure 45: Gantt chart for distance 1=995km

The next step was to analyze the evolution of the waiting percentage during the phase of components installation (Figure 46). The waiting percentage represents the proportion of waiting times over the total duration of the phase. In the graph (Figure 46), it is nearly constant until 655km. It seems logical as until this distance, the lead time of the components installation is not affected by the phase of the components transport. After 655km, it is increasing as it has to wait for the components transport from the components' source until the assembly site. This components' transport is taking more time when the distance is higher. In addition, the delay for the components installation phase is longer when distance 1 is higher.

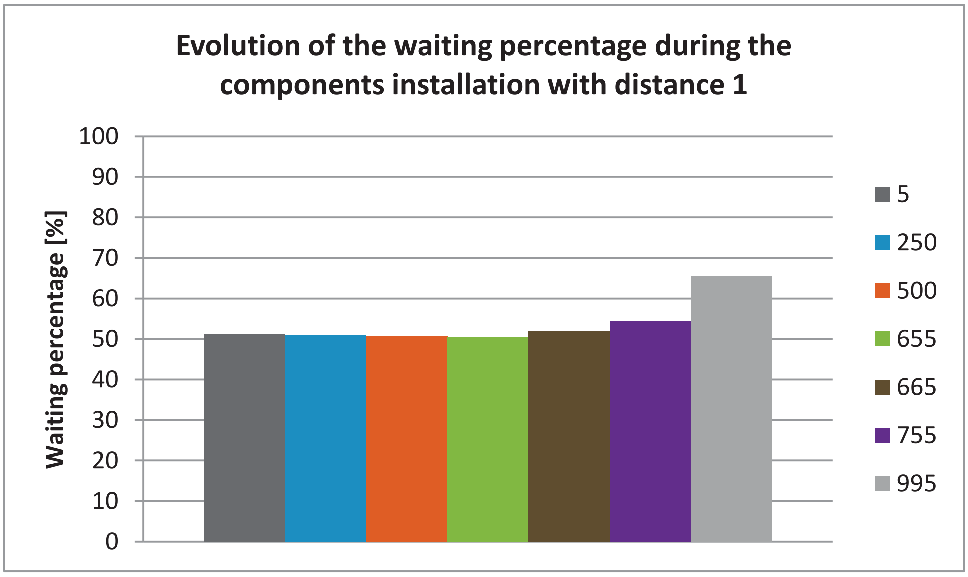


Figure 46: Evolution of the waiting percentage during the components installation with distance 1

In the table below, there are some percentages of difference with the reference situation. These percentages will allow us to know which distance has the most influence on the lead time.

Distance 4 [km]	Percentage of difference between distance 4 and the reference situation (150km) [%]	Lead time [Day:Hour:Min]	Percentage of difference between the lead time of distance 1 and the lead time of the reference situation
250km	-50%	217:06:42	0%
400km	-20%	217:06:42	0%
600km	+20%	217:06:42	0%
750km	+50%	232:11:22	+7%
1000km	+100%	296:11:12	+36.4%

1.2 DISTANCE 2

Distance 2 is covered directly by an installation vessel. No feeder vessel is used. The average speed of the installation vessel is of 12km/h and the transport can be realized if the wind speed is smaller than 10m/s and the wave height is smaller than 1.5m.

In Figure 47, we can see the evolution of the lead time with distance 2. In order to obtain this graph, we had to run 100 simulations. Distance 2 varies from 5km until 500km with a step of 5km.

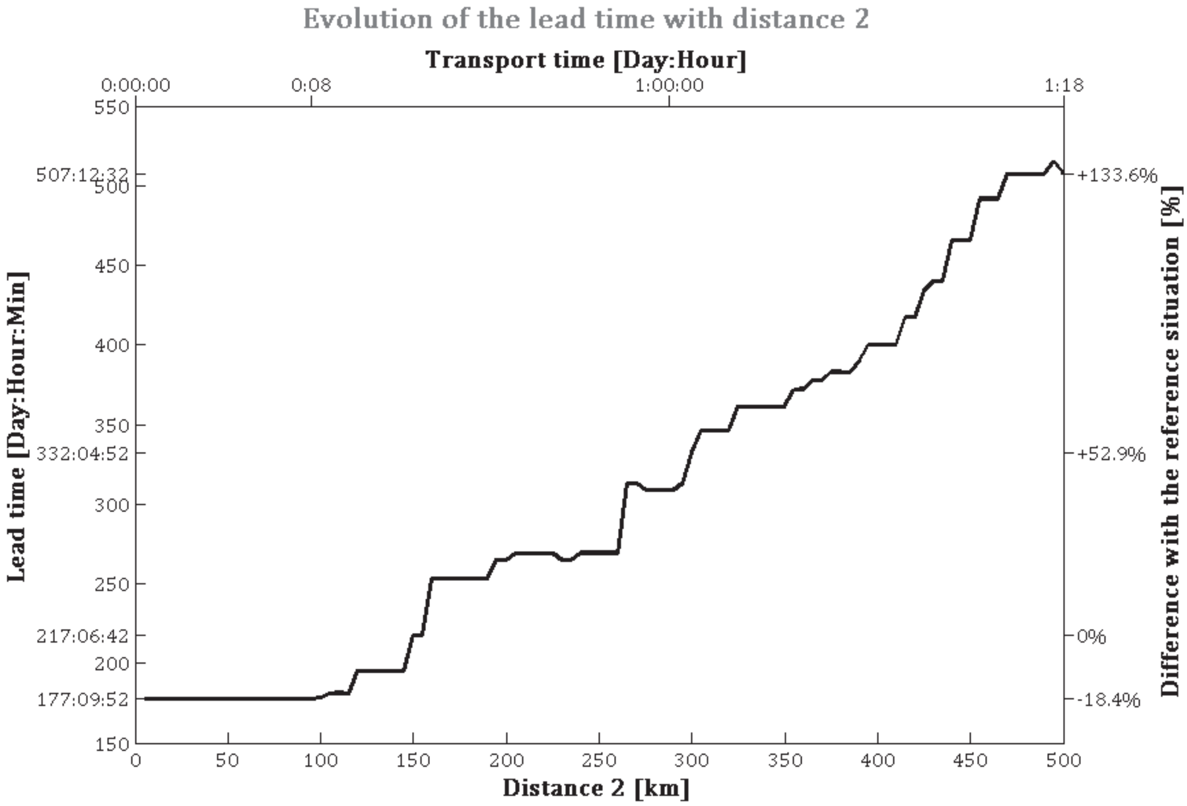


Figure 47: Evolution of the lead time with distance 2

The lead time is constant until 95km (8 hours of transport time) and then it is increasing. Indeed, if the distance increases, the time window needed to transport the jackets also increases, but the weather data are the same for every distance. It is more difficult to find a long available time window than a short one.

In order to understand why the lead time doesn't change between 5km and 95km, the Gantt charts (Figure 48 and Figure 49) can be used. It is obvious that for the two distances the Gantt charts for the piling phase, the turbines components transport and the turbines components installation are similar. However, the jacket phase is different. Indeed, in the case of 5km, the jacket phase ends on the 5th of September 2006, while for 95km, it ends on the 16th of September 2006. However, the installation of the three last turbine can only begin on 19th of September 2006 in the two cases due to the arrival date of the components at the harbour. This is why the end of the jacket phase in the case of 95km doesn't delay the installation of the last turbine.

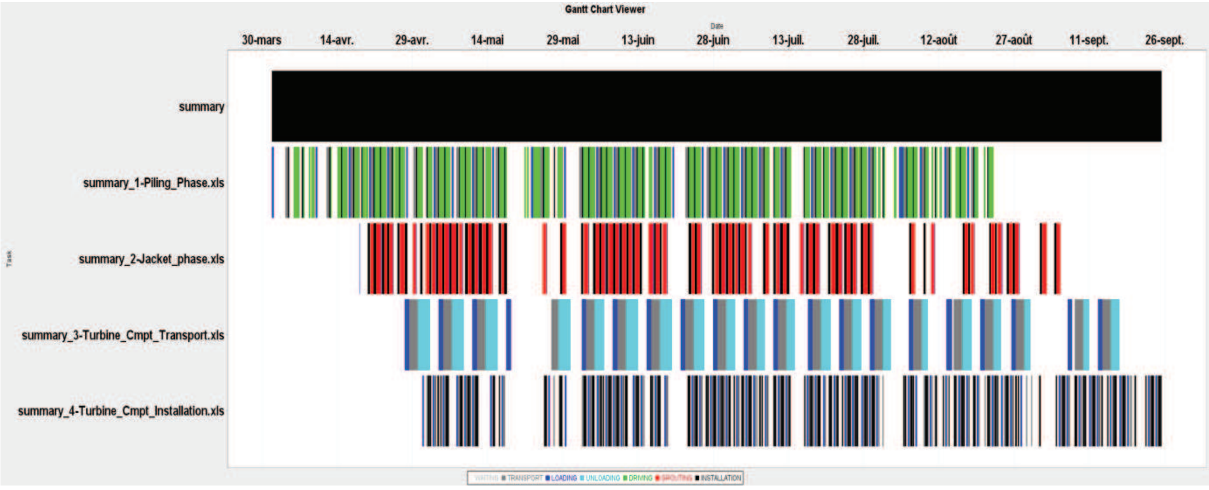


Figure 48: Gantt chart for distance 2=5km

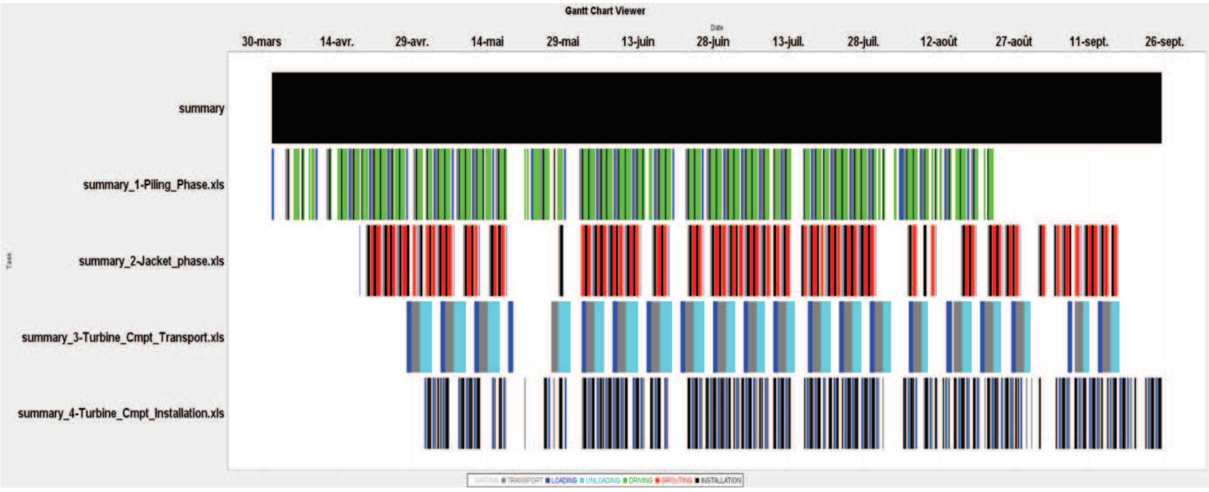


Figure 49: Gantt chart for distance 2=95km

For 100 km, the lead time increases. We can see in Figure 50 that this is due to the fact that after 100km, the jacket phase takes more time than the turbines components transport. Before 100km, the installation of the last turbines begins when the turbines components are on the assembly site and when the time window is available. In the case of 100km, even if the parts are on the assembly site and the time window is available, the installation can't be realized because it has to wait until all jackets are installed before installing the two last turbines. The three Gantt charts presented in this section are described in full size in annex-C

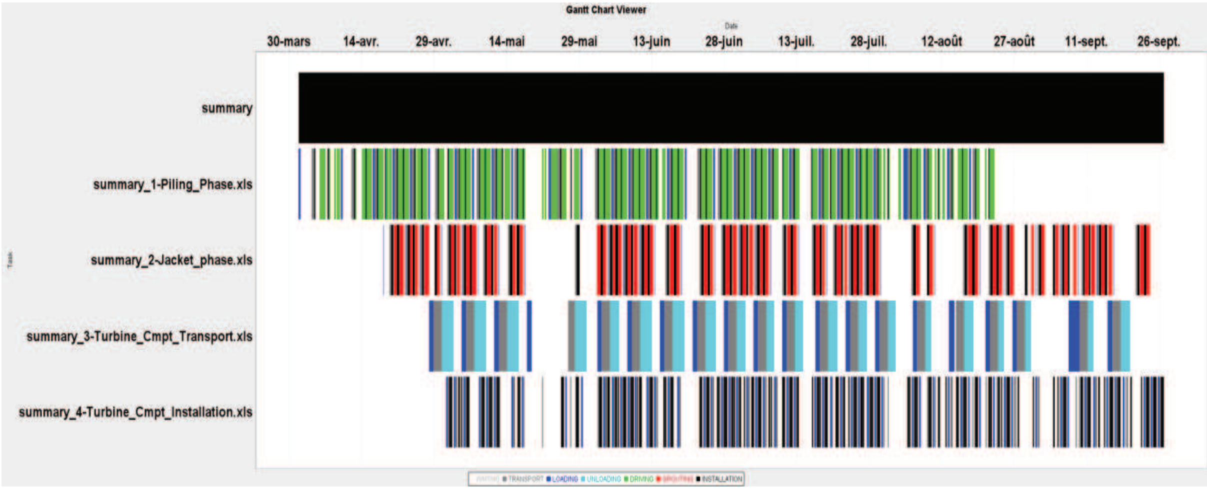


Figure 50: Gantt chart for distance 2=100km

As explained, after 95km, the lead time increases due to the fact that after this distance, we have to wait until all jackets are installed before installing the last turbines. This explanation is confirmed by the graph below (Figure 51). We can see that after 95km the waiting percentage of the phase corresponding to the turbines components installation increases. Indeed, before 95km, it is constant because it is only waiting for the good time window and for the arrival of the components at the assembly site. After 95km, it increases because it has to wait for the end of the jacket installation. Moreover, the bigger the distance between the jackets source and the offshore site, the longer the lead time of the jacket phase.

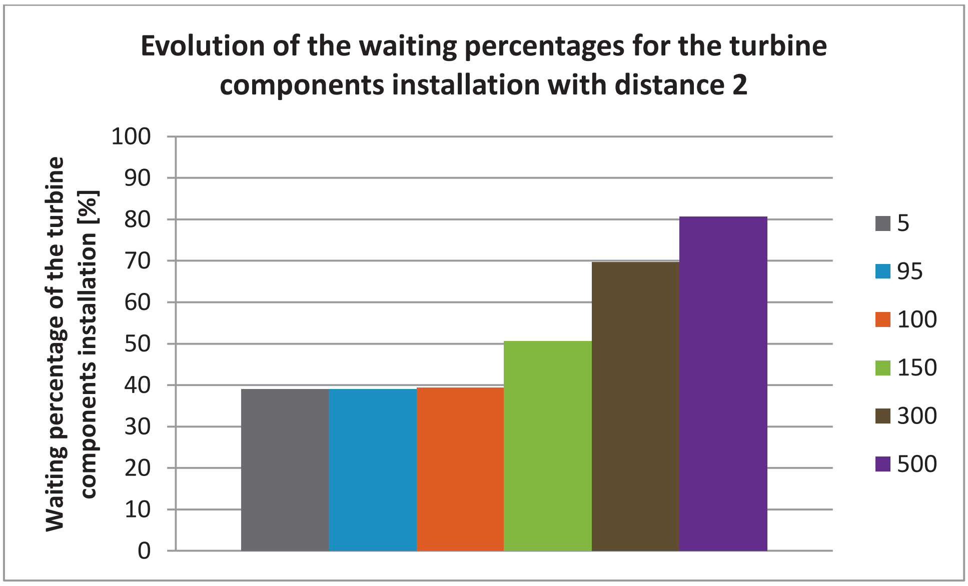


Figure 51: Evolution of the waiting percentage for the components installation with distance 2

In the table below, there are some percentages of difference with the reference situation. These percentages will allow us to know which distance has the most influence on the lead time.

Distance 4 [km]	Percentage of difference between distance 4 and the reference situation (150km) [%]	Lead time [Day:Hour:Min]	Percentage of difference between the lead time of distance 2 and the lead time of the reference situation
75km	-50%	177:09:52	-18.3%
120km	-20%	195:11:52	-10%
180km	+20%	253:04:22	+16.5%
225km	+50%	269:02:22	+23.8%
300km	+100%	332:04:52	+52.9%

1.3 Distance 3

Distance 3 is the last distance covered as it is the distance between the port and the offshore site. This distance is covered by an installation vessel in order to install the turbines components. This vessel has an average speed of 12km/h and its workability limits for the transport are 17m/s for the wind speed and 1.25m for the wave height. We are now going to analyze the influence of distance 3. In order to make this analysis, we decided to vary distance 3 from 5km to 500 km with a step of 5km.

In Figure 52, we can see the evolution of the lead time with distance 3. In order to obtain this graph, we had to run 100 simulations.

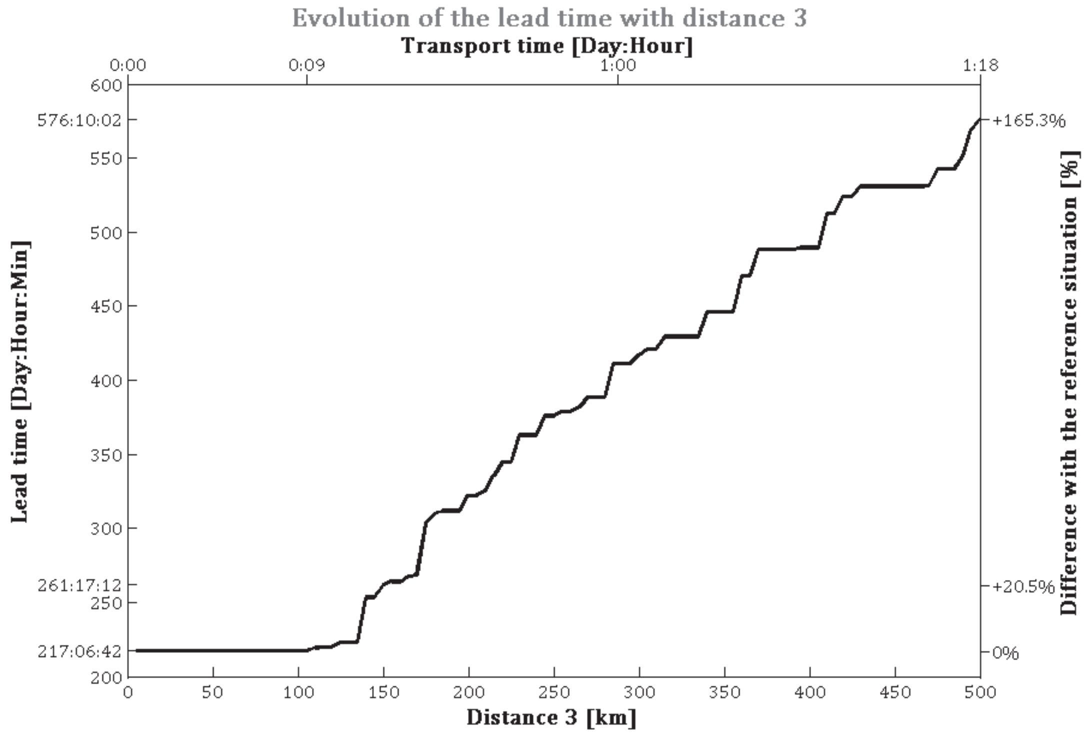


Figure 52: Evolution of the lead time with distance 3

As seen in the above graph (Figure 52), the lead time is constant until 105km. This is due to the meteorological conditions. Even if the distance is lower than 105km, the ships still must wait for the appropriate time window with good weather conditions. We can see it in both Gantt charts below (Figure 53 and Figure 54). Both lead times are the same because in both cases, the installation of the turbines must wait until the corresponding jackets are installed. Between the 26th of august 2006 and the 5th September 2006, there is a gap in the jacket phase due to the weather conditions. For distance 3 equal to 5 km, the installation of the next turbine, the 45th one, must also wait not due to the weather conditions, but due to the fact that the corresponding jacket is not installed. When distance 3 is equal to 105km, there is no gap, but the installation of the 45th turbine still begins at the same time. The two Gantt charts in their full size are present in annex-D.

Figure 53: Gantt chart for distance3=5km

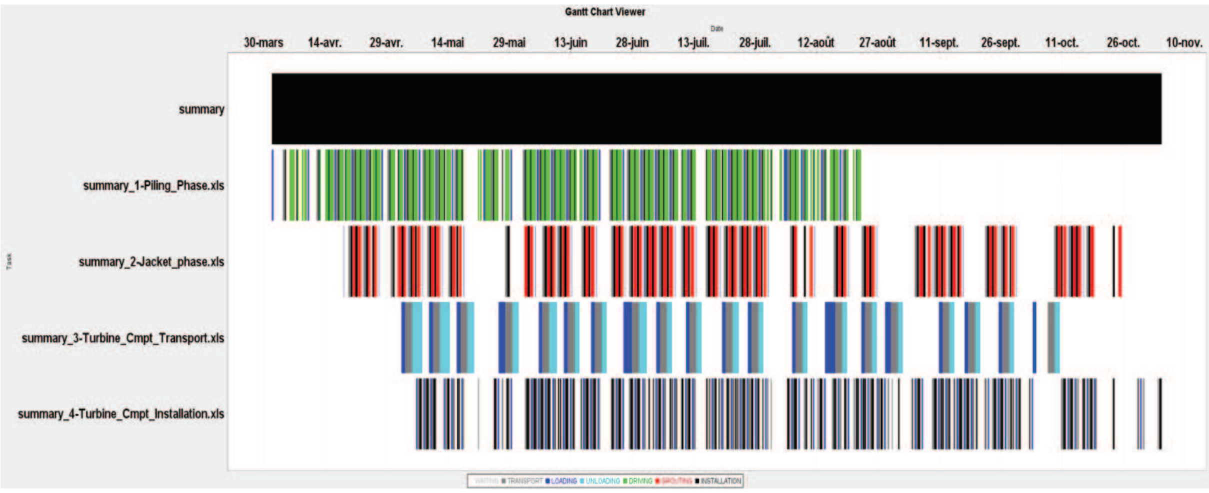


Figure 54: Gantt chart for distance3=105km

In the table below, there are some percentages of difference with the reference situation. These percentages will allow us to know which distance has the most influence on the lead time.

Distance 3 [km]	Percentage of difference between distance 3 and the reference situation (75km) [%]	Lead time [Day:Hour:Min]	Percentage of difference between the lead time of distance 3 and the lead time of the reference situation
60km	-20%	217:06:42	0%
32.5km	-50%	217:06:42	0%
90km	+20%	217:06:42	0%
137.5km	+50%	238:02:47	+9.6%
150km	+100%	261:17:12	+20.5%

Due to the constant line, there is only a significant difference for +50% and +100%.

We are now going to analyze the waiting percentage of the turbines components installation (Figure 55). We can see that this percentage decreases until 105-110km. This is logical because the duration of the turbines components installation is constant between 5 and 105km, but the transport time is longer. After 110km, the waiting percentage increases because it is harder to find an appropriate time window.

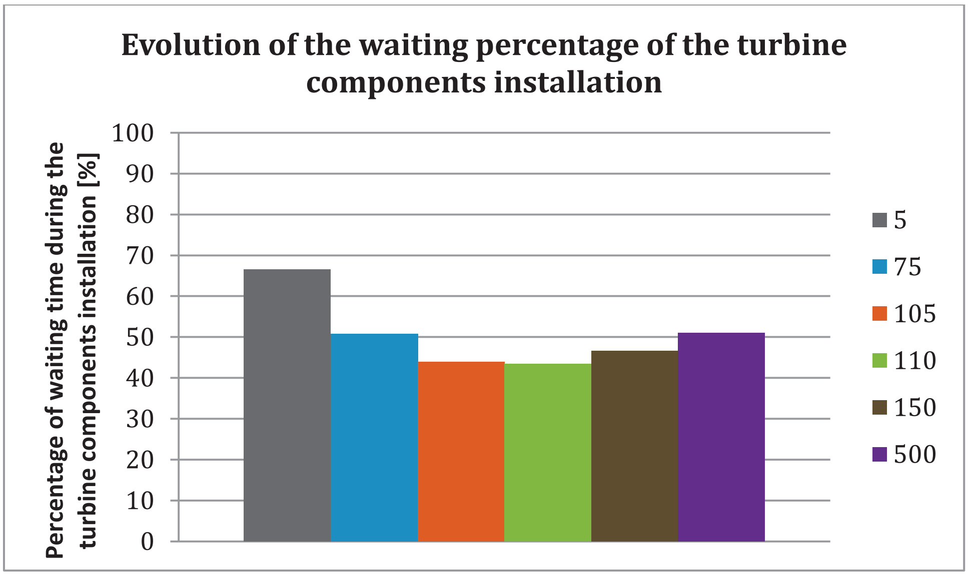


Figure 55: Evolution of the waiting percentage of the turbines components installation

1.4 DISTANCE 4

Distance 4 is the distance between the source of the piles and the offshore site. This distance is not covered by an installation vessel, but by a feeder vessel. The average speed of this feeder vessel is 12 km/h, which is the same speed as the installation vessel for the jackets. However, the workability limits are higher with a feeder vessel. Indeed, we don't have any wind speed limit and the wave height limit is 3m.

In order to analyze the influence of distance 4 on the lead time, we decided to simulate the construction of the 60 turbines with distance 4 varying from 5km to 500 km with a step of 5km. The graph showed in Figure 56 could be realized running 100 simulations.

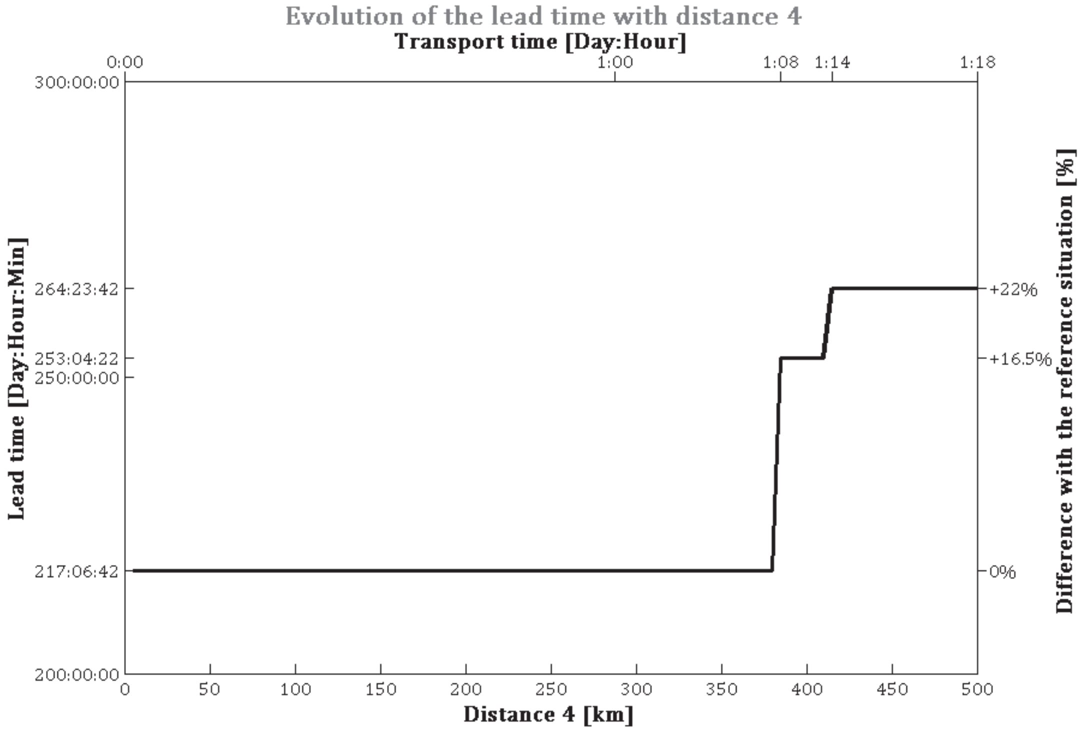


Figure 56: Evolution of the lead time with distance 4

Until 380 km (1 day and 8 hours of transport time), the distance between the source of piles and the offshore site doesn't have any influence. From 380km until 500 km, the lead time increases with two steps (one of 33 days and one of 14 days).

These steps are due to the fact that after 380km, the vessel that installs the jacket has to wait until the four piles of the next jacket are installed. This doesn't occur before 385 km. Indeed, in all cases, the installation of the jackets only begins after the installation of 20 piles. When distance 4 is lower than 380km, the installation of the piles is fast enough and the installation of the jackets is never delayed by their installation. However, if distance 4 is higher than 380km, at a certain moment, the installation of piles is too slow and delays the installation of the jackets, as a jacket can only be installed if its four piles are installed.

Due to this fact, for the installation of the 37th turbine, the vessel waits for 1 day 1 hour and 26 minutes at the harbour if distance 4 is equal to 385km. While it only waits 8 minutes in the case of 380km. A small lag like this can then be amplified by the fact that the installation vessel of the jackets misses a time window and has to wait for the next one.

In the table below, there are some percentages of difference with the reference situation. These percentages will allow us to know which distance has the most influence on the lead time.

Distance 4 [km]	Percentage of difference between distance 4 and the reference situation (150km) [%]	Lead time [Day:Hour:Min]	Percentage of difference between the lead time of distance 4 and the lead time of the reference situation
120km	-20%	217:06:42	0%
75km	-50%	217:06:42	0%
180km	+20%	217:06:42	0%
225km	+50%	217:06:42	0%
300km	+100%	217:06:42	0%

We can easily see that distance 4 doesn't have a lot of influence as it is constant until 385km.

The waiting percentages of the jacket phase for some key values are presented in Figure 57.

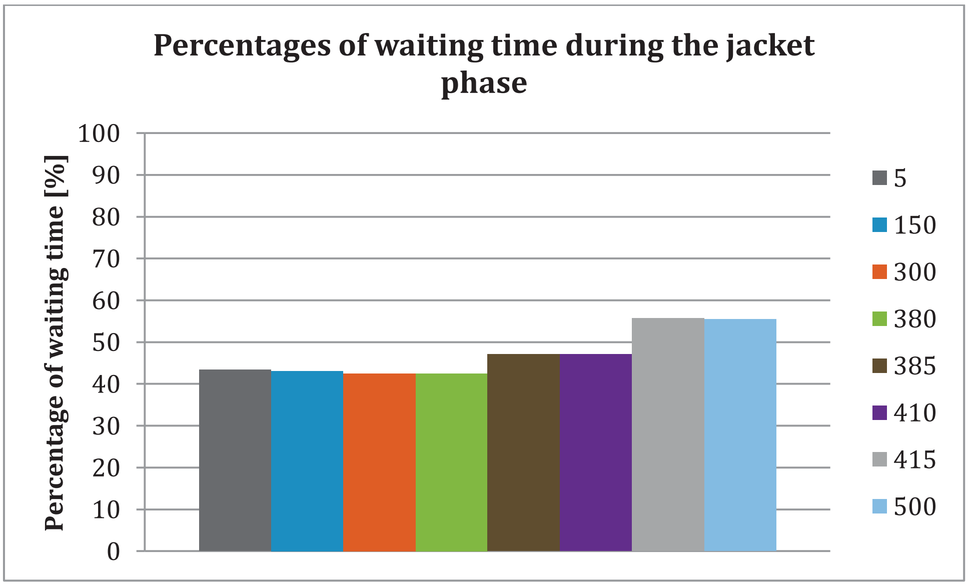


Figure 57: Percentages of waiting time during the jacket phase

As expected, the waiting percentage during the jacket phase increases with two steps. These two steps are due to the fact that the waiting times after 385km are not only composed by waiting times for the good time window, but also by waiting times for the installation of the piles.

1.5 Conclusions about the distances

In Figure 58, we compare the graphs of the various distances. Distance 3 is the one that affects the most the lead time. However, distance2 is the only one that allows a reduction of the lead time lower than the reference situation.

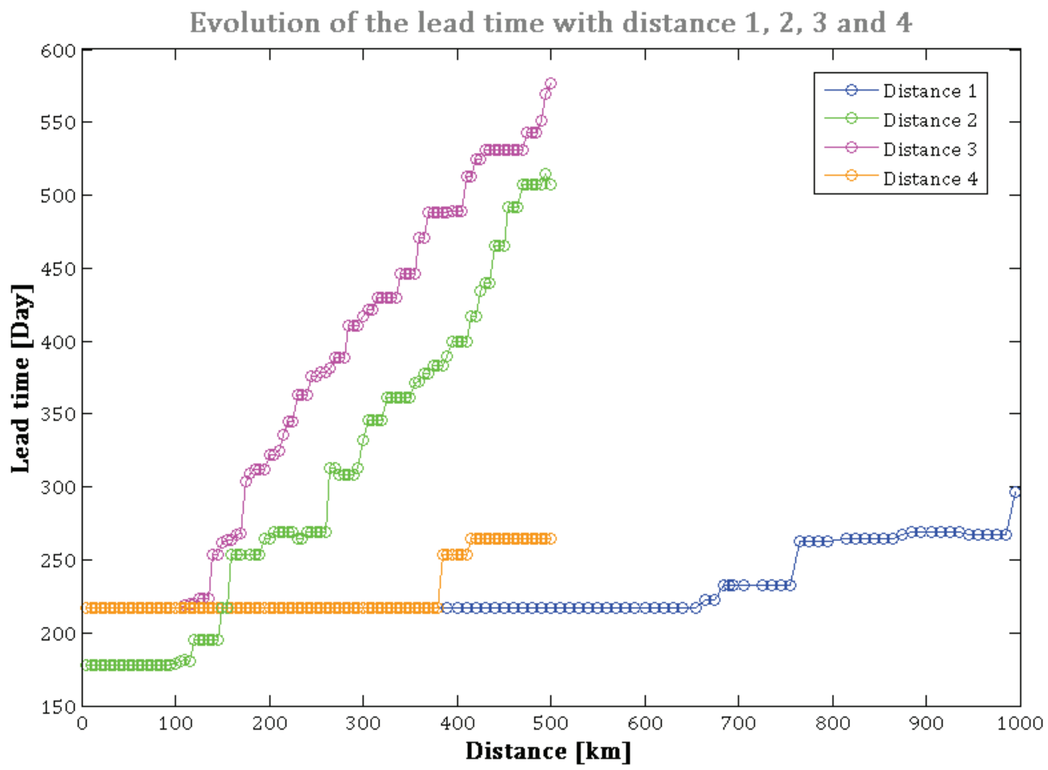


Figure 58: Evolution of the lead time with distance 1, 2, 3 and 4

Now, we are going to compare the percentages of difference with the reference situation we calculated for distance 1, 2, 3 and 4 in the previous sections.

Percentage of difference between distance 1, 2, 3 or 4 and the reference situation [%]	Percentage of difference between the lead time of distance 1 and the lead time of the reference situation	Percentage of difference between the lead time of distance 2 and the lead time of the reference situation	Percentage of difference between the lead time of distance 3 and the lead time of the reference situation	Percentage of difference between the lead time of distance 4 and the lead time of the reference situation
-20%	0%	-18.3%	0%	0%
-50%	0%	-10%	0%	0%
+20%	0%	+16.5%	0%	0%
+50%	+7%	+23.8%	+9.6%	0%
+100%	+36.4%	+52.9%	+20.5%	0%

In the table above, we compare the percentage of difference with the reference situation of the different distances. Distance 2 is the distance that affects the mostly this percentage of difference. While, with distance 4, there is no difference with the reference situation.

2 SPEEDS

To analyze the influence of the speed, we decided to vary various speeds (Figure 59):

- SPEED 1: Speed of the transport ship between the source(s) of the turbines components and the onshore assembly site.
- SPEED 2: Speed of the jack-up vessel between the source of the jackets and the wind farm site.
- SPEED 3: Speed of the jack-up vessel between the onshore assembly site and the wind farm site.
- SPEED 4: Speed of the piles transporter between the piles source and the wind farm site.

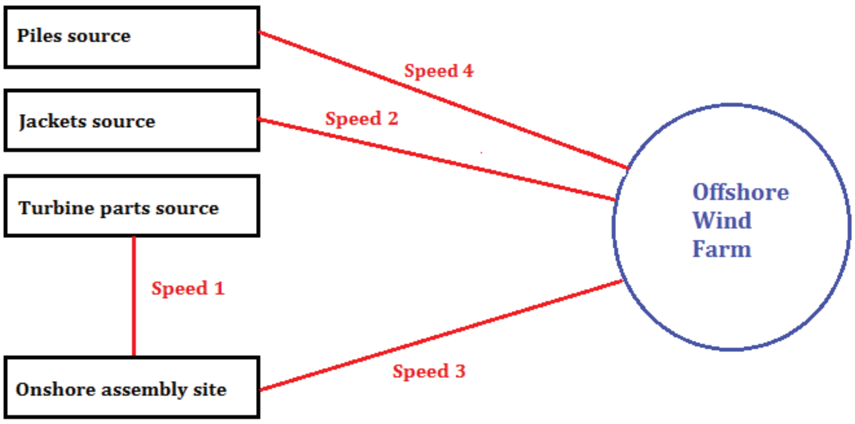


Figure 59: Various speeds

The reference situation is the following one:

Speed 1 [km/h]	Speed 2 [km/h]	Speed 3 [km/h]	Speed 4 [km/h]	Lead time [Day:Hour: Min]
12	12	12	12	**217:06:42**

2.1 *SPEED 1*

Speed 1 is the speed of the transport vessel that covers the distance between the source of the turbines components and the assembly site. In Figure 60, we can see the influence of speed 1 on the lead time. In order to obtain this graph, we had to run 57 simulations by varying speed 1 from 2km/h until 30km/h with a step of 0.5km/h. We couldn't run the simulation for a speed lower than 2km/h because below this speed the lead time was too high. Indeed, below this speed, it is very difficult to find a time window big enough (20 days and 20 hours of transport time for speed 2=1km/h) to transport the components.

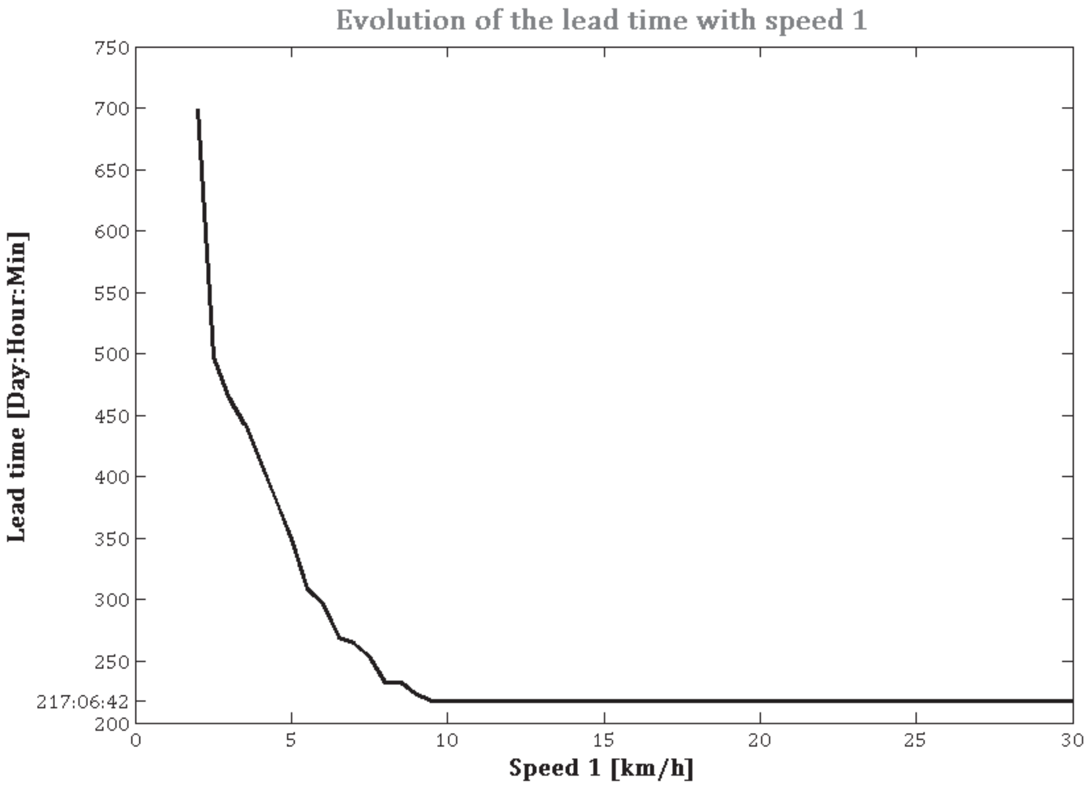


Figure 60: Evolution of the lead time with speed 1

In the graph (Figure 60), we can see two asymptotes: one vertical and the other horizontal. The horizontal asymptote is due to the fact that after 9.5km/h (2 days and 5 hours of transport time), an increase in the transport ship's speed doesn't have any influence on the lead time. The vertical asymptote is due to the fact that when the speed is too low, it is impossible to find a time window large enough with good weather conditions.

As we can see, in this particular project, a faster transport ship for the turbines components transport doesn't change the lead time.

2.2 Speed 2

Speed 2 is the average speed of the installation vessel (jack-up type) that covers the distance between the source of the jackets and the offshore site. Figure 61 shows the influence of speed 2 on the lead time. This graph was realized thanks to 55 simulations by varying speed 2 from 3km/h until 30km/h with a step of 0.5km/h. It was not possible to run the simulation for a speed lower than 3 km/h because the lead time was too long. Indeed, for a speed equal to 2km/h, we have 3 days and 3 hours of average transport time. In the case of an installation vessel, the workability limits are more restrictive than for a transport vessel and it is hard to find an available time window of 3 days and 3 hours to transport the jackets.

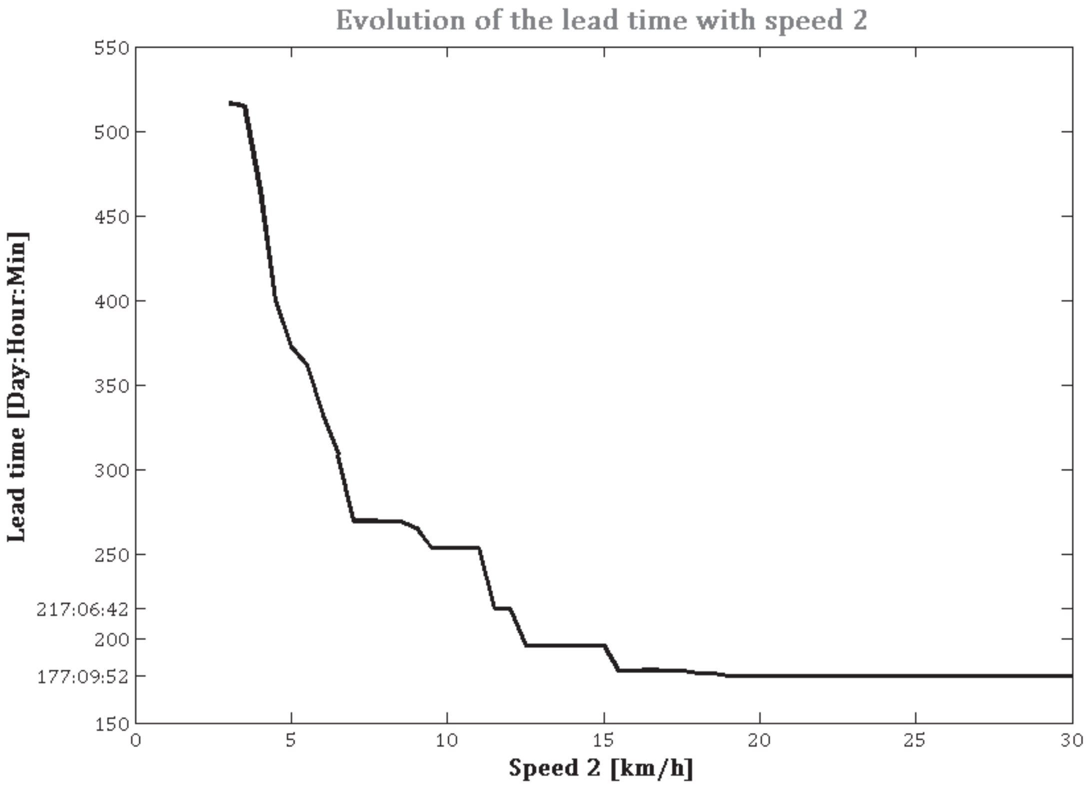


Figure 61: Evolution of the lead time with speed 2

Once again, we have a horizontal asymptote and a vertical one. The lead time is constant after 19km/h (8 hours of transport time). In this case, an installation vessel only half a kilometer per hour more rapid (12.5km/h) allows a saving of 21 days and 19 hours.

2.3 SPEED 3

Speed 3 is the average speed of the installation vessel (jack-up) that installs the turbines components. Figure 62 shows the evolution of the lead time with speed 3. In order to realize this graph, we had to run 57 simulations varying speed 3 from 2km/h until 30km/h with a step of 0.5km/h.

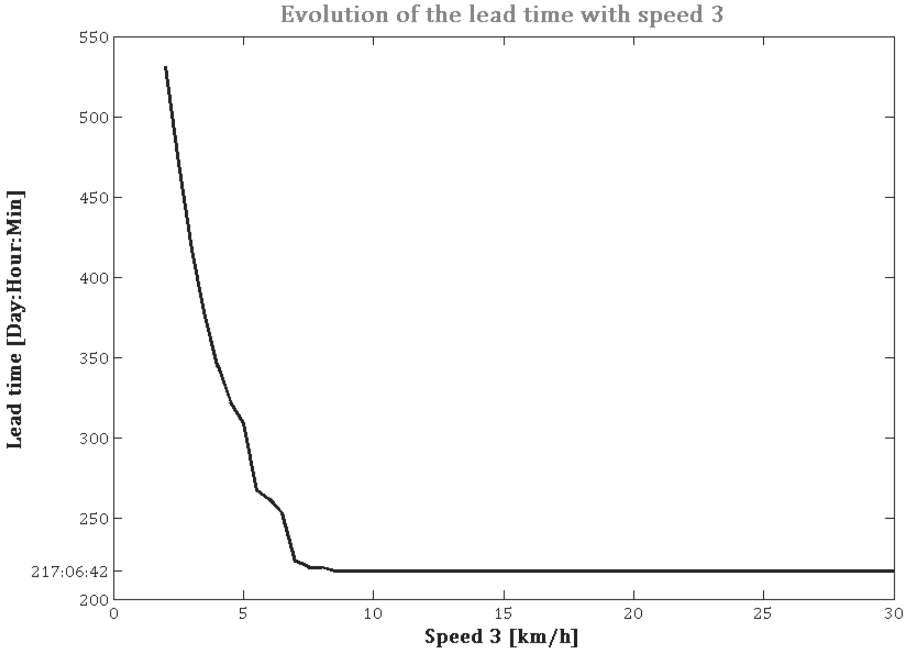


Figure 62: Evolution of the lead time with speed 3

Once again, we can see two asymptotes: one horizontal and one vertical. The explanations are the same as for the evolution of the lead time with speed 1 and 2. The lead time is constant after 8.5km/h (9 hours of transport time). In this case, increasing the speed of the installation vessel for the turbines components wouldn't have decreased the lead time.

2.4 SPEED 4

Speed 4 is the average speed of the transport vessel that transports the turbines components from the harbour to the offshore site, where they are transferred to the installation vessel. Figure 63 shows the evolution of the lead time with speed 4. In order to obtain this graph, we had to run 57 simulations by varying speed 4 between 2km/h and 30km/h with a step of 0.5km/h.

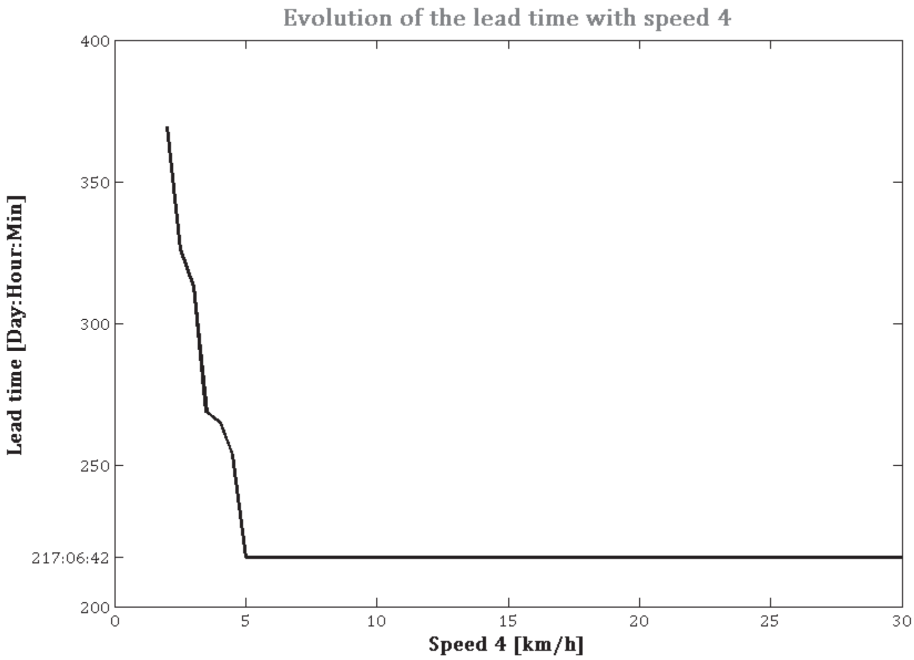


Figure 63: Evolution of the lead time with speed 4

Once again, we have two asymptotes, but this time the graph consists nearly in two lines with a change of slope at 5km/h (1 day and 6 hours of transport time).

2.5 CONCLUSIONS ABOUT SPEEDS

In order to compare all these results we decided to put them on the same graph (Figure 64).

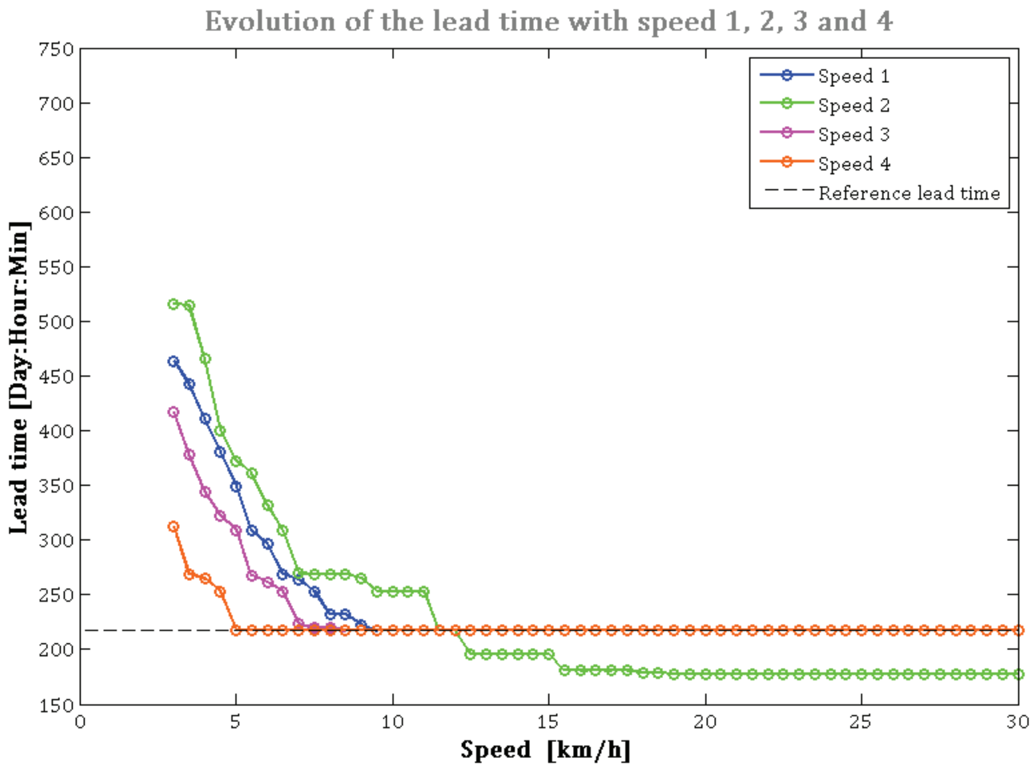


Figure 64: Comparison of the speeds

Speed 2 (speed of the installation vessel that transports and installs the jackets) is the one that has the most influence on the lead time. Indeed, if the speed is lower than the reference situation (12km/h), this speed is the only one for which the lead time is still decreasing and if it is higher than the reference situation, the lead time is higher than for all the others speeds.

The second speed, that has the most influence on the lead time, is speed 1 (speed of the transport ship for the turbines components). Then, we have speed 3 (speed of the installation vessel for the turbines components) and finally, speed 4 (speed of the installation vessel for the piles).

In the graph above, we compare speeds. The four average speeds of the reference situation are the same: 12km/h, but the distances covered by these different boats are different. In the graph below, we are going to analyze the transport times. We name them with the same numbers as the ones used for the speeds and the distances. Knowing the speeds and the distances, it is easy to know the transport time.

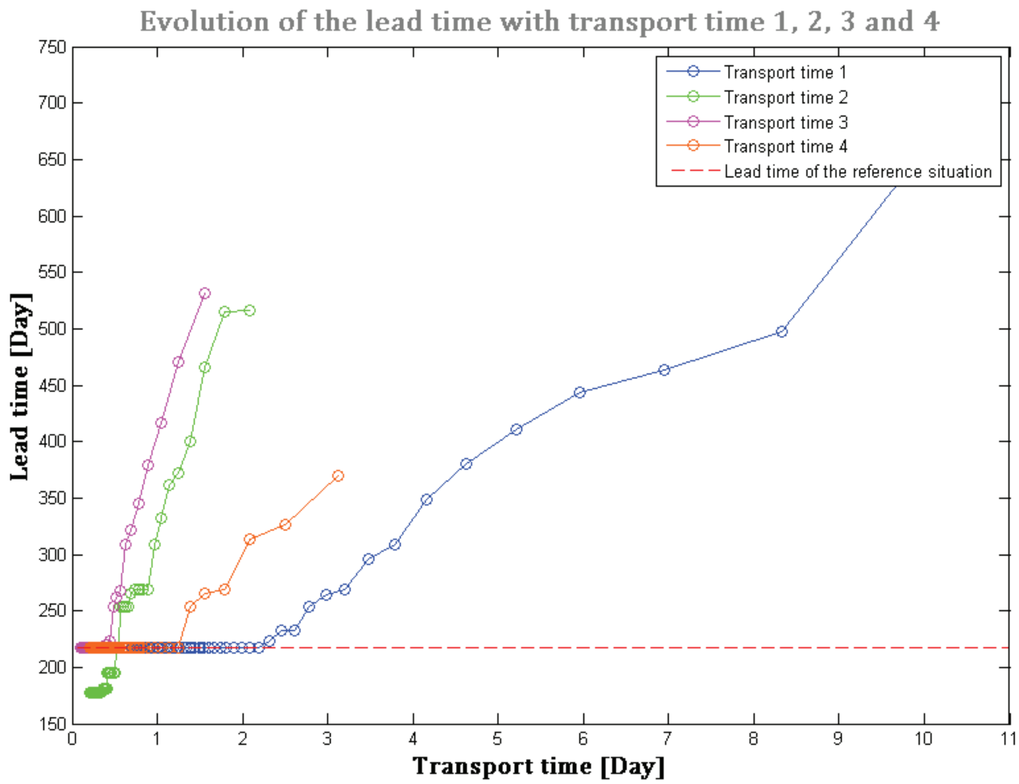


Figure 65: Comparison of the transport times

If the transport time is higher than in the reference situation, it is the transport time between the harbour and the offshore site that has the most influence. It is logical as it is the last realized operation. However, if the transport time is lower than this reference situation, we can see that the transport time between the jackets source and the offshore site is the only one that allows a diminution of the lead time.

3 Number of turbines

We also decided to analyze the influence of the number of wind turbines on the lead time (Figure 66). The number of turbines varies between 6 and 120 with a step of 2 in the graph below. The total number of turbines of the reference project is 60.

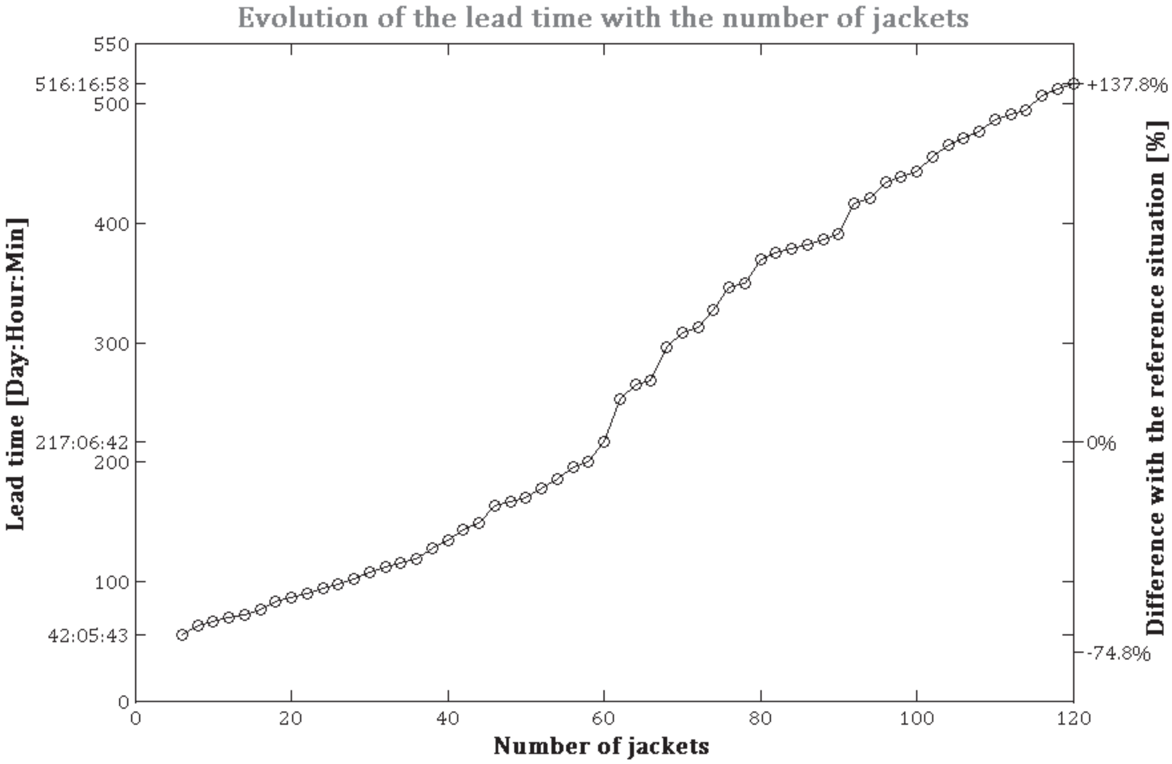


Figure 66: Evolution of the lead time with the number of jackets

The lead time progresses nearly linearly with some leaps due to the weather conditions.

4 WIND SPEED LIMITS

We are now going to analyze the influence of the following wind speed limits:

- wind speed limit for the transfer and the driving of the piles (12m/s in the reference situation);
- wind speed limit for the transport of the jackets (10m/s in the reference situation);
- wind speed limit for the installation of the jackets (12m/s in the reference situation);
- wind speed limit for the components' transport by the transport ship and by the jack-up vessel (17m/s in the reference situation);
- wind speed limit for the installation of the lower tower section, the upper tower section and the nacelle (10m/s in the reference situation);
- wind speed limit for the installation of the rotor (9m/s in the reference situation).

4.1 WIND SPEED LIMIT FOR THE TRANSFER AND THE DRIVING OF THE PILES

The wind limits for the transfer and the driving of the piles were the same in the reference situation. We decided to vary them simultaneously. Figure 67 represents the evolution of the lead time with this wind speed limit varying from 5m/s until 30m/s.

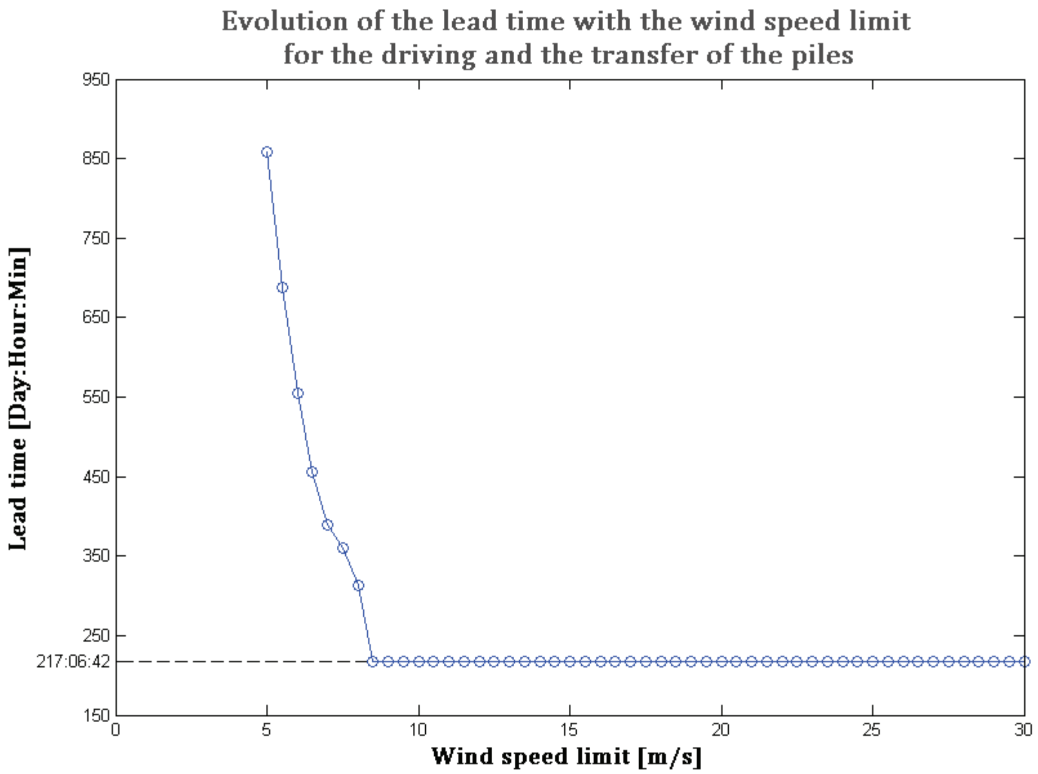


Figure 67: Evolution of the lead time with the wind speed limit for the transfer and the driving of the piles

From 8.5m/s until 30m/s, the lead time is not affected by the wind speed limit. The lead time is growing very fast between 8.5m/s and 5m/s. For a limit lower than 5m/s, the simulation ends after 31th of December 2008. This date is the end limit we fixed for our simulations because the lead time becomes too high after this date. It explains why we begin our simulations at a limit of 5m/s.

4.2 WIND SPEED LIMITS FOR THE TRANSPORT AND THE INSTALLATION OF THE JACKETS

We decided to put these two limits in the same graph because they affect the same phase of the construction: the jacket phase. The wind speed limits vary from 5m/s until 30m/ in Figure 68.

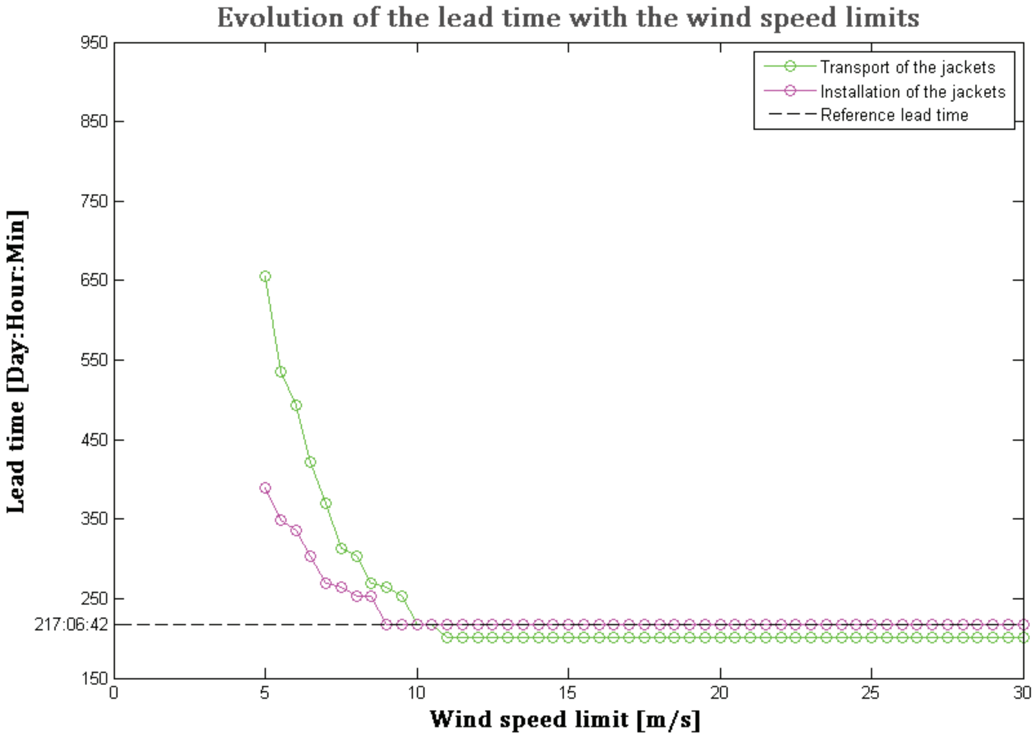


Figure 68: Evolution of the lead time with the wind speed limits of the jacket phase

Before 10m/s (wind speed limit in the reference situation for the jackets transport), it is the wind limit for the transport that affects the most the lead time. After 10.5m/s, it is for the installation that we obtain the highest lead time. A reduction of 1m/s of the reference wind speed limit for the transport allows a saving of 17 days. In the case of the installation, using vessels and cranes with a higher wind limit wouldn't affect the total duration of the construction. It is even possible to use equipment with lower limits for the installation (until 9m/s) without affecting the total duration.

4.3 *WIND SPEED LIMIT FOR THE COMPONENTS TRANSPORT*

We decided to vary simultaneously the wind speed limits for the components transport by the transport ship or by the installation vessel as they were the same in the reference situation (Figure 69).

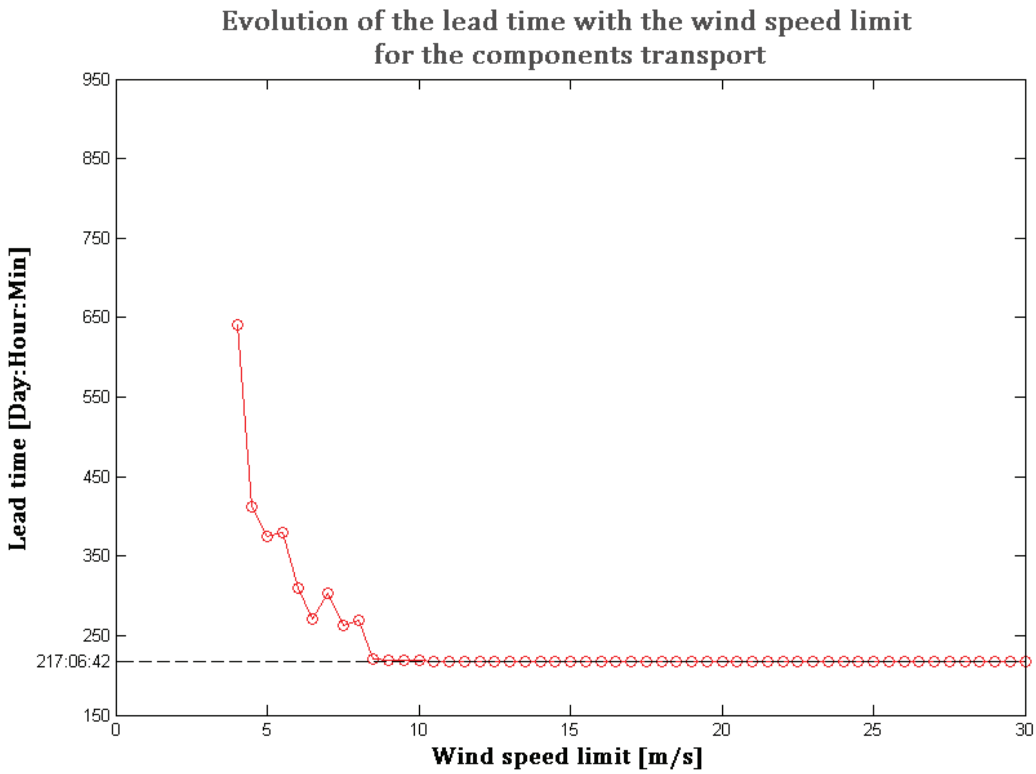


Figure 69: Evolution of the lead time with the wind speed limit for the components transport

This graph shows us that we still have to be critical while analyzing the results we obtained. Indeed, one point of this graph isn't logically situated. We can see that between 6m/s and 6.5m/s, the lead time is increasing while it should be the contrary. This point shows us that there are still small imperfections in the assumptions we make in the model.

However, except for this point the general shape is like expected. There are two asymptotes: one vertical because when the limit is too low, it is impossible to find a time window and one horizontal because when the limit is higher than a certain level (8.5m/s), it doesn't affect the lead time anymore.

4.4 WIND SPEED LIMITS FOR THE INSTALLATION OF THE TOWER SECTIONS, THE NACELLE AND THE ROTOR

We decided to put the evolution of the lead time with the wind speed limits for the installation of the tower sections, the nacelle and the rotor on the same graph. We varied them between 5m/s and 30m/s.

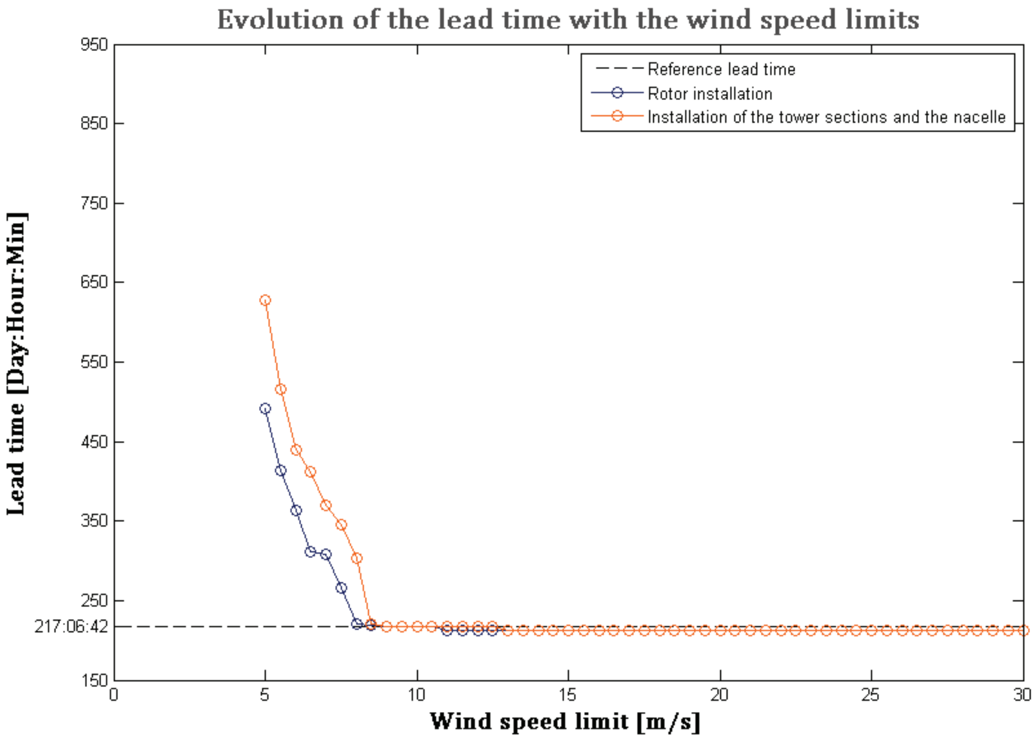


Figure 70: Evolution of the lead time with the wind speed limits for the installation of the tower sections, the nacelle and the rotor

The limit for the installation of the tower sections and the nacelle affects more the lead time than the other one.

In the case of the rotor installation, the lead time is constant from 8m/s until 30 m/s and for the installation of the nacelle and the tower sections from 8.5m/s until 30m/s.

4.5 *COMPARISON OF THE WIND SPEED LIMITS*

In order to compare the influence of the different wind speed limits, we put them on the same graph.

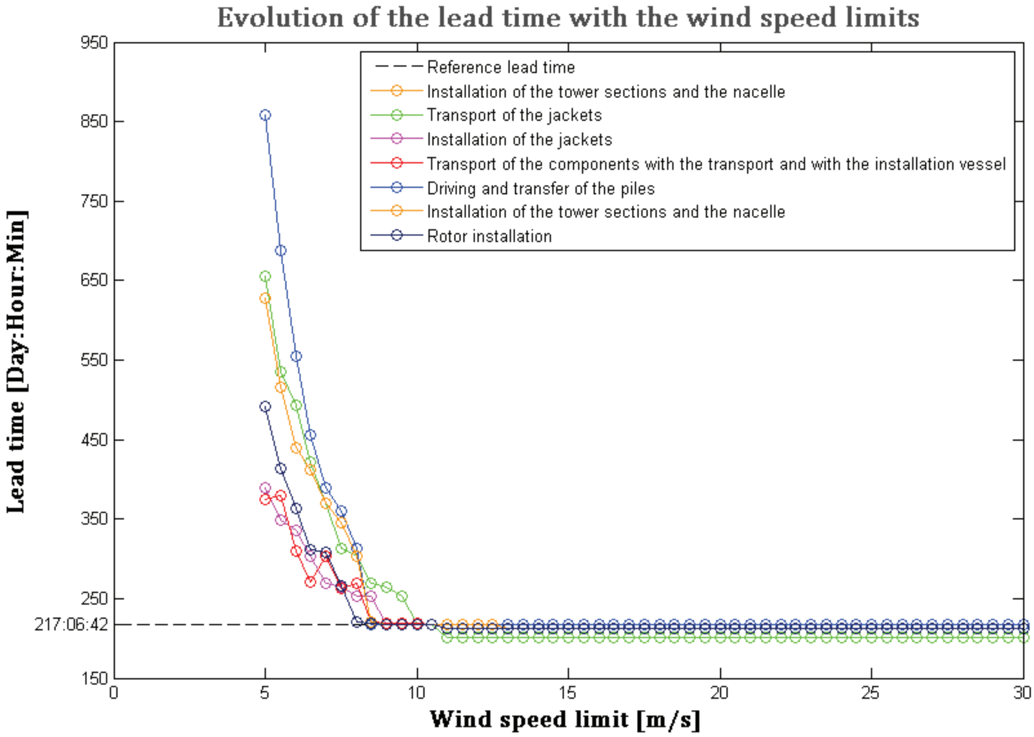


Figure 71: Evolution of the lead time with the wind speed limits

From 5m/s until 8m/s, the highest lead time is obtained with the wind limit for the transfer and driving of the piles. From 8m/s until10m/s, it is the limit for the transport of the jackets and after we obtain the reference lead time or a duration a little smaller than the reference one.

5 WAVE HEIGHT LIMITS

We are now going to analyze the impact of the wave height limits of the following operations:

- transport of the piles (3m in the reference situation);
- transfer of the piles (1.25m);
- driving of the piles (1.5m);
- transport of the jackets (1.5m);
- installation of the jackets (0.75m);
- grouting of the jackets (1.5m);
- transport of the turbines components on the transport ship (2m);
- transport of the turbines components on the jack-up vessel (1.25m).

5.1 WAVE HEIGHT LIMITS FOR THE PILING PHASE

We decided to put all the wave height limits corresponding to steps of the piling phase on the same graph. These steps are: the transport, the transfer and the driving of the piles. The limits vary from 0.5m until 4m with a step of 0.25m in Figure 72.

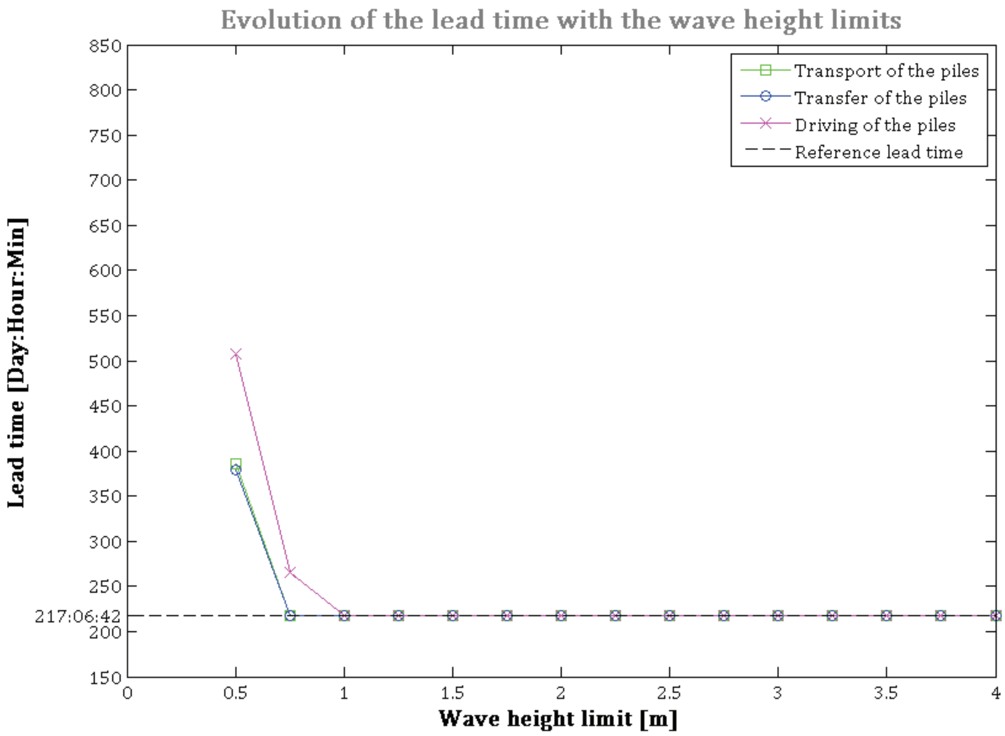


Figure 72: Evolution of the lead time with the wave height limits for the piling phase

The highest lead time is obtained with the limit for the driving of the piles. We can see that if the limit is higher than 1m, the lead time is constant and equal to the one of the reference situation. For the transport and the transfer, the lead time is constant except for 0.5m.

5.2 WAVE HEIGHT LIMITS FOR THE JACKET PHASE

We decided to put all the wave height limits corresponding to steps of the jacket phase on the same graph. These steps are: the transport, the installation and the grouting of the jackets. The limits vary from 0.5m until 4m with a step of 0.25m in Figure 73.

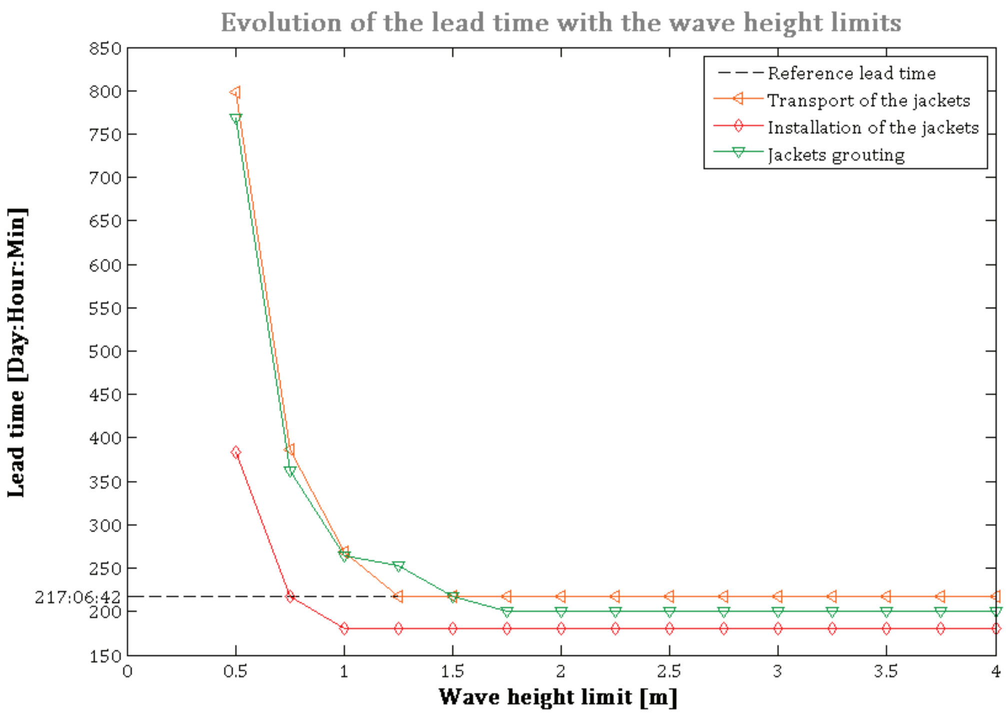


Figure 73: Evolution of the lead time with the wave height limits of the jacket phase

The highest lead time is obtained with the limit for the transport except between 1m and 1.5m, where it is the grouting. A reduction of 36 days of the total duration of the construction can be obtained with a limit for the installation of the jackets only 0.25m higher than the reference one.

5.3 *WAVE HEIGHT LIMITS FOR THE TRANSPORT OF THE COMPONENTS BY THE TRANSPORT SHIP OR BY THE INSTALLATION VESSEL*

We decided to put the limits for the transport of the components by the transport ship and by the jack-up vessel on the same graph in order to compare them. The limits vary from 0.5m until 4m with a step of 0.25m in Figure 74.

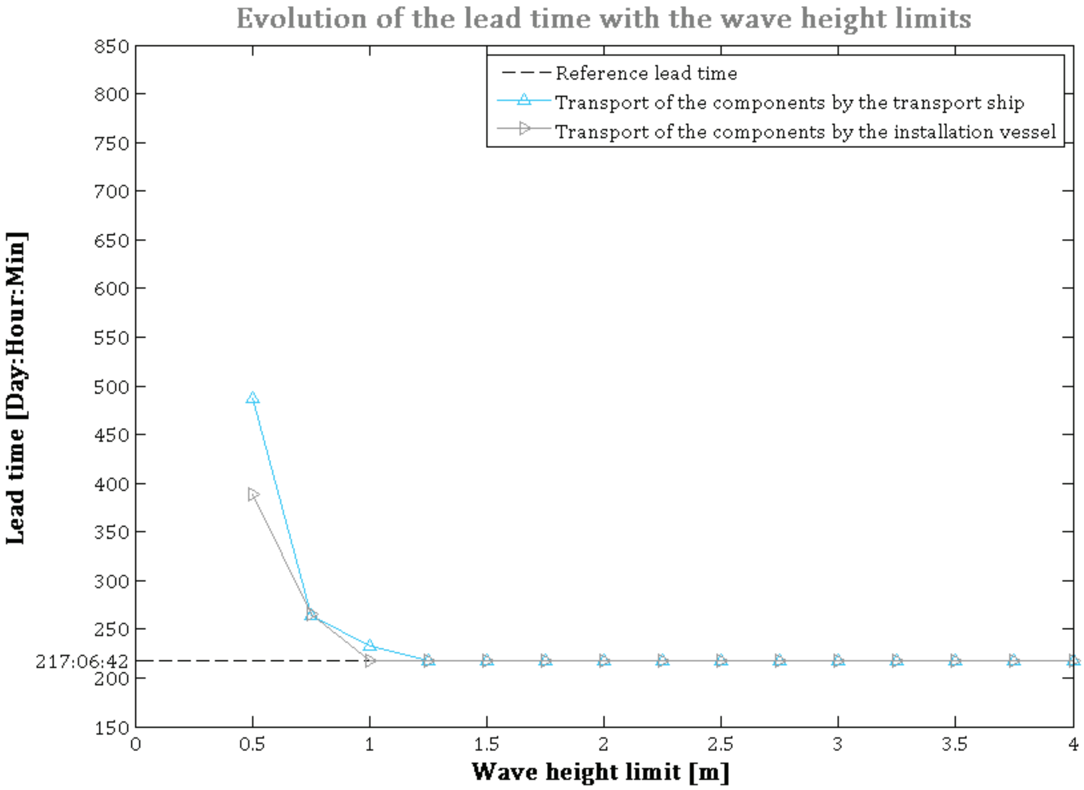


Figure 74: Evolution of the lead time with the wave height limit for the transport of the components by the transport or by the installation vessel

We can see that the lead time is higher for the wave height limit of the transport ship. The limit of the jack-up vessel affects less the lead time.

5.4 *COMPARISON OF THE WAVE HEIGHT LIMITS*

We put all the evolutions of the lead time with the wave height limits on the same graph (Figure 75) in order to know which one affects the most the lead time.

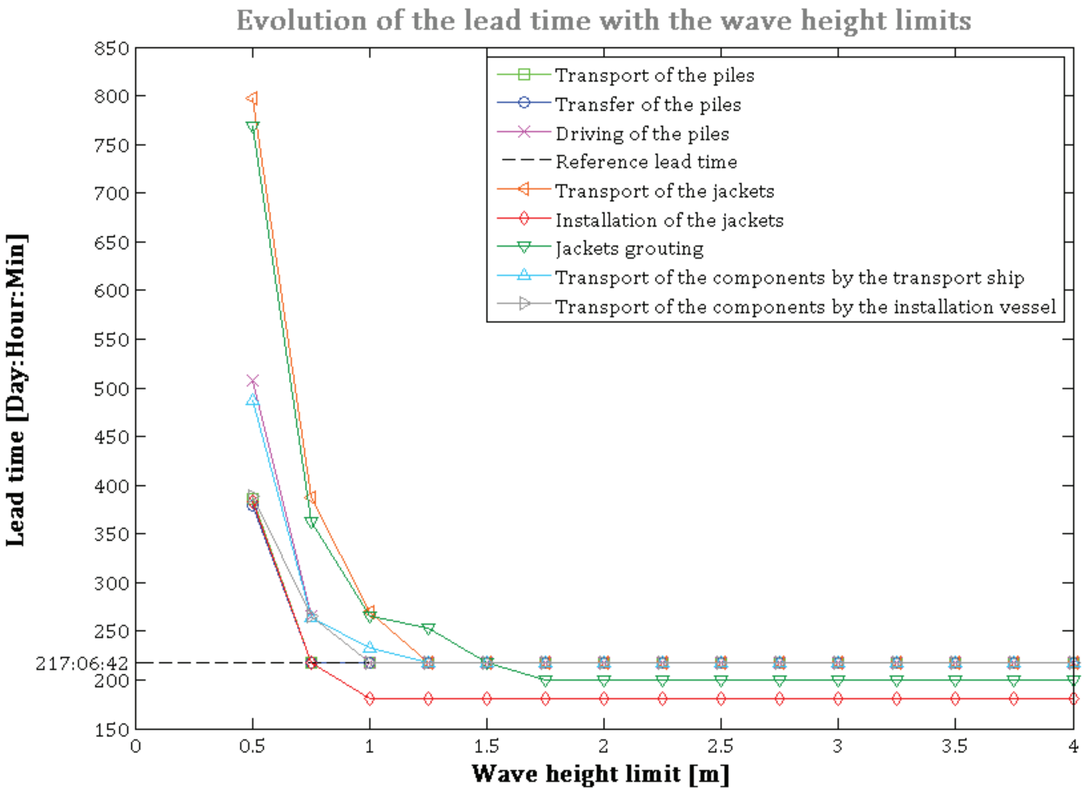


Figure 75: Evolution of the lead time with the wave height limits

From 0.5m until 1m, it is the limit for the transport of the jacket that affects the most the lead time. From 1m until 1.5m, it is the jackets grouting. From 2m until 4m, all the evolutions are constant. Only two limits allow a reduction of the reference lead time: the one for the grouting and the one for the installation of the jackets.

This graph shows us that the wave height limits of the jacket phase are the ones that affect the most the lead time.

6 NUMBER OF JACKETS CARRIED BY TRIP

The results presented in this chapter were obtained for a constant number of jackets transported by trip: two. In the previous chapter, we talked about a condition we developed that chooses if it is better to take one or two jackets at a certain moment. We are now going to compare the results we obtain with this condition with the ones we obtain with a constant number of jackets per trip: one or two. In order to realize this comparison, we vary the distance between the source of the jackets and the offshore site in the graph showed in Figure 76.

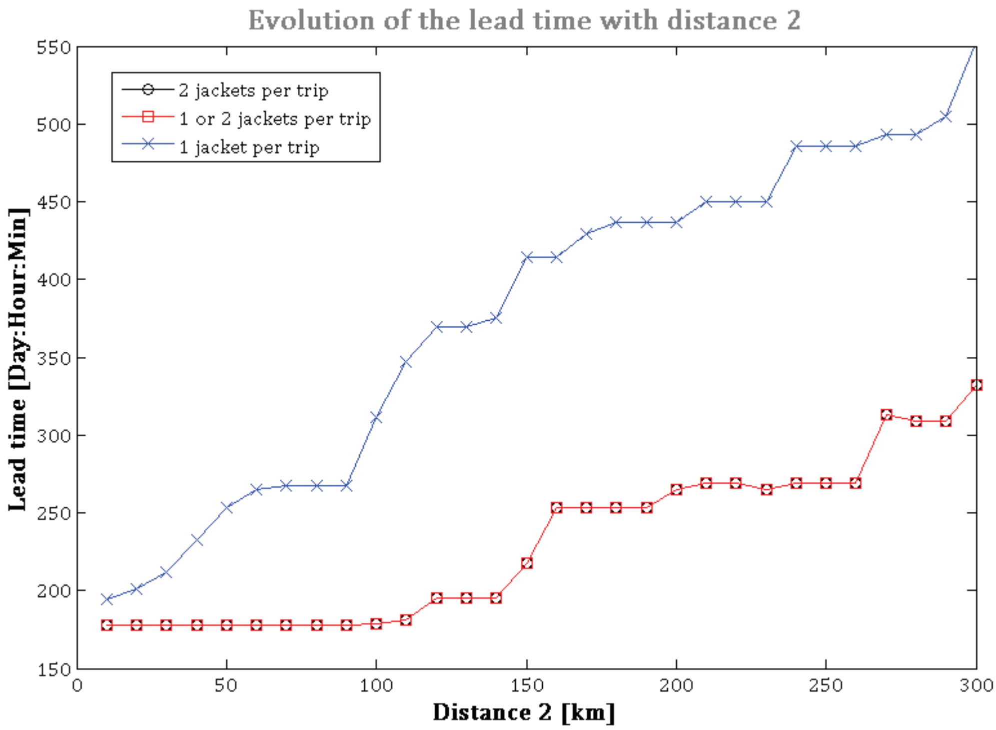


Figure 76: comparison of the evolutions of the lead time with distance 2 obtained with one or two jacket(s) transported per trip

The results obtained with the condition are exactly the same as the ones obtained with constantly two jackets per trip. It means that it is never advantageous to take one jacket per trip for this project. The lead time obtained with constantly one jacket per trip is far longer than the one obtained with two jackets per trip. However, the difference between the two lines decreases for small distances.

CHAPTER 6 BUNNY EAR METHOD

In this chapter, we are going to compare the bunny ear method and the fully assembled rotor method.

In the bunny method, the rotor is preassembled on the onshore site with only two blades. Once installed on the offshore site, the third pale is installed.

In the fully assembled rotor method, the rotor is fully preassembled on the onshore site with its three blades. Then, it is transported and installed on the offshore site.

The goal is to determine the limits for which it would be more interesting to use the bunny ear method, instead of the fully assembled rotor.

1 COMPARISON OF THE REFERENCE SITUATIONS

The parameters used in the reference situation for the bunny ear strategy are the same than the ones used for the fully assembled rotor method. The reference lead times we obtain are given in the table below.

Fully assembled rotor method	Bunny ear method
217:06:42	217:18:23

The duration of the construction with the bunny ear strategy is slightly higher than with the other installation strategy. However, a difference of 12 hours over a total duration of 217 days doesn't have a real impact in practice.

We are now going to analyze the process flow of the two strategies (Figure 77 and Figure 78). We can see that with the fully assembled rotor method, there is less time between the jacket phase and the components' installation. This last step follows nearly directly the installation of the jackets.

For the bunny ear method, it is also the case but only at the end. Before the installation of the 42th turbine the installation of the turbine doesn't follow directly the installation of the jacket.

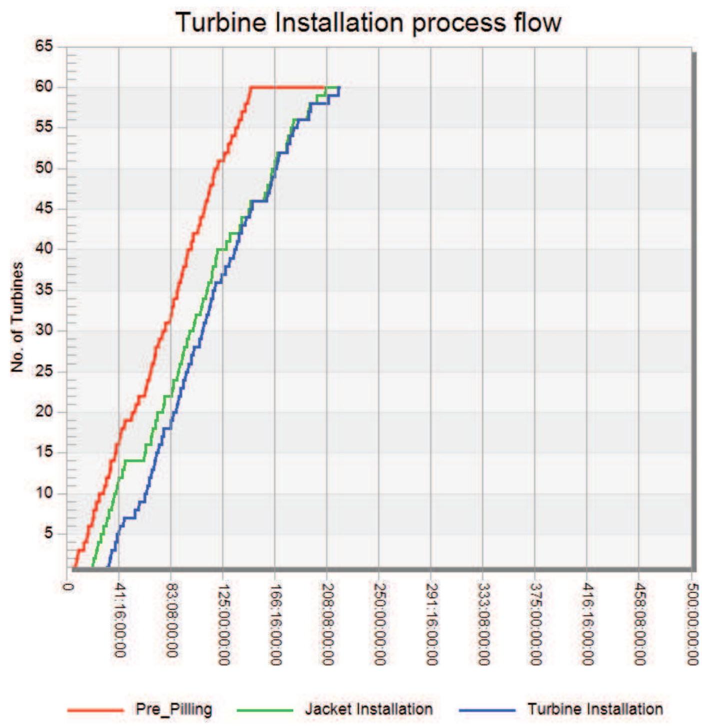


Figure 77: process flow of the bunny ear method

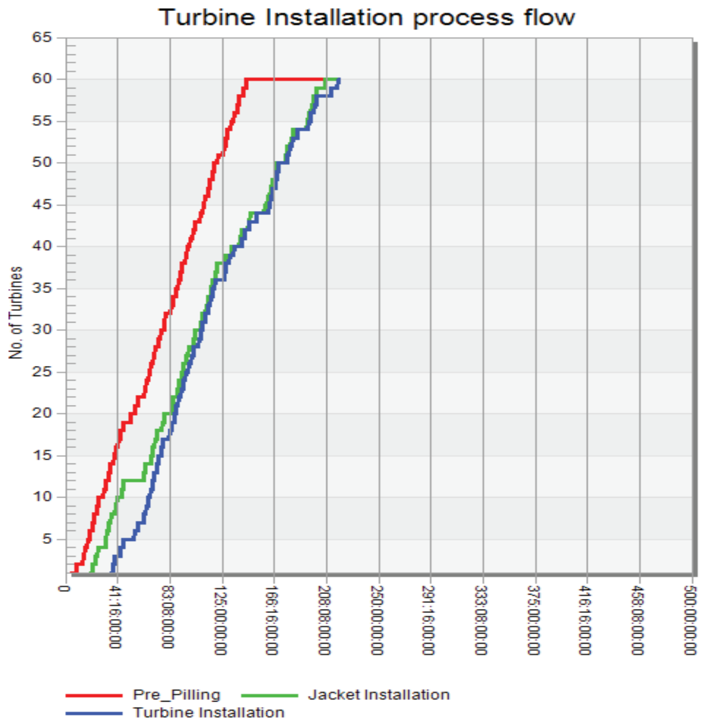


Figure 78: Process flow of the fully assembled rotor method

2 DISTANCES

In the following section, we are going to name the distances with the same numbers as the ones used in the previous chapter.

2.1 DISTANCE 1

In Figure 79, distance 1 varies from 5km until 995km with a step of 10km.

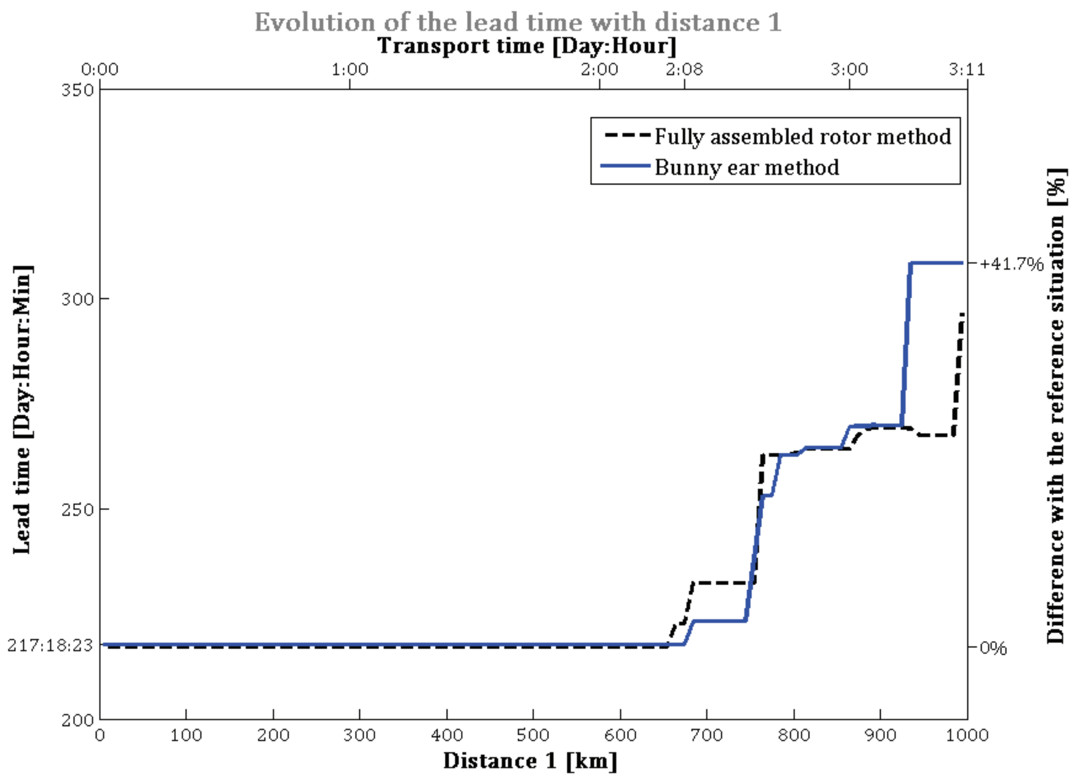


Figure 79: Evolution of the lead time with distance 1 for the two methods

Until 675km (2 days and 8 hours of transport time), the lead time is constant. The construction only takes 12 hours more with the bunny ear method compared to the fully assembled rotor method. That represents 0.2% of difference. We can assume this difference to be negligible until 655km. From 655km until 775km, the bunny ear method is more advantageous. From 775km until 995km, the fully assembled rotor method allows a lower lead time.

The graph showed in Figure 80 represents the evolution of the percentage of difference between the two methods with distance 1. This graph clearly confirms what we have said above. We can see that for distance 1, equal to 685km-745km, the lead time obtained with the bunny ear method is 4% lower than the lead time obtained with the fully assembled rotor method. However, for distance 1 in the range of 945km-985km, the lead time obtained with the bunny ear method is 15.3% bigger than with the other method.

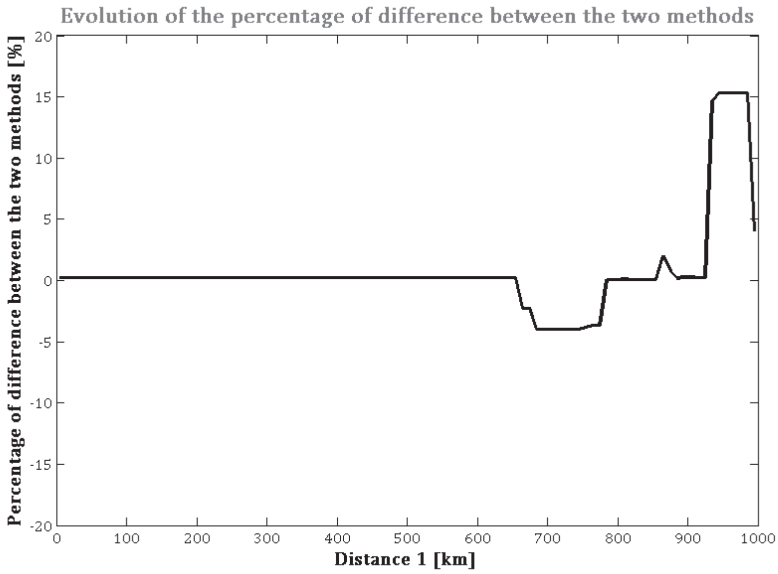


Figure 80: Evolution of the percentage of difference between the two methods with distance 1

2.2 DISTANCE 2

In Figure 81, distance 2 varies from 5km until 500km with a step of 5km.

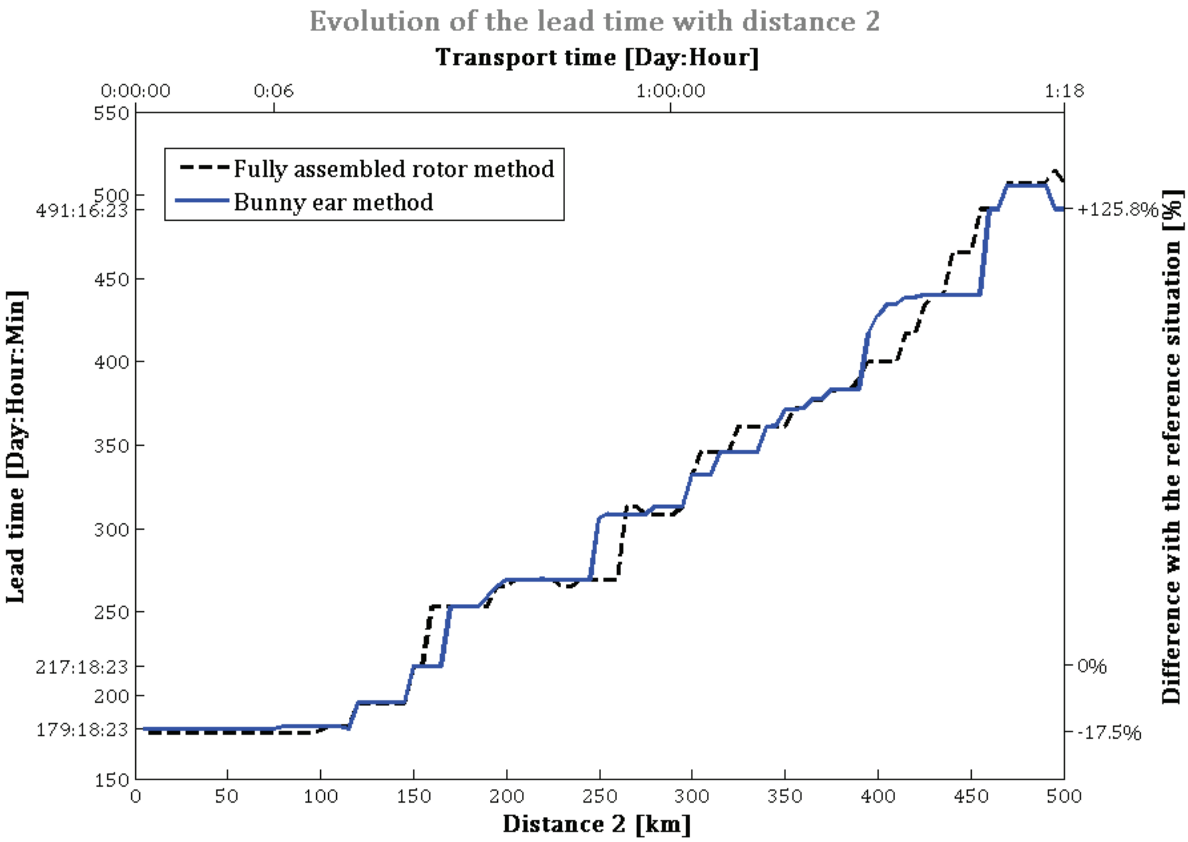


Figure 81: Evolution of the lead time with distance 2 for the two methods

It isn't possible to write general conclusions from this graph. We can just see that the shapes of the two graphs are similar. However, we can't identify limits in order to know which method is the best.

The minimum percentage of difference is -14% for 165km. In this case the bunny method allows a saving of 35 days. The maximum percentage of difference is +14.7% for 255km. In this case the fully assembled rotor method takes 39 days less.

2.3 DISTANCE 3

In Figure 82, distance 3 varies from 5km until 500km with a step of 5km.

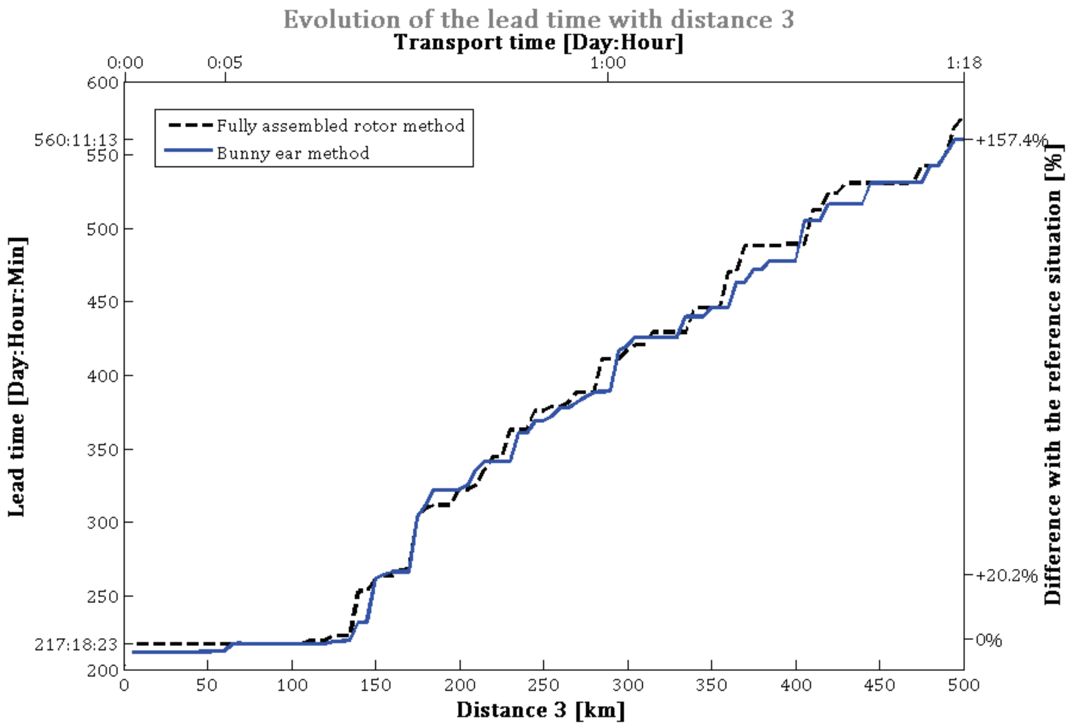


Figure 82: Evolution of the lead time with distance 3 for the two methods

Once again, it is hard to identify limits in order to know which method is the best. Indeed, the two graphs have similar shapes and cross each other several times.

The distance for which the bunny ear method is the most advantageous is 145km (-8.3% of difference with the other version) and the less advantageous is 185km (+3.4% of difference).

2.4 DISTANCE 4

In Figure 83, distance 4 varies from 5km until 500km with a step of 5km.

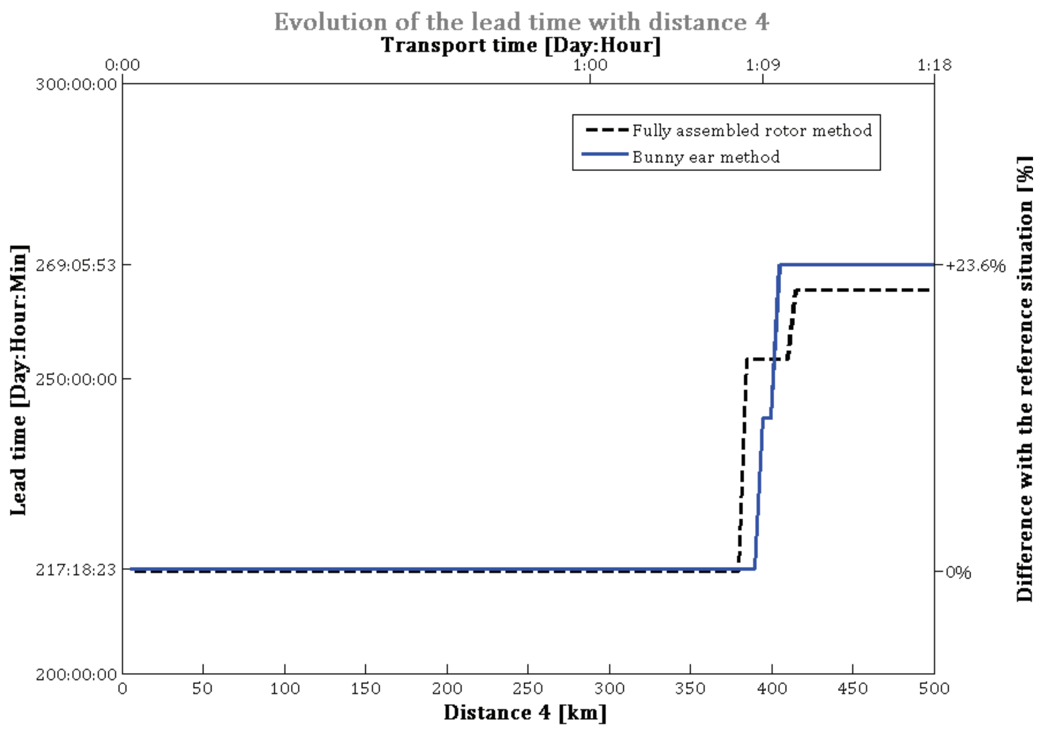


Figure 83: Evolution of the lead time with distance 4 for the two methods

From 5km until 385km, the lead times are nearly the same (0.2% of difference). However, from 385km until 400km, the bunny ear method is more advantageous. After, between 400km and 500 km, it is the contrary.

In Figure 84, we can see that for 385km-390km, the bunny ear method allows a saving of 14% (36 days). For 410-415km, it is the opposite: the bunny ear method is 6.3% longer.

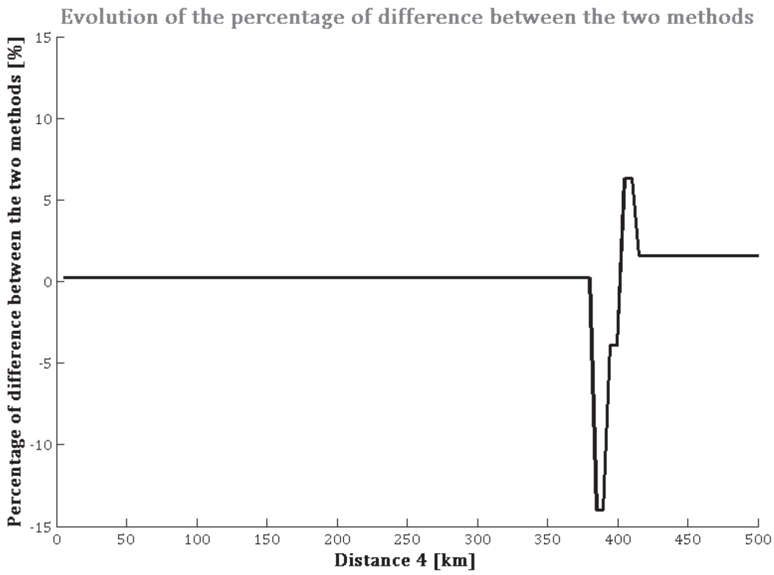


Figure 84: Evolution of the percentage of difference between the two methods with distance 4

3 SPEEDS

Once again the numbers used to identify the various speeds are the same as the ones used for the analysis of the fully assembled rotor method.

3.1 SPEED 1

In Figure 85, we can see the evolution of the lead time with speed 1 varying from 2km/h until 30km/h with a step of 0.5km/h.

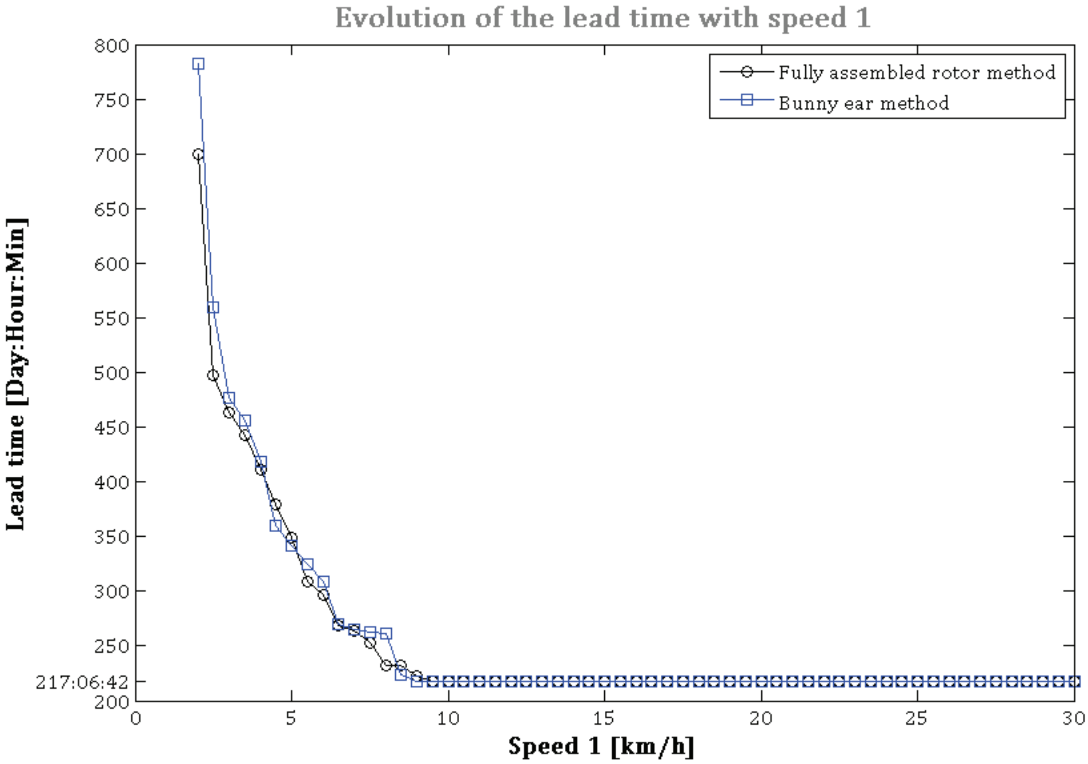


Figure 85: Evolution of the lead time with speed 1 for the two methods

The lead times are approximately the same, except when the speed is very low (2km/h or 2.5km/h). For 2km/h, the bunny ear method is 83 days longer than the other strategy. There are also some values for which the fully assembled rotor strategy takes more time. For example, for 4.5km/h it takes 31 days more.

3.2 SPEED 2

In Figure 86, we can see the evolution of the lead time with speed 2 varying from 3km/h to 30km/h with a step of 0.5km/h.

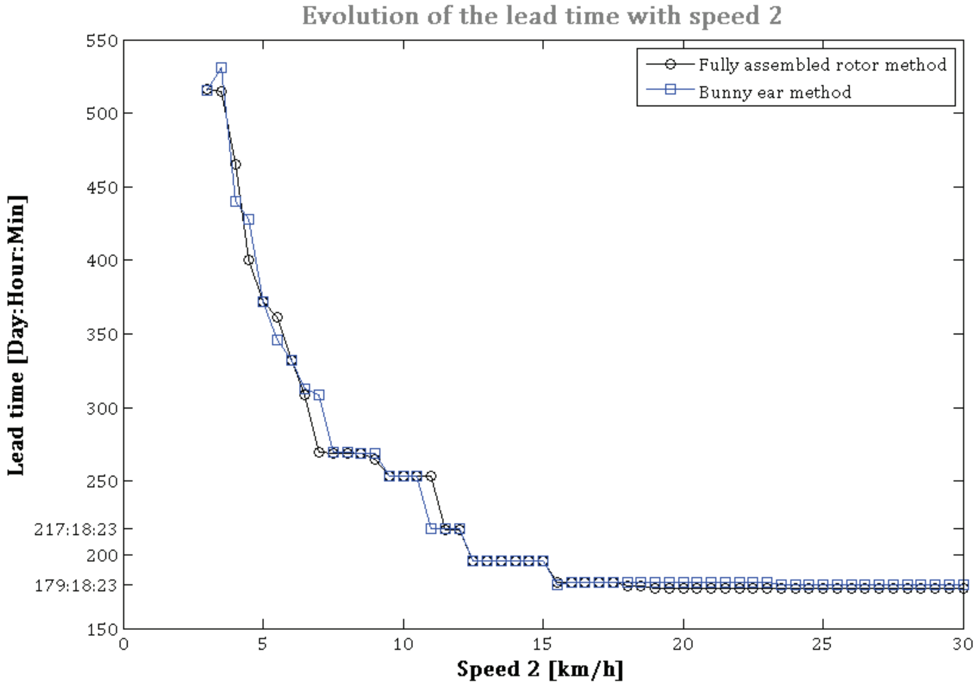


Figure 86: Evolution of the lead time with speed 2 for the two methods

Here, the highest difference doesn't appear for the lowest speeds. The highest difference appears for speed 2 equal to 7km/h. The lead time of the bunny method is 39 days longer. For speed 2 equal to 11km/h, the fully assembled rotor method is 36 days longer.

3.3 Speed 3

In Figure 87, we can see the evolution of the lead time with speed 3 varying from 2km/h until 30km/h with a step of 0.5km/h.

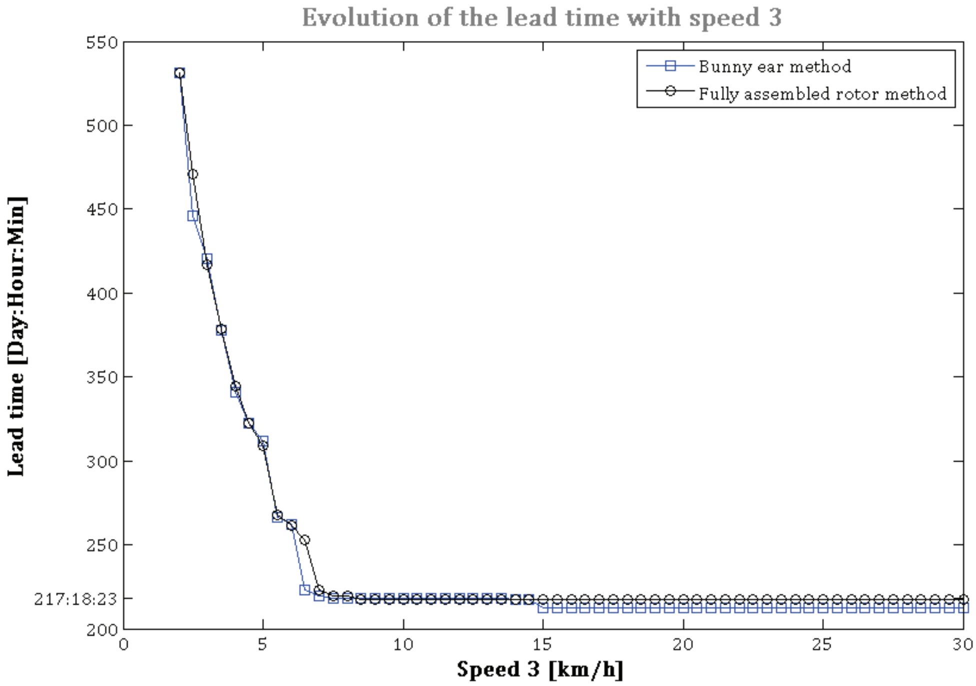


Figure 87: Evolution of the lead time with speed 3 for the two methods

For this case, after 15km/h, we obtain a constant lead time 5 days smaller for the bunny method. In this graph, the lead time of the bunny ear method is always smaller or equal to the lead time of the other strategy, but never bigger. For speed 3 equal to 6.5km/h, there is a maximum difference of 31 days.

3.4 SPEED 4

In Figure 88, we can see the evolution of the lead time with speed 4 varying from 3km/h until 30km/h with a step of 0.5km/h.

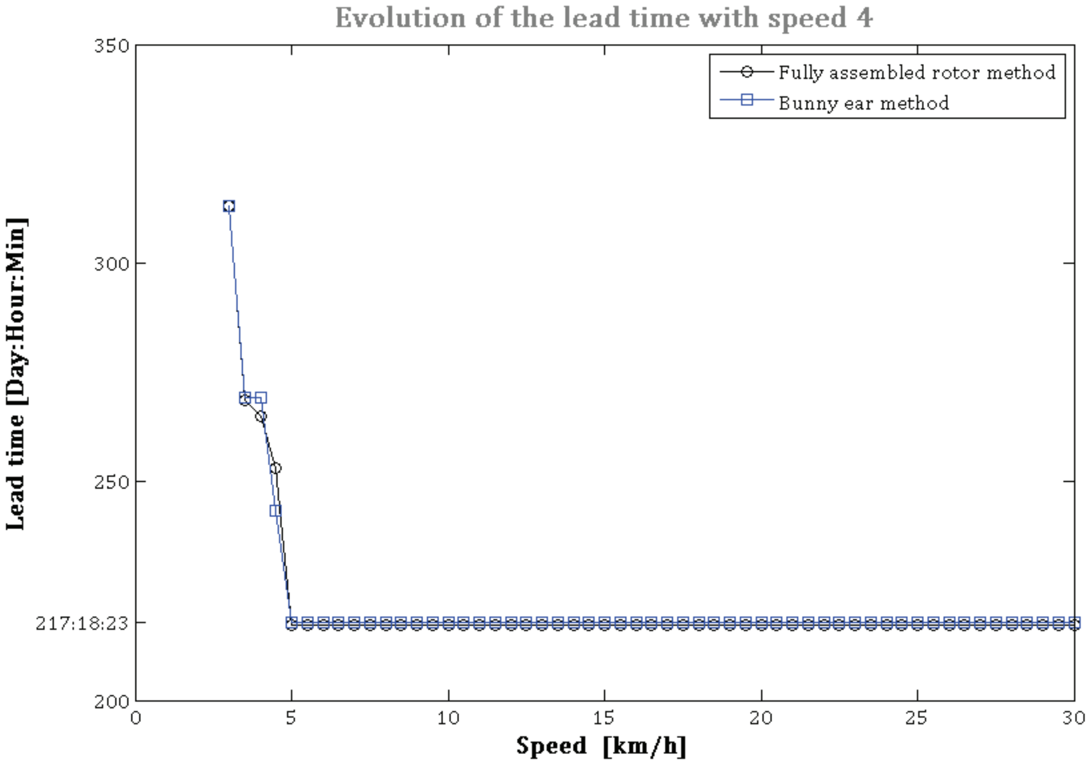


Figure 88: Evolution of the lead time with speed 4 for the two methods

In this graph, there are only two values of the speed for which the difference between the graphs is significant: 4km/h (5 days longer with the bunny ear strategy) and 4.5km/h (10 days longer with the fully assembled rotor method).

4 NUMBER OF JACKETS

In Figure 89, the number of jackets varies from 6 to 120 with a step of 2 jackets.

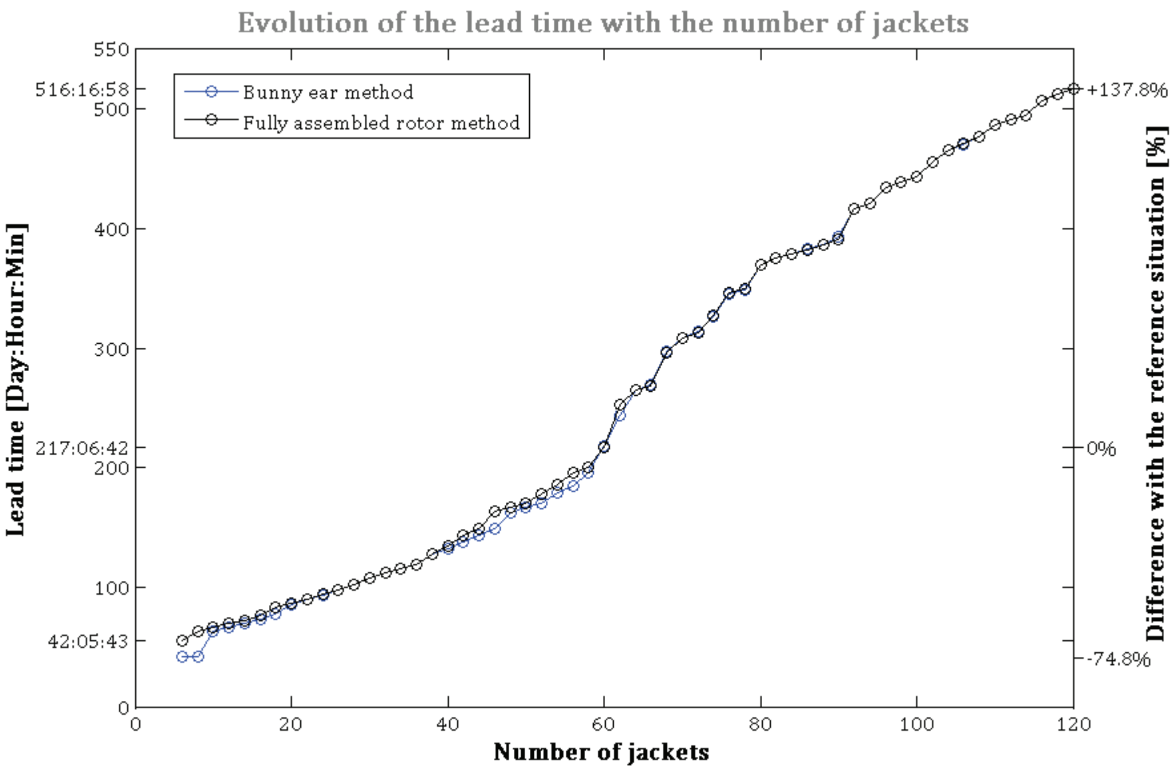


Figure 89: Evolution of the lead time with the number of jackets for the two methods

We can see that the graph for the bunny ear method is always below the graph for the fully assembled rotor method. The maximum difference happens for a small number of turbines (eight) and is equal to 20 days.

CHAPTER 7 CONCLUSIONS

In this report, we first got familiar with the offshore wind sector thanks to a state of the art presenting the market and the technologies used.

Afterwards, we studied the influence of various parameters in order to know which one impacted mostly the lead time.

Related to the analysis of the distances, we could identify the distance that causes the highest increase in the lead time: the distance between the harbour and the offshore site. However, the reduction of only one distance allows a saving of time in comparison to the reference project. It is the distance between the source of the jacket foundations and the offshore site. We got the same conclusions about the transport times.

In the specific studied project, the speed that impacts the most the total duration of the construction is the speed of the jack-up vessel that transports and installs the jackets. Once again, it is the only speed that allows a reduction of the reference lead time.

The next topic is related to the workability limits. By varying the various wind speed limits, we could identify that the two wind speed limits that impact the most the lead time are the limit for the driving and transfer of the piles and the one for the transport of the jackets. Once again, the transport of the jackets is the only operation that allows a saving of time when its wind speed limit is higher than the reference one. With regards to the wave height limits, the jacket phase is the one that impacts the most the duration of construction.

After analyzing various parameters, we compared two assembly scenarios: the fully assembled rotor method and the bunny ear method. We first compared these two methods with the reference situation of the project. The total duration of construction is more or less the same with the two strategies for that specific project, but the process flow is different. Indeed, in the case of the fully assembled rotor method, the installation of the turbines components follows directly the installation of the corresponding jacket, whereas with the bunny ear method it is not the case.

By varying some parameters, we could remark that there are some distances that impact more the difference between the two methods. We could identify limits of distance for which it would have been more useful to use the bunny ear method. These limits could only be identified for two distances: the one between the source of the components and the harbour and the one between the source of the piles and the offshore site. Related to the analysis of the speeds, we could see that the highest difference of lead time between the two methods was obtained for small values of the speed of the transport ship that covers the distance between the source of the turbines components and the harbour. For small values of this speed, the bunny ear method was less advantageous. By analyzing the influence of the number of jackets, we noted that for a high number of jackets, there is nearly no difference of duration between the two methods.

This type of analysis realized on a specific project can be useful in order to choose between different construction options. However, this analysis has to be done with different starting dates. This has to be done in order to know what happens during bad or good weather years because we don’t know what kind of weather conditions will occur for the studied project. Studying the same project with various starting dates allows a better evaluation of the risk linked to the weather conditions. Moreover, we still have to be critical with the results because like we already said some assumptions had to be made in order to model the construction steps.

Despite these assumptions, we still have quite a precise idea of the duration of the construction. The analysis that can be realized thanks to the software EOSIM can clearly help to assess the risk linked to various strategic decisions. A further useful development would be to implement the use of stochastic weather input instead of real weather data as the real data of the previous decade are not available for every project. Moreover, it would be useful to implement the construction steps of other types of foundations as the only one implemented in the program are linked to the jacket foundations, only.

We can conclude by saying that discrete event simulation is a useful tool for the strategic decisions linked to the construction of an offshore wind farm. Optimizing the construction will be a key challenge for this growing market and the type of analysis realized in this work will help to take the best decisions in order to minimize the duration of the construction.

CHAPTER 8 ANNEXES

ANNEX-A: PORTS FOR OFFSHORE WIND CONSTRUCTION IN EUROPE

No	Port	MP[1]	M[2]	OWE[3]
1	Aalborg	●	●	✓
2	Aarhus	◎	◎	✓
3	Barrow	●	◎	✓
4	Belfast	●	◎	✓
5	Bremerhaven	●	●	✓
6	Brest	◎	◎	×
7	Caen	○	○	×
8	Cherbourg	◎	◎	×
9	Copenhagen	◎	◎	×
10	Cape Firth	◎	◎	×
11	Cuxhaven	●	●	✓
12	Dieppe	◎	◎	×
13	Dundee	◎	◎	×
14	Dunkirk	●	◎	✓
15	Eemshaven	●	◎	✓
16	Emden	●	●	✓
17	Esbjerg	●	●	✓

No	Port	MP[1]	M[2]	OWE[3]
18	Frederikshvn.	○	○	✓
19	Gdansk	◎	◎	×
20	Great Yarmouth	●	◎	✓
21	Hartlepool & tees	◎	◎	✓
22	Humber	◎	●	✓
23	Hunterston	◎	◎	×
24	Le Havre	◎	◎	×
25	Zeebrugge	◎	◎	×
26	Lubmin	◎	●	✓
27	Malmo	◎	◎	×
28	Medway	◎	●	×
29	Methil	●	●	✓
30	Milford H	◎	◎	×
31	Montrose	◎	◎	×
32	Mostyn	●	○	✓
33	Newhaven	◎	○	×
34	Nyborg	●	◎	✓

No	Port	MP[1]	M[2]	OWE[3]
35	Peterhead	○	○	×
36	Portland	◎	○	×
37	Ramsgate	●	○	✓
38	Riga	○	◎	×
39	Rostock	●	●	✓
40	Rotterdam	●	●	✓
41	Sassnitz	●	◎	✓
42	Southampton	◎	◎	×
43	St Malo	○	○	×
44	St Nazaire	◎	◎	×
45	Stavanger	◎	◎	✓
46	Swansea	◎	◎	×
47	Tallin	◎	◎	✓
48	Tyneside	◎	◎	×
49	Vlissingen	◎	◎	✓
50	Wismar	◎	◎	×

Notes:
1. "MP": suitable as Mobilisation Port
2. "M": Manufacturing infrastructure serving the offshore wind sector
3. "OWE": Offshore Wind Experience

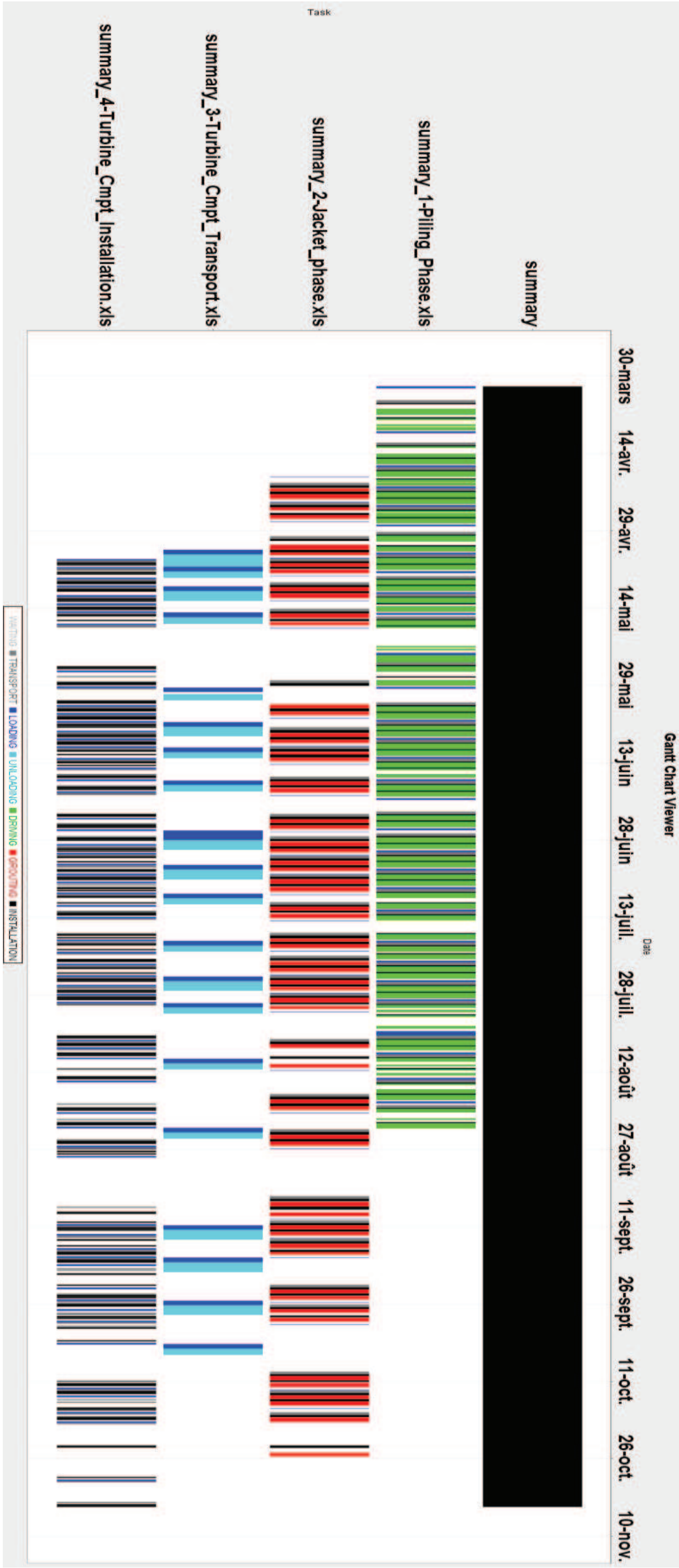
Legend:
● Currently or likely in future
◎ Possible in future
○ Unlikely

[35]

[35] E.W.E.A., *Wind in our sails,* 2011, p.89

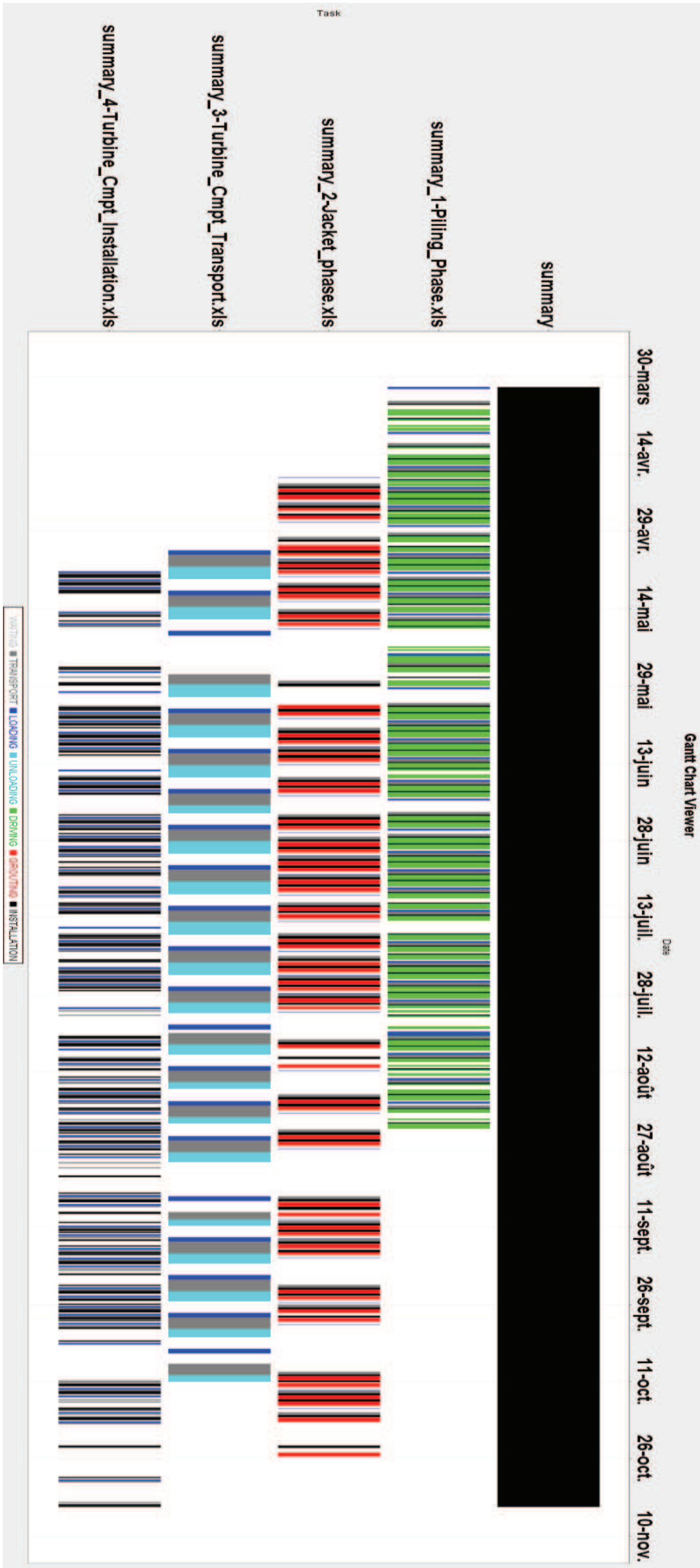
ANNEX-B: GANTT CHARTS FOR DISTANCE 1

Gantt chart for distance 1=5km

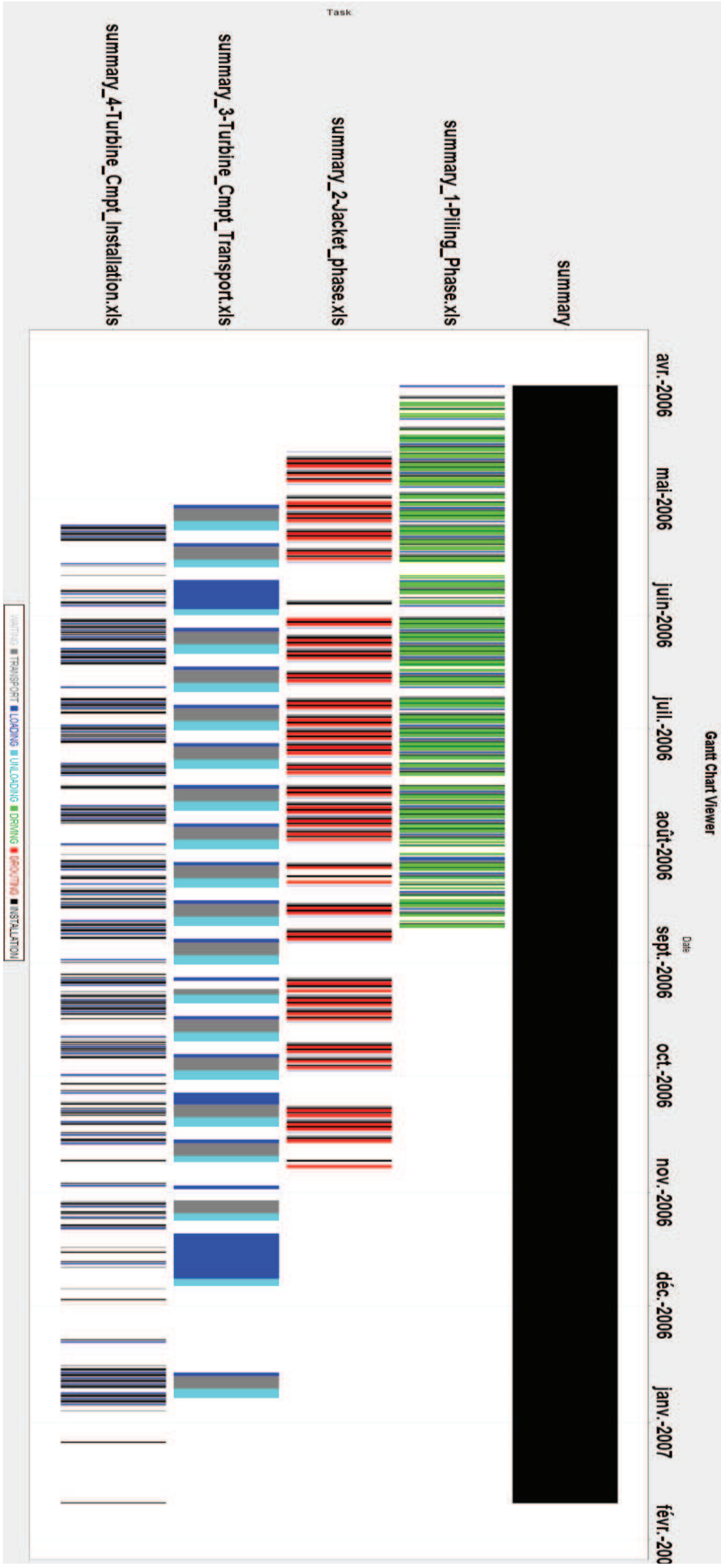


ANNEXES

Gantt chart for distance 1=655km

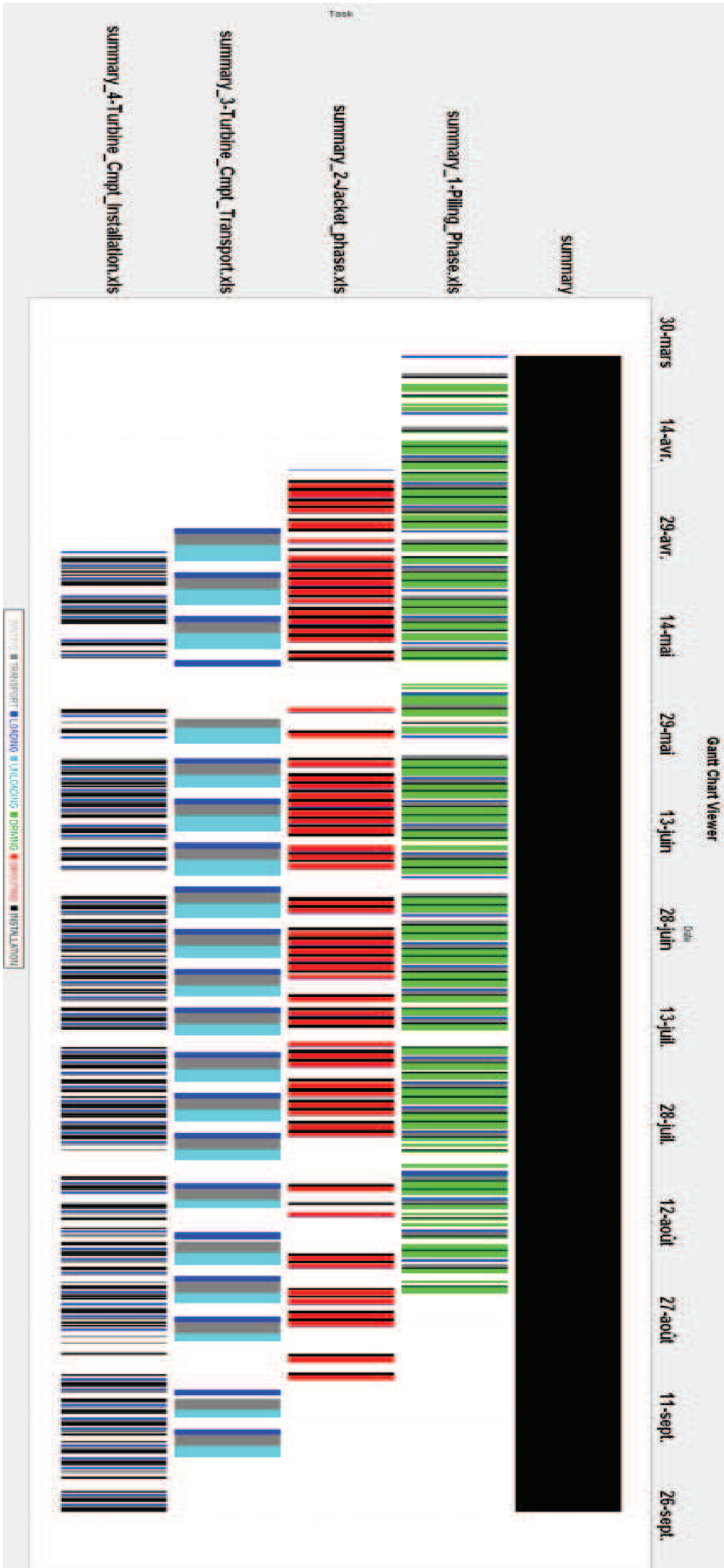


Gantt chart for distance 1= 995km

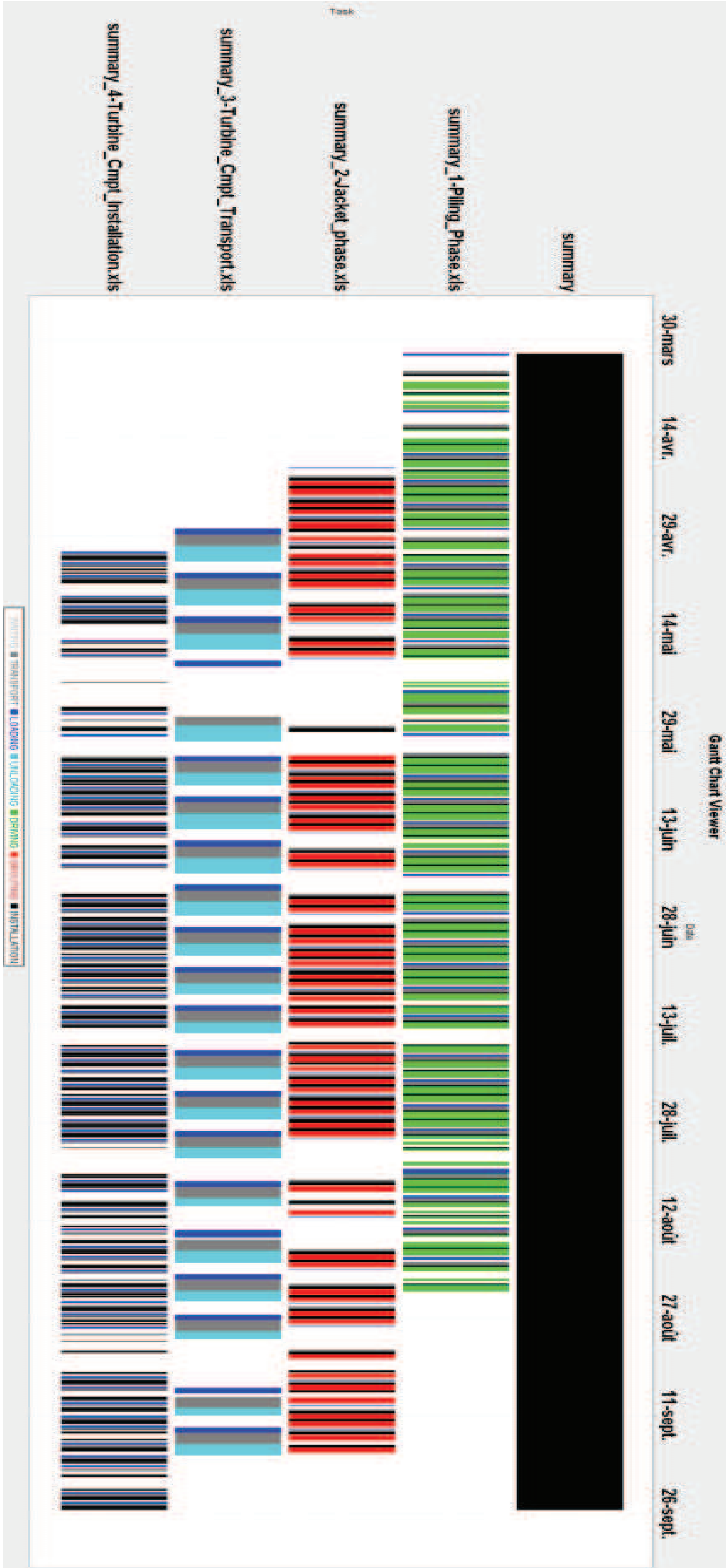


ANNEX-C: GANTT CHARTS FOR DISTANCE 2

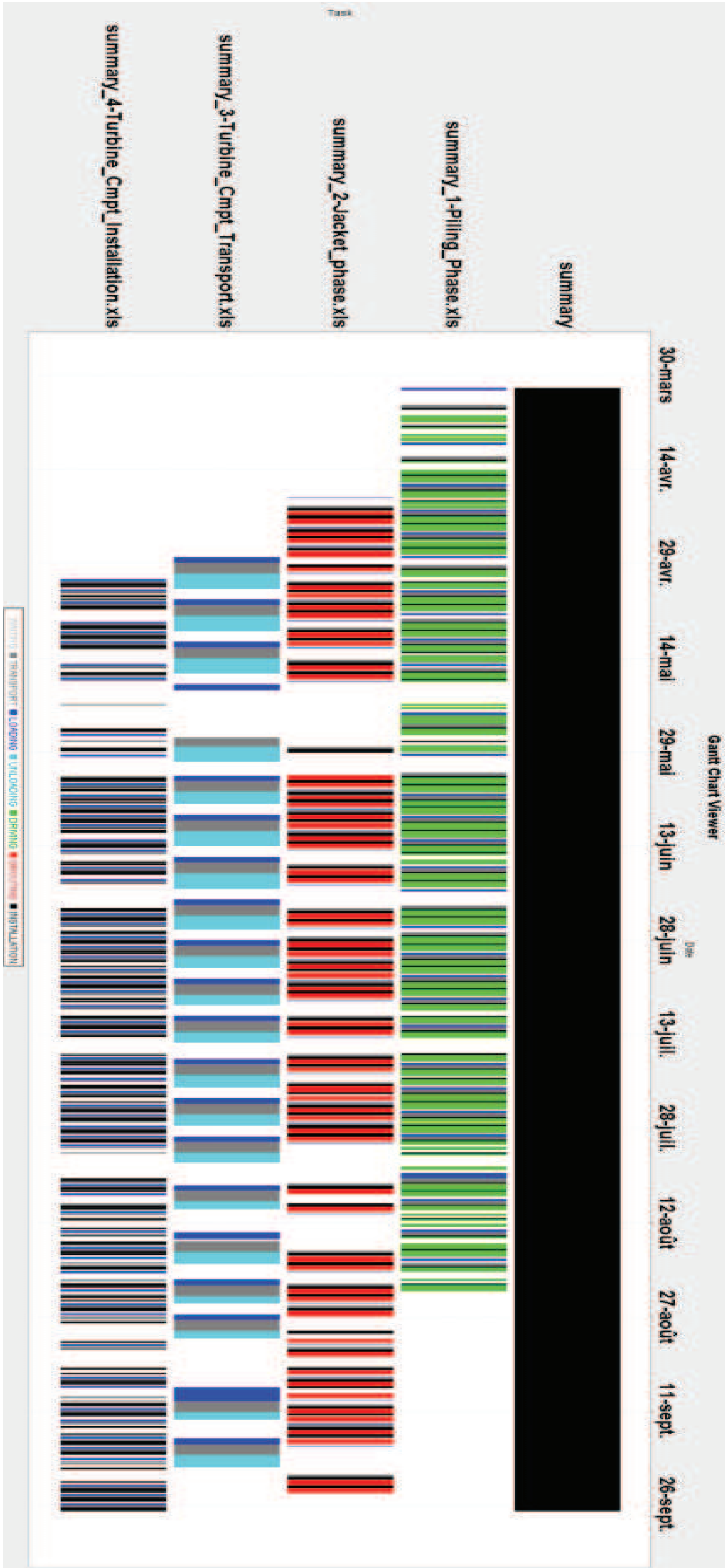
Gantt chart for distance 2=5km



Gantt chart for distance 2= 95km

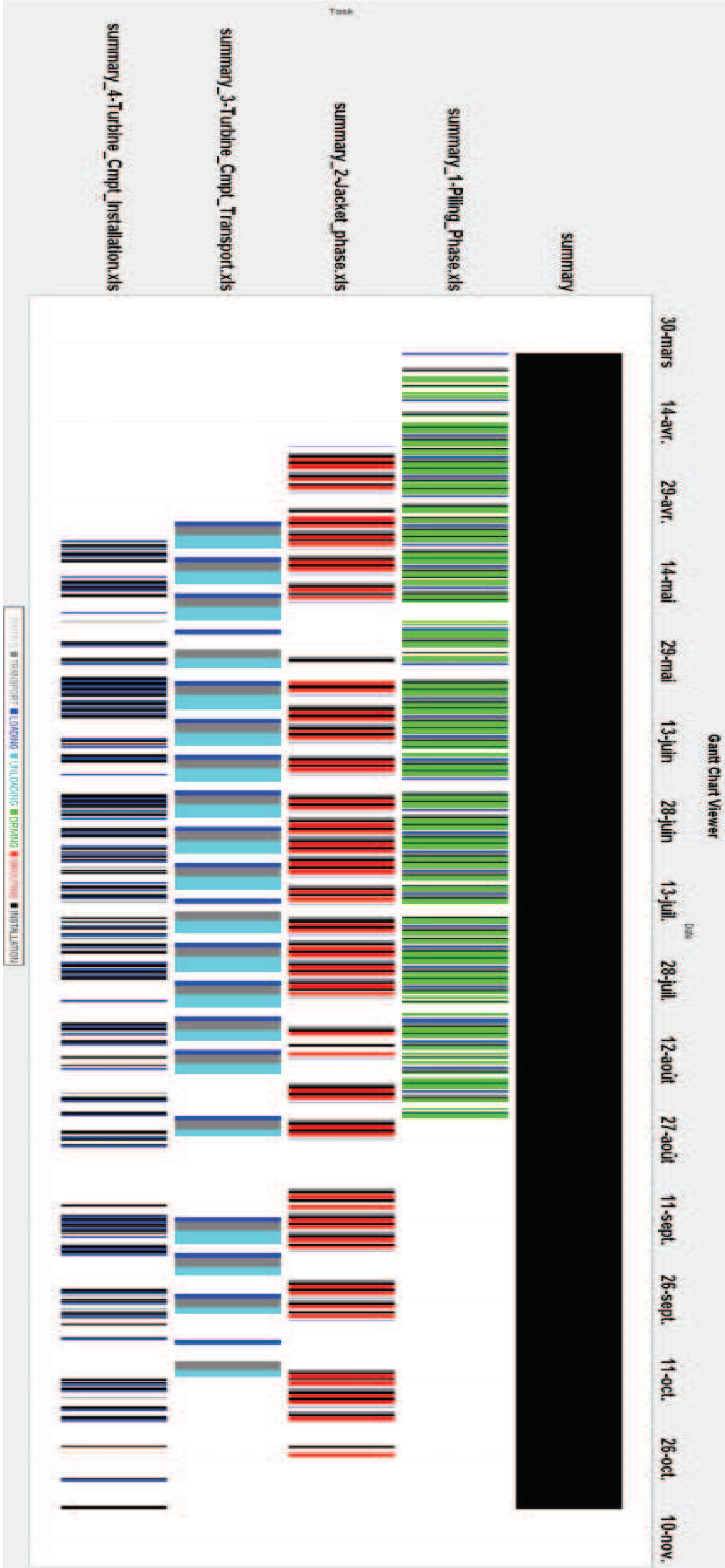


Gantt chart for distance 2=100km



Annex_D: Gantt charts for distance 3

Gantt chart for distance 3=5km



Gantt chart for distance 3=105km