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Interreg
North Sea Region
Decom Tools
European Regional Development Fund
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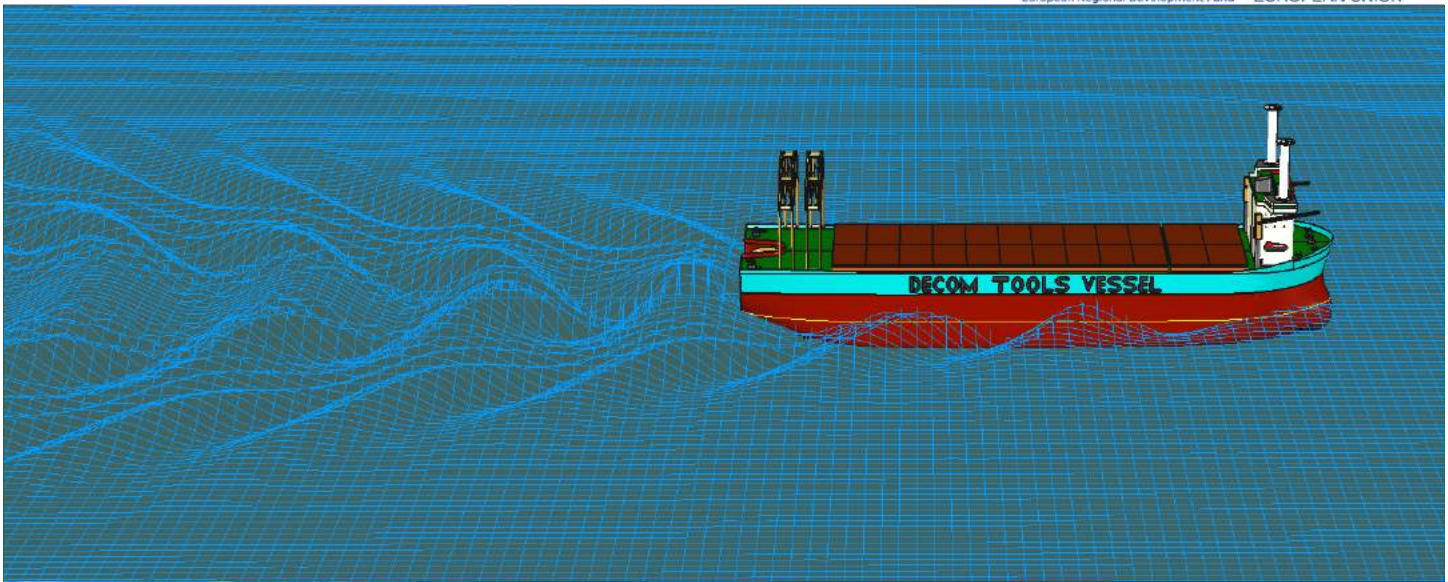

Decom Tools Vessel Design

Presenting an Ecco-Sustainable Approach to Decommission Offshore Wind Parks by Designing a New Ship, New Tools and Efficient and Reliable Procedure

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List of Abbreviations

No.	Abbreviation	Description
1	A&R	Abandonment and Recovery
2	AC	Alternating Current
3	AHT	Anchor Handling Tug
4	BDC	Bottom Dead Center
5	C/B	Cargo Barge
6	C/V	Cargo Vessel
7	CLV	Cable Laying Vessel
8	CO	Carbon Monoxide
9	CO_2	Carbon Dioxide
10	COG	Centre of Gravity
11	CPP	Controllable Pitch Propeller
12	CR	Control Room
13	CRP	Contra-Rotating Propeller
14	CTV	Crew Transer Vessel
15	DC	Direct Current
16	DGPS	Differential Global Positioning System
17	DP	Dynamic Positioning
18	DWT	Deadweight Tonnage
19	ECA	Emission Control Area
20	EEDI	Energy Efficiency Design Index
21	EEXI	Energy Efficiency Existing Ship Index
22	EEZ	Exclusive Economic Zone
23	ELT	External Lifting Tool
24	ES	Full-Electric Ships
25	GB	Gravity Base
26	GHG	Greenhouse Gas
27	GBS	Gravity Base Structure
28	GT	Gross Tonnage
29	H.P.R.S	Hydroacoustic Position Reference System
30	HES	Hybrid Ships
31	HFO	Heavy Fuel Oil
32	HLC	Heavy Load Carrier
33	HLV	Heavy Lift Vessel

34	ICPC	International Cable Protection Committee
35	IGF	The International Code of Safety for Ships using gas or other low-flashpoint fuels
36	ILT	Internal Lifting Tool
37	IMO	International Maritime Organization
38	JU	Jack Up
39	LARS	Launch and Recovery System
40	LBP	Length between perpendiculars
41	LNG	Liquefied natural gas
42	LOA	Length Overall
43	LS MGO	Low Sulfur Marine Gasoil
44	LSA	Life-Saving Appliances
45	MARPOL	International Convention for the Prevention of Pollution from Ships
46	MDF	Marine Diesel Fuel
47	MGO	Marine Gasoil
48	MGR	Marine Growth Removal
49	MP	Monopile
50	NOx	Nitrogen Oxides
51	OEM	Original Equipment Manufacturer
52	OWF	Offshore Wind Farm
53	OWP	Offshore Wind Park
54	OWT	Offshore Wind Turbine
55	PHES	Plug-In Hybrid Ships
56	PM	Particulate Matter
57	PPE	Personal Protective Equipment
58	PS	Port Side
59	PSL	Permissible Surface Load Per Area
60	PTI	Power Take In
61	PTO	Power Take Out
62	PV	Photovoltaic
63	ROV	Remotely Operated Vehicle
64	SEEMP	Ship Energy Efficiency Management Plan
65	SimOps	Simultaneous Operations
66	SOLAS	International Convention for the Safety of Life at Sea
67	SOx	Sulphur (Sulfur) Oxides
68	SPMT	Self-Propelled Modular Transporter

69	STBD	Starboard Side
70	SWL	Safe Working Load
71	T&I	Transportation and Installation
72	TDC	Top Dead Center
73	TP	Transition Piece
74	TPC	Tons per Centimeter
75	VLCC	Very Large Crude Carriers
76	VLFSO	Very Low Sulfur Fuel Oil (VLSFO)
77	VSP	Voith Schneider Propeller
78	WOC	Waiting on Client
79	WOW	Waiting on Weather
80	WT	Wind Turbine
81	WTIV	Wind Turbine Installation Vessel

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Definition

Vessel:

Vessel is a catch-all term, like 'watercraft', which describes any floating object used for the carriage of people or goods. It can be barge, ship, tug, mobile offshore unit, crane vessel or other ship-shaped unit involved in a marine operation (DNV.GL 2016).

Boat and Ship:

Generally smaller and less complex vessels are 'boats", whilst larger and more complex vessels are "ships".

Relevant types of boats in this study are as following:

- Tugboat,
- Crew boat,
- Anchor handling tug etc.

Barge:

A large flat-bottomed towed or self-propelled pontoon used mainly for river, canal and transport of heavy goods or bulk cargo.

Heavy Lift Vessel:

In this document heavy lift vessel is the vessel which is equipped with crane with high lifting capacity (normally the crane with SWL of > 1000 tones). In some cases, this type of vessel is called crane vessel.

Installation Vessel:

In this document the installation vessel and construction vessel have same function. Therefore, these terms are used interchangeably. They can be wind turbine installation vessel, jack up with heavy lift crane or heavy lift vessel.

Heavy-Lift Carrier[1]

General cargo ship with cargo hold(s) and cargo handling gear (cranes, derricks) giving a single lift of minimum 100 tons SWL.

[1] http://forum.shipspotting.com/index.php?topic=12365.0;wap2

1. Decommissioning and Decom Tools Project

1.1 Introduction

This research has been conducted as a part of curriculum of two master students, Namely Hamed Askari and Ahmad Halimah during their education for the Master of Maritime Operations at University of applied science Emden/Leer. The research has been undertaken to accomplish some of the objectives of Decom Tools project which is about decommissioning of offshore wind parks (OWP) in the North Sea Region. The finding of this study reveals that one of the bottlenecks in the decommissioning of offshore wind parks is lack of suitable cargo vessel to transport the wind turbine components from offshore site to port or vice versa. This omission to have suitable vessels compel the main contractors of this industry to use a construction vessel as means of transportation and installation of wind turbines during installation of offshore wind parks. Therefore, the overall working hours of construction vessel which is relatively expensive machine contribute to increase the overall cost of project. Furthermore, enlarging the size of the installation vessel in order to carry more set of wind turbines makes this vessel to consume more fuels which lead to more emission and environmental impact.

Thus, after extensive and detailed investigation, the authors reach to conclusion that having a suitable cargo vessel in this industry can slash the overall cost of construction operations and mitigate the environmental footprint of decommissioning project significantly. The results of the primary research were enough cogent that persuade the authors to research more in this field. Then after reviewing specifications of various vessels in the oil and gas industry as well as wind industry[2] the vital parameters that a cargo vessel can have to improve the productivity and efficiency of the projects in terms of technical, financial and environmental perspective are discerned and identified. The result of this research is design of a multi-function and multi-purpose green vessel which can transport considerable numbers of various generations of wind turbines that pave the way for lower number of voyages, less working hours of equipment and crew and lastly less CO_2 emission. Not only the Decom Tools Vessel is planned to transport the materials, but also can it extract the monopiles, retrieve the cable, cut the blades, cut the transition pieces and remove the marine growth.

More importantly, the detailed offshore decommissioning procedures for disassembly and removal of offshore wind farm components are explained with drawing in chapter 6 of this document. During the course of this research, a myriad of meetings with different specialists of various industries namely the cutting companies, the engine designers, the solar and hybrid engineers, pumps manufacturer, crane manufacturer, oil and gas specialist, cable installation contractors, ship

[2] List of reviewed vessels is listed in the chapter 12.

brokers and so on have been held in order to conduct the research precisely that can have reliable output.

Not only the Decom Tools Vessel is a multi-function and multi-purpose vessel, but also it is a green and hybrid vessel in that it is equipped with wind assisted propulsion system, solar system and batteries. This state-of-the-art vessel can be used both for installation and decommissioning of offshore wind parks as well as serve the projects of oil and gas industry. The designed vessel allows to cut the blades into the small pieces during voyage without spreading the dust resulted from cuttings which means protecting the workers and environment from harms of this non-recyclable materials. More importantly, the vessel has pile extraction system which enables the contractors to entirely extract the (mono)piles from the seabed without generating noise which prevent harms to the mammal and sea species. A couple of sets of grippers are designed as part of the Decom Tools vessel which can hold the large-sized monopile and transition piece for further removal and extraction operation. Not only do the grippers extract the mono(pile) but also the vessel can maintain the position by the grippers during the course of offshore operations.

Furthermore, the automatic and manual marine growth system is engineered and incorporated as a part of this vessel to overcome the hurdle of fouling removal.

Equally significant, the Decom Tools vessel can retrieve and extract the submarine power cables with some basic and widely available machineries. The current practice and proposal of majority of the offshore wind parks developers is to leave the cables in-situ after the lifespan of offshore wind farm. Keeping any materials in the field, notably submarine cable, may cause technical, financial and legal issues in the long run. To tackle this problem, a cable retrieval system with a simple and proper procedure along with cutting mechanism are designed. Implementing this system and following the procedure help the contractors to retrieve the cables from seabed, cut them into the small pieces, marshal and ultimately transport them safely.

1.1.1 Decom Tools Project

Since the offshore wind energy is a nascent industry, the omission or oversight to devise the coherent strategy to decommission the offshore wind parks from the early stage of the design (development phase) did not take into consideration. Therefore, the project by the name of Decom Tools has been defined by a consortium including 14 companies and organizations[3] which will issue the deliverables to the Interreg for the North Sea Region. The Decom Tools project contains

[3] For more information please refer to Decom Tools Website with following link: https://northsearegion.eu/decomtools/

seven (7) work packages which under each of them different partners cooperate and work in order to fulfil the requirements of the project. The main objectives of the project are as following:

1. Reduce the overall costs of decommissioning of an OWF by 20%.
2. Mitigate the CO_2 emission by 25%.
3. Increase the overall safety of operations and,
4. Increase the know-how and expertise of involved stockholders in the region.

To attain these objectives, a comprehensive study regarding installed wind farms, the supply chain and logistic, offshore and marine operations and port and onshore process should be carried out to find the bottlenecks and the variables that can be optimized.

These targets can be accomplished by optimizing the engineering, appropriate project management, introducing new concepts and equipment including designing of new tools to improve the overall operations, logistic and supply chain.

Under work package four (4) of the project new tools and vessel can be introduced in order to fulfil the objectives of the project. In addition, one of the deliverables of work package five (5) is assessment of offshore logistical requirement. Furthermore, study of recycling concepts should be undertaken under work package six (6).

This document contains three different end results and upshots namely a new multi-function and multi-purpose green vessel, a couple of new tools such as gripper, adjustable and reusable seafastening for blade and blade cutting tool as well as reliable and safe procedures for offshore decommissioning.

1.1.2 Contribution to the Decom Tools Project

In this research the authors, made tremendous effort to fill the existed industry gap between the wind turbine manufacturer and installation contractors by designing a new multi-function and multi-purpose green vessel, new tools and reliable and safe procedure. Specifications of the vessel has been defined by studying various generations of wind turbines, the specifications of the offshore wind parks (OWP) in the region, development of the industry during last decades and new coming generation of wind turbines. With regards to the Decom Tools projects objectives, the vessel is equipped with the latest available technologies and many innovative tools which new procedures can be defined for decommissioning operations. Thus, in the second chapter a thorough study has been conducted on the installed OWP in order to see the magnitude of the decommissioning market, to see the specifications of the offshore wind parks in order to make the best possible decision and design in terms of marine operation, logistic and recycling to optimize the cost, safety, environmental impact and so forth.

1.1.3 What Is the Definition of Decommissioning?

All the required operations to make the assets, in particular offshore wind park, inoperative disassemble, decontaminate, and recycle is called decommissioning. Decommissioning of offshore wind parks can have three different phases entailing pre-decommissioning, decommissioning (disassembly and removal) and post-decommissioning. Pre-decommissioning operations are the preparatory activities to make the site and assets ready for removal. Removal is the process of disassembly of the wind turbine, metrological mast, offshore high voltage substation and their associated support structure. Removal also includes recovery of cables from seabed. Post-decommissioning operations include all the activities after removal of mentioned materials to ascertain that the decommissioning has been conducted successfully according to projects documents and agreed codes and standards. Furthermore, after removal of materials from site, the responsible organization should be notified including hydrographic office and local organizations and authorities.

1.1.4 When to Decommission an Offshore Wind Park?

Every asset has a designed lifetime and economic lifetime which some certain measures need to be taken after these lifespans. The designed lifetime can be affected by a plethora of factors including but not limited to engineering, material selection, manufacturing process, quality of workmanship and material, installation process, weather/site condition, condition monitoring and maintenance and so on. The designed lifetime of asset normally is defined on the early stage of the project during engineering phase. It is defined "the time period that was considered for the strength verification when the device was designed" (DNV.GL 2016).

However, the economic lifetime can be assessed while the assets are in service. For instance, the designed lifetime of offshore wind parks is mostly between 20-25 years. If the operation and maintenance cost of assets are more than replacing the components, it means the assets are not feasible to maintain, then other scenarios will be studied such as lifetime extension, repowering and decommissioning. For instance, the onshore wind farms are repowered on average after 18 years operation (Komusanac 2020, 13). Besides, in some cases the maintenance cost is lower than above-mentioned scenarios, then lifetime extension[4] under certain circumstances can be undertaken. Figure 1-1 shows the definition of lifetime and lifetime extension. In such cases, the lifespan varies with designed lifetime which is called economic lifetime, operating life or service life of asset. This time is the lifetime from commissioning to decommissioning of a component or the wind turbine (DNV.GL 2016).

[4] Life-time extension can be conducted without replacement of component.

According to Figure 1-1, the term "total lifetime" is lifetime after manufacturing of the component or asset until de-construction (DNV.GL 2016).

In this document, the authors will presume that decommissioning is the main scenario after reaching the designed lifetime of asset.

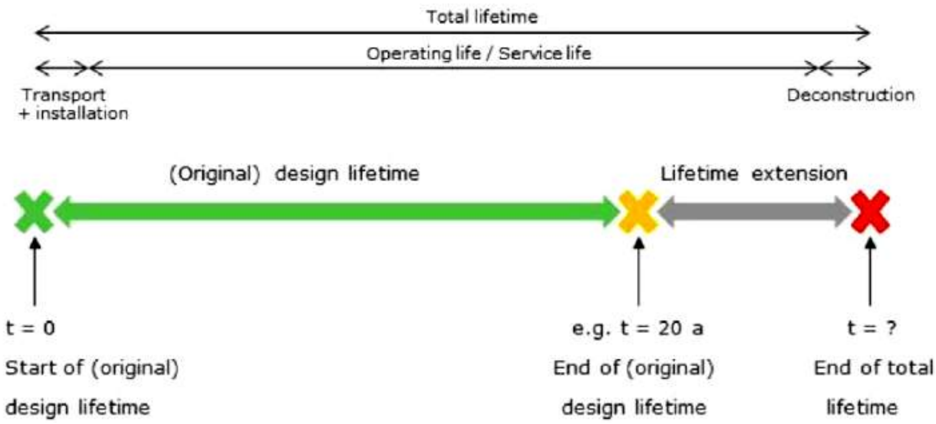


Figure 1-1 Definition of Lifetime & Lifetime Extension

Source: (DNV.GL 2016)

2. Facts and Figures on Development of Offshore Wind Parks

2.1 Market of Offshore Wind Energy

The European Union has a long-term commitment to reduce greenhouse gas emissions by 80-95% compared to 1990 levels by 2050. Wind energy is one of the key players to reach the EU's renewable goals (LEANWIND Consortium 2017). It means that more investment will be made on this industry and the development will not be stopped.

In December 2013, the Levelized Cost of Energy (LCoE) for offshore wind energy was €140/MWh. Vattenfall's offshore wind price bid of €49.9/MWh in 2016 for the Kriegers Flak project. In 2019, the Dutch Government has awarded Vattenfall in a tender to develop the twin Hollandse Kust Zuid offshore wind farms to be built by 2022 without public subsidy. One can come to conclusion that two different factors lead to such reduction in LCoE. On one hand the technological advancement in this industry including development of original equipment manufacturer (OEM), enhancement of supply chain, innovation of new equipment and tools reduced the LCoE which means the wind turbine manufacturers, logistic companies and others involved companies made tremendous efforts and investment for this achievement.

On the other hand, the decision makers exhort the industry for this stride by introducing subsidies, decarbonization incentives and so forth. With regards to above measures, the installation of offshore wind farms soared in the last decades.

Evidently, the more installation necessitates more decommission in future. Therefore, not only should the industry have outlook to the design and development of offshore wind parks, but also should consider the decommissioning from early stages of the design of OWF.

2.2 Statistic of Offshore Wind Parks in Europe

In this chapter, the main focus is to introduce some major specifications of installed offshore wind parks across the Europe, notably, in the North Sea region in order to show how this nascent industry has been developed up to date[5]. However, before showing the stride of the wind industry during last two decades, the regions that the most installation of offshore wind parks took place across Europe until January 2021 is shown in the Figure 2-1. Figure 2-1 shows the cumulative offshore wind energy installation in four (4) different regions. Referring to Figure 2-1, the most installation executed in the North Sea Region (79% of installed wind farms) which means this area is favourable and strategic region for the investors due its resources and valuable geographical location in terms of potential to capture the wind energy and electricity transmission. In 2019, all the wind park installation took place in the North Sea Region except the 33MW wind farm installed in the Atlantic Ocean (WindEurope 2021).

[5] December 2020

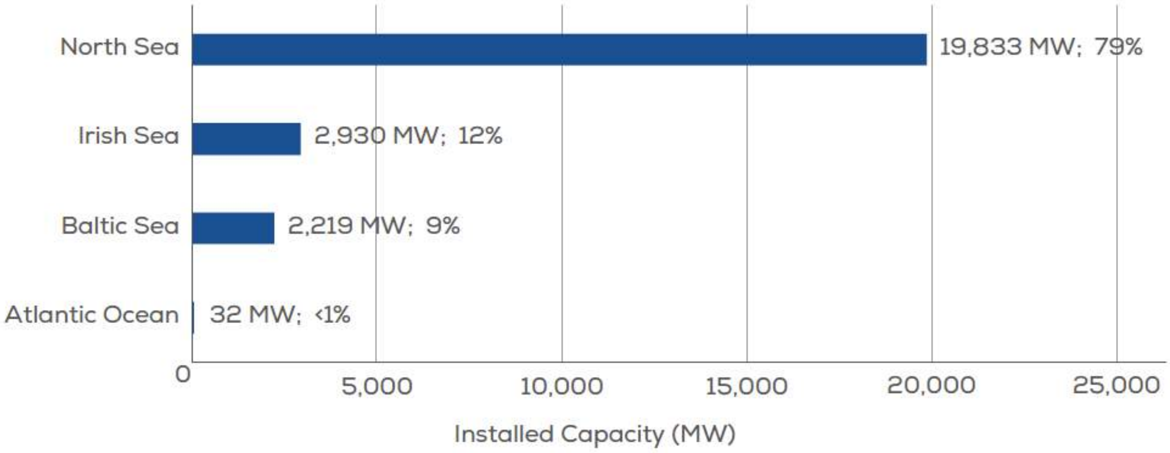


Figure 2-1 Cumulative Installation of Offshore Wind Parks Across EU

Source: (WindEurope 2021)

2.3 Installed Wind Farms and Decommissioning Prediction

It is necessary to assess what will be the status and magnitude of market of decommissioning of OWPs in near future in the North Sea Region. One study has been conducted under work package three (3) of Decom Tools project and the predicted finding shows when the wind farms will need to be decommissioned in near future based on their lifetime (20 years lifetime is considered). Figure 2-2 depicts the expected year of decommissioning of offshore wind parks in North Sea Region for the next 18 years. As it shows, until 2038, the highest demand for decommissioning of offshore wind farms will be in 2030. However, until 2030, approximately 400 numbers of offshore wind turbines need to be decommissioned.

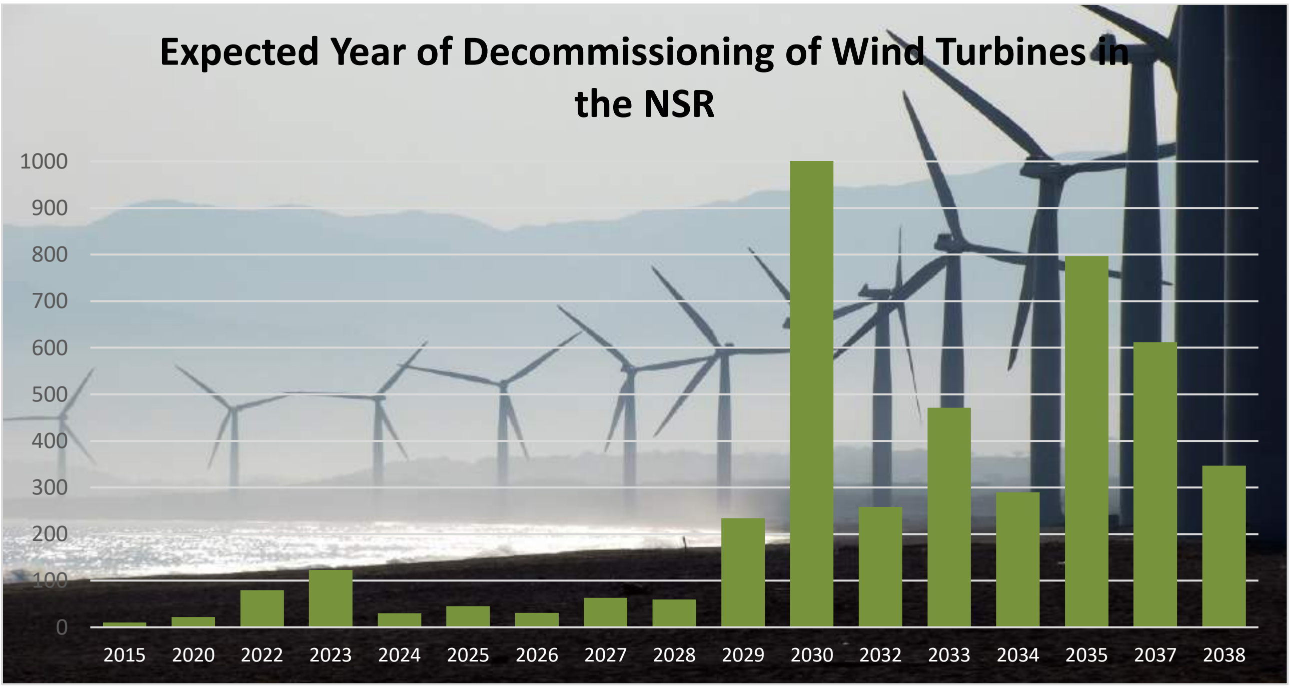


Figure 2-2 Expected Year of Decommissioning of Offshore Wind Turbine In North Sea Region

In order to predict what is the market of decommissioning of offshore wind parks in each country across the Europe, it is logic to see when the installation of infrastructure did take place. In 2019, just 502 new offshore wind turbines across 10 wind parks are connected to the grid in the Europe. In 2020, 356 numbers of offshore wind turbines are connected across nine wind farms across the Europe.

Europe now has installed 5402 number of offshore wind turbines with total capacity of 25,014 MW. There are now 116 offshore wind farms in 12 European countries

According to Figure 2-3, UK has the largest amount of offshore wind capacity in Europe, with 42% of all installations. Germany is second with 31%, followed by Netherlands (10%), Belgium (9%) and Denmark (7%) (WindEurope 2020). Furthermore, it illustrates the cumulative installed number of wind turbines as well as overall production capacity of offshore wind farms in the five (5) European countries (WindEurope 2020). 2294 number of wind turbines installed in the UK followed by 1501 in Germany. To put it more simply, the market of decommissioning will be bigger in countries that have more wind farms which means UK, followed by Germany, the Netherlands, Belgium and Denmark respectively.

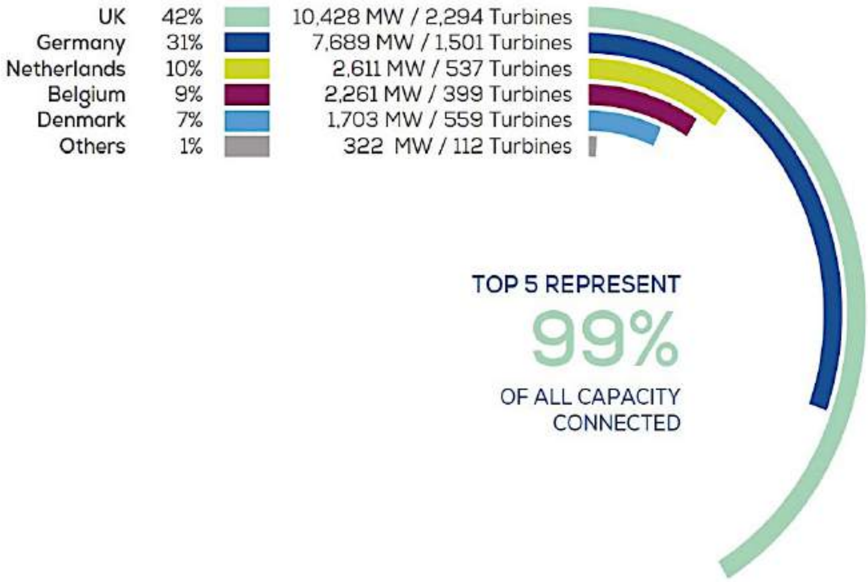


Figure 2-3 Overall Installed Offshore Wind turbine and Production Capacity in EU

Source: (WindEurope 2021)

Referring to the Figure 2-4, the maximum power installed by offshore wind industry conducted in 2019. It means that highest decommissioning will take place on 2044, if the economic lifecycle[6] of offshore wind parks is 25 years.

[6] Designed lifecycle of offshore wind turbines is between 20-25 years, depends on manufacture engineering. But sometimes, the wind turbine can work more depending on their health situation which is depends on a multitude factor. However, it is possible that due to depreciation of wind turbines, it is not economic to maintain and keep the wind turbine until their designed lifecycle. Therefore, the developers may prefer to install new set of wind turbine.

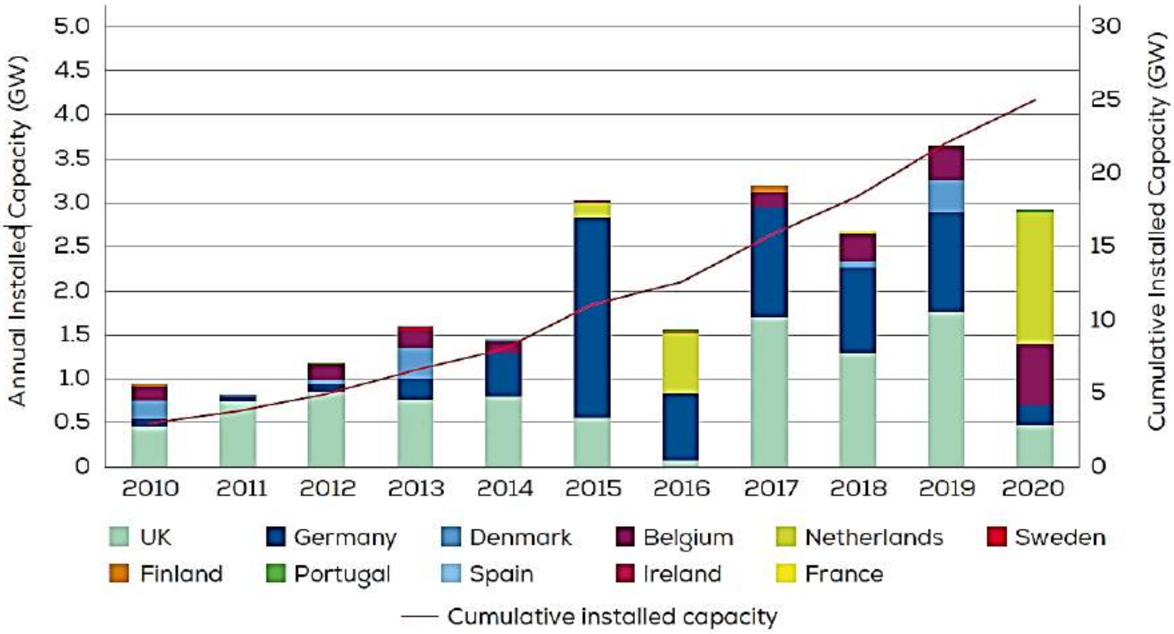


Figure 2-4 Annual Installed Offshore Wind Parks Based on Capacity (GW) in EU

Source: (WindEurope 2021)

2.4 Size of Installed Wind Turbine & The Most Installed Size

The output power of wind turbine has direct correlation with the size of wind turbine. The more output means larger and heavier wind turbine. One can understand the development of offshore wind energy industry in the Figure 2-5 in terms of production output. The mentioned figure depicts that the average output of installed wind turbine in 2009 is about 3MW and the installed wind turbine in 2020 has the average output of 8.2MW approximately (WindEurope 2020). However, it should be noted that Siemens Gamesa unveiled the 14 MW wind Turbine and the GE installed two 12MW wind turbines with the rotor size of 220m in the Rotterdam port as well as Blyth in order to get certificate for further installation in other offshore wind parks.

It is evident that larger wind turbines and wind parks necessitate larger equipment for handling, transportation and installation. It requires more complex logistics and management. It can be seen that many of the installation vessels including wind turbine installation vessel (WTIV) and other type of installation vessels are not capable to install the recently launched extra-large wind turbine. It is clear that wind turbine manufacturers are ahead of transportation and installation (T&I) contractors. In other words, heftier turbines are launched every year to the market, but vessels to install the large-sized wind turbine come to the market with delay which exhort and force the industry to hire the vessels from oil and gas industry or change the installation method such as fabrication of wind turbine's tower in multiple segments. Downsizing of component is not an appropriate method for installation of large-sized wind turbine since it is possible just to downsize some components of the wind turbines such as tower. By downsizing the components, the number of offshore and onshore lifts will be increased which means more duration of offshore operations which lead to higher installation cost and CO_2 emission eventually. All in all, lack of suitable vessels for transportation and installation of new generation of wind turbines limit the developers in sense of selection of vessels and contractors.

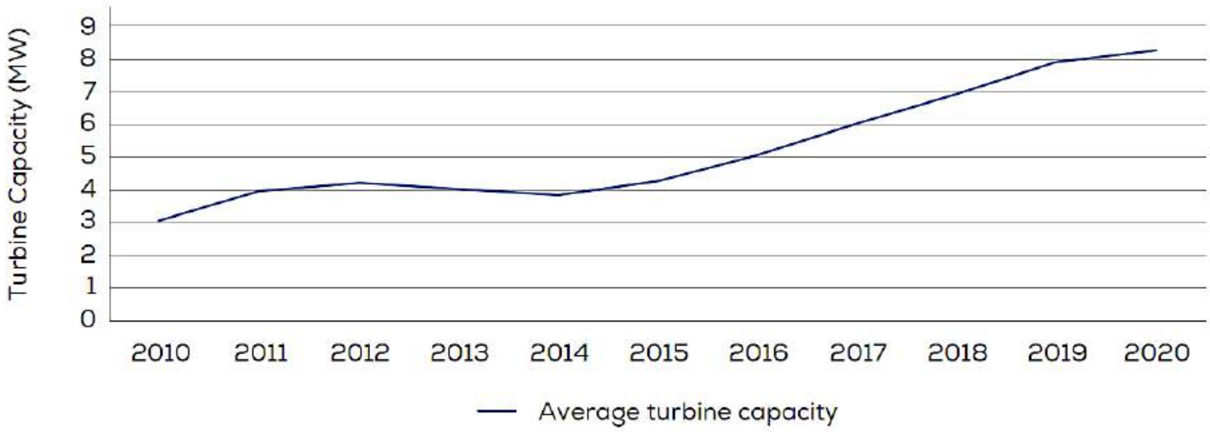


Figure 2-5 Average Output of Installed Offshore Wind Turbine From 2009 to 2019 in EU

Source: (WindEurope 2020)

Table 2-1 shows the most installed offshore wind turbine so far.[7] According to table 1, in the North Sea Region, 5 MW wind turbine is the most installed size of offshore wind turbine following by 6MW /6,15 MW /6,3 MW and 3,6 MW. Having considered that the most installed wind turbine is 5MW, then authors mainly focused to show how many numbers of 5 MW and 3.6 MW wind turbine can be transported by this vessel (Decom Tools Vessel).

However, the vessel that we are going to present in this document is not limited to the installed wind turbines, but also it can provide service to the extra-large wind turbine such as new 12MW GE wind turbine.

Table 2-1 Most Installed Wind Turbine Size in North Sea Region

Sr.	Output of Wind Turbine	Number of Installed WT	Remark
1	5 MW	1462	
2	6 MW & 6.15 MW & 6.3MW	1299	775 No. of 6MW, 377 No of 6.15MW 147 No. of 6.3 MW
3	3.6 MW	829	

[7] The reference for this data is 4C Offshore

2.5 Depth and Distance of Offshore Wind Parks

Not only does the number and size of installed wind turbines increased during last decades, but also the distance of offshore wind parks from the shore increased and eventually the water depth increased. The average distance to shore 52 km and water depth 44 m continue to increase even though most wind farms are bottom-fixed (WindEurope 2020). There exist a couple of reasons for installation of wind parks further which one of them is more energy can be harvested in deeper water[8] (Equinor n.d.) also intrusive vision is another issue.

Figure 2-6 shows the average distance of the installed offshore wind parks to shore. It shows the most wind farms in 2000 were installed close to shore but in 2020 the average distance of OWP from shore is about 52 km. Distance of OWP from shore play a colossal role in the cost of decommissioning and CO_2 emission. The larger distance requires more sailing time for all type of involved vessels such as cable laying vessel, heavy lift vessel, transportation vessel, crew boat etc. which lead to more fuel consumption and ultimately more CO_2 emission. Furthermore, the higher wind speed in the offshore wind park result in bigger motion of vessel which may cause the vessel unable to operate in that weather condition (more vessels stand-by).

All in all, the development of wind farms further offshore in deeper water requires advances in both turbine foundation technology and the vessels required to construct, service and decommission these wind farms (LEANWIND Consortium 2017).

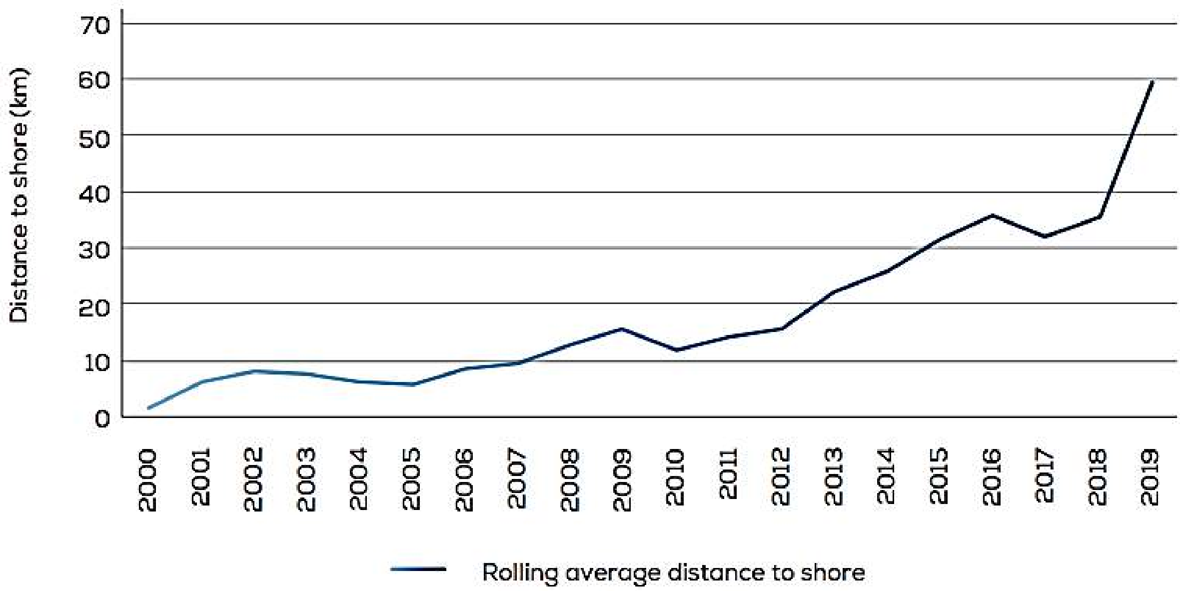


Figure 2-6 Distance of Offshore Wind Park from Shore Between 2000 to 2019 in EU

Source: (WindEurope 2020)

8 Winds are stronger and more consistent further out to sea. Close to 80% of the world's offshore wind resource potential is in waters deeper than 60 meter (Equinor n.d.)

2.6 Types of Installed Structures

The installation of foundations can be taken place in two different methods including floating and bottom fixed foundation. Figure 2-7 shows the various type of installed foundation. So far, low number of wind turbines are installed with floating foundation. Furthermore, monopiles remain the most installed foundation, with 4681 units (81.2%) up to date [9]. Monopiles are likely to remain the most preferred option in the future (LEANWIND Consortium 2017) (Gavin and Doherty 2012). Figure 2-7 demonstrates all foundations installed with and without grid connection. The jackets share (9.9%, 568 number), Gravity base (5%, 289 number), tripod (2.2%, 126 number), and tripile (1.4%, 80 number) follow the cumulative share. Having considered above data, the intention of authors is to focus on monopile structure as well as jacket foundation. Therefore, the finding of this research is based on monopile, however, the vessel is multi-purpose and can be used for other types of foundations such as jacket, tripile and tripod.

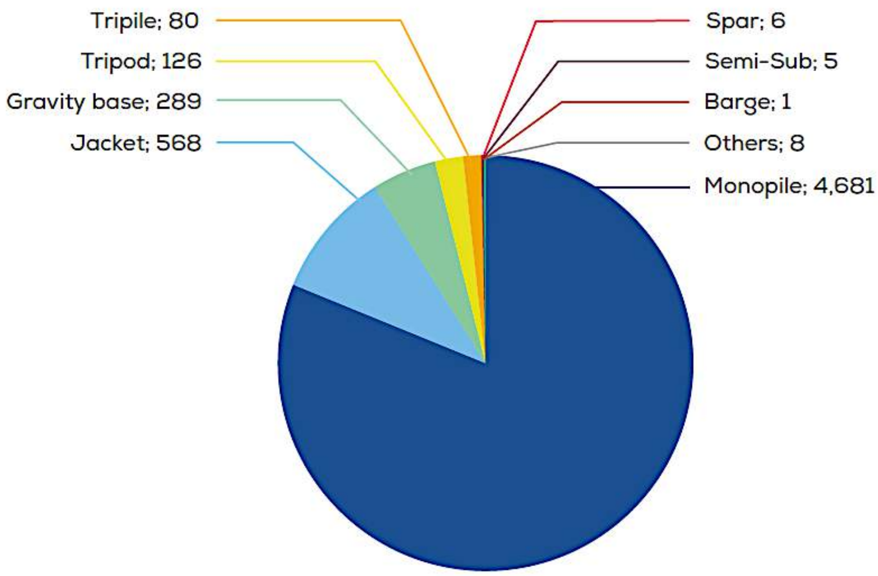


Figure 2-7 Installed Various Offshore Wind Turbine Structure in EU

Source: (WindEurope 2020)

In this chapter, the specification of offshore wind parks such as size, number of installations, distance to shore, water depth and so forth was explained. In order to conduct decommissioning a comprehensive study on the existing wind farm should be undertaken in order to do the best possible design and engineering. Furthermore, the development and installation of offshore wind farms were addressed which can show the market of decommissioning in futures across the European countries.

[9] Until February 2012

2.7 Summary

- Wind energy is under development at a fast-paced.
- North Sea is the most favorable and strategic location for wind industry and overwhelming majority of wind farms are installed in the North Sea region.
- The turbine manufacturer launches bigger and heftier turbine every year. The average rated capacity of turbines installed in 2020 was 8.2 MW (and was 8 MW in 2019).
- Regardless of enlargement of wind turbine, yet monopile structure is the most suitable and reasonable choice.
- The distance of offshore wind farms from shore is getting far and far (in 2020 average is 52km).
- The water depth of newly selected sites is considerably deeper than last decade (in 2020 average is 42m and the average water depth in 2019 was 39 meters).
- 5MW turbine is the most installed wind turbine size in the North Sea region.
- It is expected about 400 numbers of wind turbines will be decommissioned in 2030, if either lifetime extension or repowering does not occur.
- Peak of decommissioning operations will be in 2030 having considered above-mentioned conditions.

2.8 Conclusion

- Strategies for the decommissioning should be devised from early stage of wind park design.
- Required methods and equipment for decommissioning of brown field site which need to be decommissioned in near future should be devised soon.
- With regards to technological advancement in manufacturing and installation of wind turbines, the supply change, the equipment manufacturer and so on, the decommissioning program should be in a way to cover mostly all wind farms specifications (vessels capable to disassemble and or transport all size of wind turbines or work in wide range of water depth and so forth). From a structural perspective, the priority is to design equipment and methods for removal of monopile foundation.
- Most of jack up vessels can work in the depth of to 50 meters.
- Long-term plan should be devised for the peak of decommissioning 2030. It means that installation and transportation contractors, labours training, recycling companies, ports etc. should invest and prepare their business for the peak of decommissioning time.

3 Logistic Strategies

3.1 Offshore Logistics Management

In installation of offshore wind parks various types of vessels are used which each of them has specific purpose. For instance, there are various types of installation vessel including heavy lift vessel (HLV), semi-submersible vessel, jack up installation vessel- normally called wind turbine installation vessel (WTIV) which are used for the installation of offshore structures including wind turbine, wind turbine support structure, offshore high voltage substation (OHVS) etc. Moreover, there are cargo vessels, barges, and heavy load/lift carrier for transportation of components. In addition to the transportation and installation vessel, other types of vessels including cable laying vessel (CLV), tugboat, anchor handling tug (AHT), crew boat or crew transfer vessel (CTV), survey vessel, supply boat etc. need to be involved during different phase of project.

The omission to design and construct a suitable transportation vessel for this industry, in particular, the new developed large and extra-large wind turbines can be seen in the wind industry. Therefore, in this document a multi-function and multi-purpose green vessel according to installed wind turbines (current market) and future extra-large wind turbines (future market), specifically, Heliad-X 12 MW GE wind turbine has been designed. The designed vessel fulfils the demands of this industry both during installation and decommissioning operations. The vessel is primary a transportation ship (or cargo vessel (C/V) or Heavy Lift Carrier Ship (HLCS) which can be used for transportation of offshore wind turbine components from wind farm to shore or vice versa. However, it has several functions which one of its functions is transportation. It can extract the monopile, remove the transition piece and more importantly retrieve the submarine cables. However, adjustable seafastening and cutting tools for the blades as well as automatic marine growth removal system are designed as part of this research. The procedure and functions of the vessel are described with necessary drawings under chapter 6 Offshore Operation Manual of Decom Tools Vessel.

This unique vessel is equipped with wind assisted propulsion system (tiltable Flettner rotors), solar system, batteries and LNG-powered engines (dual fuel engines) to have minimum environmental impact and higher efficiency during operation. Furthermore, the gripper system allows the vessel to maintain the position without using the DP system which reduce the fuel consumption and ultimately the emission.

One of the major cost drivers in the decommissioning of offshore wind parks is marine operation which is discussed in the next sections. Consequently, any optimization in this part of the decommission operation will impact the overall cost of project as well as influence the environmental footprint.

Figure 3-1 shows the various activities for decommissioning of an offshore wind parks. The activities inside red sections are influenced and optimized by finding of this research.

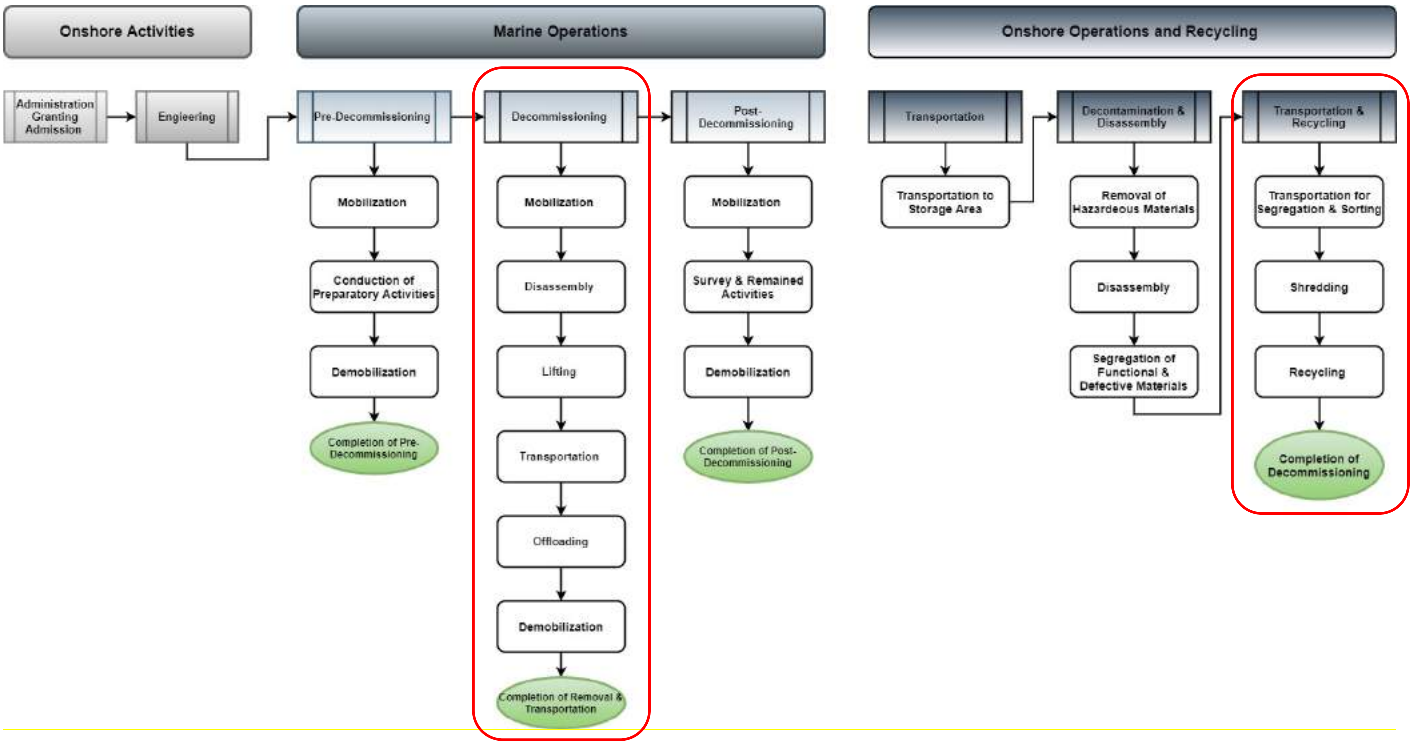


Figure 3-1 Overall Phases of Decommissioning of an OWP

3.2 Logistic Configurations in The Installation of Oil and Gas Structures

There are some similarities in transportation and installation of offshore oil and gas structures and wind industry which this nascent industry can take the advantage of experience and lesson learnt of oil and gas industry which is mature industry. Consideration should take into account that in the Oil and Gas field development, maximum a couple of structures are installed in one field whereas in the wind industry, in some fields, over 100 structures are installed (like Anholt wind farm, Hornsea 1 and so on). This difference impacts the overall engineering including logistic strategy, supply chain, and management of the project.

In overwhelming majority of installation project in oil and gas industry, a vessel which is normally a none-propelled barge are used for transportation of oil and gas structure from fabrication yard to the site and one installation vessel which mostly is a heavy lift vessel (HLV) is used for lifting, and installation of the module (please refer to Figure 3-2). This combination of the fleet which is called feeder configuration is the most prominent combination of fleet in the oil and gas industry. However, there exists some vessel such as Pioneering Spirit[10] which is capable to transport and

[10] https://allseas.com/equipment/pioneering-spirit/

install the structure in one campaign. The structure can be loaded out from fabrication yard to this vessel, it transports the structure to the field and install it in one campaign. It means that transportation and installation take place with one vessel in one campaign (please refer to Figure 3-3). It should be noted that this heavily depends on the size of structure, the deck space and deck loading capacity of the vessel. There are not so many similar vessels in the market across the world to transport and install the oil and gas module the same as Pioneering Spirit.

Figure 3-2 The Jacket is loaded onto the C/V and Tied up to the HLV

Figure 3-3 Topside is Loaded onto the Pioneering Spirit

3.3 Common Fleet In The Installation of Offshore Wind Park

In the installation of offshore wind parks various fleet with different specification can be used. It is evident that each type of the vessel has specific mission and purpose during the installation or decommissioning of project.

Main fleets involved in installation of an offshore wind park are installation vessel (sometimes the term construction vessel is used interchangeably), transportation vessel (such as Heavy Load/lift Carrier (HLC)) and cable laying vessel. In this document, the authors do not take into account the required fleets for the pre-installation operations, post installation operations and marine spread fleet. Ergo, just removal and transportation of wind turbines has been addressed in this document. Project's specifications (the specification of wind farm) require which type of vessels need to be employed for the marine operations. However, in many cases the nominated vessel demands other types of vessels (logistic configuration and vessel type) for the successful completion of the installation/decommissioning phase of the project. For instance, if the installation vessel is equipped with mooring system (it is not DP vessel), anchor handling tug (AHT) is needed to carry out the anchor running. Therefore, the combination of required fleet for transportation and installation of offshore structures depends on a number of parameters which are discusses in further section mainly under section 3.10 of this document.

Table 3-1 shows 4 different types of vessels which can be used for lifting, installation, or disassembly of wind turbine components. The second row shows dependency of the various types of vessels. As an example, if for the decommissioning of a wind farm, a non-propelled jack up vessel is used, the contractor needs to mobilize survey vessel and tugboat(s). The most independent vessel for the lifting operation is a DP floating vessel.

Table 3-1 Dependency of Various Types of Vessels

Sr	Vessel Types	I	II	III	IX
		DP Floating HLV	**Mooring Floating HLV**	**Jack-up Vessel with DP**	**Non-propelled Jack-up Vessel**
2	**Dependency on other fleet(s)**	Independent	1. AHT[11] 2. Tugboat	1. Survey vessel[12]	1. Survey vessel 2. Tugboat

In the next sections (time-cost-emission analysis) we will show how much this independency impact the project cost, fuel consumption as well as CO_2 emission.

[11] (Anchor Handling Tug) AHT is needed for deployment of anchors

[12] The location where the spudcans have to penetrate into seabed need to be surveyed in order to see how the condition of seabed is to make sure jacking will be done safely.

3.4 Types of Vessels (Common Fleet Types)

As it stated earlier, in any offshore construction operation, various types of vessels need to be employed in order to execute the operation completely according to the common practice and in compliance with national and international regulation. They are namely construction or installation vessel, cargo vessel or heavy load carrier, crew boat, tugboat, anchor handling tug (AHT), offshore support vessel (OSV), diving support vessel (DSV) and cable laying vessel (CLV). Obviously, the project demand specifies which of above-mentioned vessel are necessary for the operations. In the following, some of the common fleet types in offshore wind industry are explained.

3.4.1 Installation (Construction) Vessel

The installation vessel mostly has been used to lift and install the foundation, transition pieces, tower, nacelle, rotor and OHVS. With regards to the operation that vessel have to undertake, they should have some certain specifications in order to install the wind turbine and foundation safely and successfully. One of the most important parameters is having a crane with enough lifting capacity (SWL)[13] and boom length. Hence, installation or construction vessel are normally heavy lift vessel (HLV) or jack up vessels, particularly, wind turbine installation vessel (WTIV) which are facilitated with heavy lifting crane.

From a propulsion system, it can be argued that in many cases, HLV or jack-up vessel are not equipped neither with propulsion system nor DP system. In this case, tugboat(s) should be used for towing the vessel to the location. For towing the construction vessels, some tugboat(s) with suitable bollard pull[14] need to be utilized in order to tow the vessel to the field. Depending on the following parameters one or a couple of tugboats are employed normally:

1. Met ocean condition during voyage including wind, wave, current etc.
2. Distance of field from port.
3. The size, draft and displacement of the construction vessel.
4. and bollard pull capability of tugboat (s).

Furthermore, anchor handling tug (AHT) is needed to position the vessels anchor (mooring system). Survey and positioning team are mobilized onboard anchor handling vessel in order to survey the location where the anchors have to be deployed. The engineering team normally make analysis and provide the document by the name of "anchor pattern" which shows the location that anchors should be deployed. Therefore, onboard AHT, survey and positioning team based on the drawing determines and survey the pre-defined location for the anchor running operation.

[13] SWL: Safe Working Load

[14] A measure of a vessel's ability to tow (DNV.GL 2016).

It is discussed that the day rate of the installation vessels is quite high. The followings are the factors that cause this day rate:

1. Existing of unique crane and lifting capacity onboard construction vessel (because of crane, the structure of vessel should be reinforced. Moreover, the margin of stability should be enough high that does not impact the overall stability of vessel during lifting operation)
2. Hight number of crew on board construction crew and high wage of construction crew, normally between 60 to 300 crew are onboard installation vessel)
3. The number of this type of vessels are low. These vessels are managed and owned by low number of companies, so, the market is not competitive for this type of vessels.

3.4.1.1 Jack-up Vessel

There exist mainly two types of Jack up vessel. The most common jack up vessel are non-propelled barge. In this type, according to Table 3-1, three different types of vessels need to be employed in order to make the barge ready for the lifting operation as following:

I. **Tugboat:** Tugboat(s) need to be hired for towing of the barge to the desired location.

II. **Survey Vessel:** Survey vessel is needed for the seabed survey where the spudcans (bottom of legs) need to penetrate into the seafloor.

The second type of jack up vessels are equipped with DP system. Obviously, this type of vessel does not need tugboat for towage operation since they are self-propelled.

It should be noted that the wind industry prefers to install the wind turbine components with jack-up vessel since they have more stable condition in the harsh maritime environment. When the legs of jack up vessel are penetrated into the seabed, all six vessels' motions such as heave, roll, pitch, yaw, sway and surge are eliminated. Therefore, the vessel behaves like a fixed structure in its position. Having this in mind, the vessel has higher stability with respect to floating vessel. Figure 3-4 shows the six degrees of motion of a floating vessel.

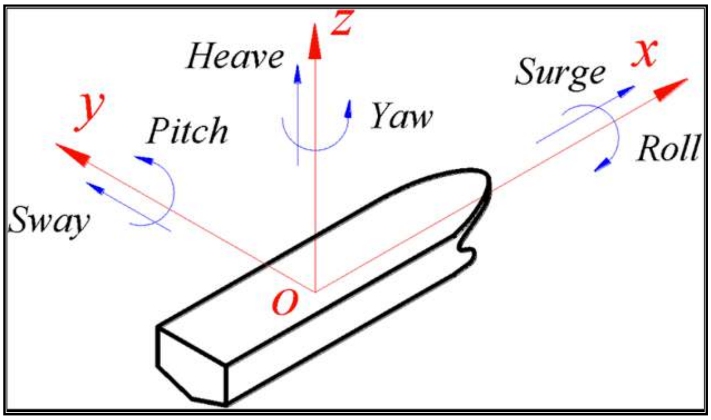


Figure 3-4 Six degrees of freedom ship motions

Source: (Winter 2018)

Utilization of jack up vessel or heavy lifting vessel has some merits and demerits. One of the merits of jack up vessel is there is not any movements while the vessel's legs are penetrated to final depth. But it should be noted that the vessel motion is not the only factor that can influence the installation of wind turbine components. Wind direction and wind speed has profound impact on the lifting operation and installation of components. Installed crane on an offshore structure has limit against wind speed. In many cases, the upper limit of crane and crane operation is 30[15] knots wind speed. However, finding shows that the blades and nacelle cannot be installed in more than 15 knots wind speed. It means regardless of vessel motion, even on a fix platform, the lifting operation above certain wind speed makes the operation unsafe for both personnel and the assets. In case the wind speed is beyond the specification of the crane, the crane gives alarm and trip, then to the operator must place the boom on the rack and stop the operation.

As it stated earlier, the utilization of jack up vessel has some demerits as well. First of all, jack up vessel cannot be positioned in any location. The location where the legs of jack up are supposed to penetrate into the seabed shall be free of any kind of assets or big debris. Therefore, prior to moving the jack up to the location, the survey shall be conducted in order to make sure for suitability of seabed as well as ascertaining that there is not any subsea asset such as pipeline or submarine cable on the location or even to make sure there is not any kind of debris and wrecked where the jack up planned to be positioned. This survey means that another offshore operation shall be conducted which lead to increase of cost of operation as well as CO_2 emission.

Second problem with using jack up vessel is that legs and spudcan of the jack up disturb the seabed. They have to be positioned in a way that its footprint does not affect other operation like cable laying. In addition, the disturbed seabed resulting from jack up vessel can cause problem for positioning of other jack up vessels. If a jack up vessel wants to be positioned again in the same location, the footprint of first jack up vessel can lead to punch through of another jack up vessel. For example, if the jack up vessel is used for installation of foundation, for the installation of wind turbine and tower with jack up, either the disturbed seabed should be rectified, or the vessel should be positioned in other direction or the vessel with other spudcan arrangement should be used. The author faced with punch through in the middle east due to imperfect survey report and careless moving of jack up barge.

Another problem of jack vessel is depth of water. Its legs are designed and constructed to operate in the certain range of water depth. The most of jack up installation vessels are designed to work to the depth of 40-55meters. However, it depends on hardness of seabed strata. In case of loose

[15] The tower crane's manual will specify the maximum wind speed at which the tower crane must be taken out of service design standards (TYPES TOWER CRANES IN MALAYSIA n.d.).For example, the wind limit for Blue Tern Jack up vessel is 30 knots approximately as per vessel specification (18 m/s).

and soft strata, the legs must penetrate more which means the vessel can work in shallower water depth. Having considered that the construction of offshore wind farms is executed in deep water, the jack up vessels cannot be a right type of installation vessel in the near future.

The most insoluble problem with jack up vessel is timing for moving and final positioning.

In order to carry out the lifting operation, legs of jack up have to penetrated sufficiently into the seabed. In general, any jack up vessel must take five steps (steps 2-6) in order to become ready for heavy lifting which are shown in Figure 3-5 and explained as following:

1. Jack up has to be towed to the location or it should sail to the desired location.
2. Jacking down and doing soft pin[16].
3. Ballast the pre-load tanks[17] with water in order to make the hull heavier to reaching the final leg penetration.
4. After reaching the final penetration, the water from the preload tanks should be deballasted.
5. The airgap between the hull and sea level should be adjusted.
6. At the end, before moving to another location, the spudcan shall be flushed with jetting system and legs should be jacked up.

The operations of positioning the jack up on the desired location regardless of sailing time including soft pinning, ballasting the tanks, jacking down to reach final penetration, and adjusting the jack up hull and deballasting constitute approximately 20% of offshore operation (except towing operation which depends on the distance and towage speed). However, this time heavily depends on the following factors:

- Experience of crew,
- Water depth,
- Volume of ballast tanks,
- Number and capacity of ballast pumps and ballast system,
- Jacking speed and
- Softness of seabed.

Therefore, any jack up vessel to do the lifting operation has to take these steps. During the preparatory steps (steps 1 to 6), the jack up cannot do lifting, decommissioning or installation operation. Therefore, the asset is not operational for each wind turbine decommissioning for at least 12 hours approximately. This time includes, jacking up which is followed by flushing the

[16] To lower the legs just with force of gearbox as much as possible.

[17] The pre-load tanks are tanks inside hull of jack up vessel which are used just for positioning the jack up. In order to penetrate the legs into the seabed, the jack up shall be filled with water to make the vessel heavy. After filling the pre-load tanks, the jacking process take places and legs moves down to reach the final penetration. The last stage is jacking up the hull till reaching the desired air gap.

spudcan, sailing toward to the next wind turbine, jacking down and soft pinning, ballasting the vessel, and finally jacking down until final penetration. In the next chapter, the figures of the duration and fuel consumption of the different modes of jack up vessel are explained in detail.

The timing of moving to final positioning depends on the following parameters:

1. Towing or sailing speed,
2. Distance of wind turbines,
3. Jacking system speed,
4. Water depth,
5. Time of ballasting,
6. Hardness of seabed,
7. Weather condition,
8. Experience of barge master and crew,
9. Levelness of seabed etc.
10. Soil conditions for jacking the legs up.

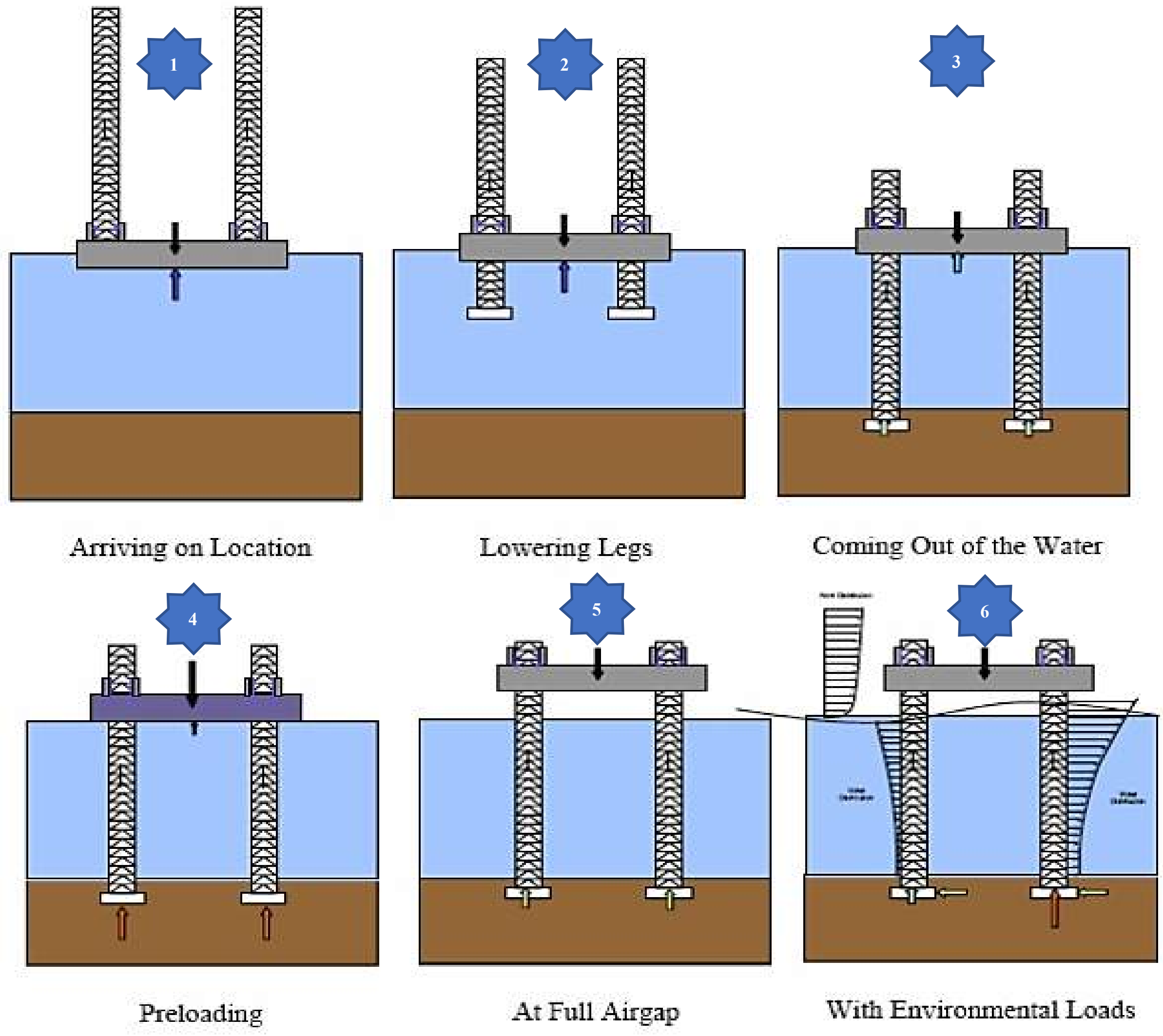


Figure 3-5 Transition Modes of a Jack up Vessel

Figure 3-6 Towage of Jack up Barge

Figure 3-7 None-propelled Jack up Barge (JB-117)

Figure 3-6 shows the wet towage operation of drilling jack up barge. Also, Figure 3-7 and Figure 3-8 shows working operation of the jack up vessels during installation of wind turbine. Figure 3-7 shows the non-propelled jack up barge and Figure 3-8 shows self-propelled jack up installation vessel.

Figure 3-8 Jack Up Installation Vessel or Wind Turbine Installation Vessel

3.4.1.2 Heavy Lift Vessel (Crane Vessel)

Heavy lift vessel (HLV) is a vessel which is equipped with crane in order to lift heavy cargos. Regardless of types of mounted crane on the vessel, the HLV can be monohull, catamaran or semi-submersible. From a propulsion stance, the HLV can be non-propelled, self-propelled without DP system and self-propelled facilitated with DP system. Among all of mentioned type, the HLV equipped with DP system has less dependency to other fleet.

Employment of heavy lift floating vessel has some advantages and disadvantages too. If the vessel is equipped with DP system, the fuel consumption is relatively higher than the jack up vessel during operation since for maintaining the vessel in the position, most of the engines should be in service. However, the fuel consumption should be calculated for the entire course of the project, not only for the operation times. The jack up vessel need to pass the above-mentioned 5 sequences in order to be ready for the operation which mean considerable amount of time, the vessel is in preparatory phases and consume fuel and have emission. Therefore, stating that consumption of jack up vessel is less than DP Vessel is not right judgment and need to be studied case by case.

If the floating vessel is equipped with mooring system, the anchor running should be deployed. The anchor running demands hiring of anchor handling tug (AHT) and survey team. Furthermore, deployment and recovery of each anchor takes approximately 6 hours depending on the experience of the crew, AHT, water depth, the length of wire, the site condition, and the number of anchors.

The advantage of using HLV equipped with DP system is that the vessel does not need time for anchor running, ballasting the preload tanks, and jacking up. As soon as arrival to the field, the vessel has to do DP-trial[18] and then can start operation. Also, this kind of vessel can operate in any field regardless of exitance of subsea assets, water depth and seabed condition.

Table 3-2 shows comparison of 4 different types of vessels. Seven different parameters which are concerned directly and indirectly in Decom Tools project are listed and compared.

Having considered this comparison, EPC contractor in the wind industry prefer to install sets of wind turbines with self-propelled DP Jack up vessel which the main reason is the stability of this vessel. In addition, the DP system increase the maneuverability of the vessel and enable the vessel to position in the field accurately. More importantly, the propulsion system on this kind of vessel provides the option for transportation of component to the field (Pendulum configuration).

However, new designed installation vessel for the installation of wind turbine foundation and support structures are floating DP vessel such as Figure 3-9 in order to reduce the duration of offshore operation, cost and emission.

Figure 3-9 Heavy Lift Vessel[19]

3.4.2 Cargo Vessel or Heavy Load/Lift Carrier

In many cases, the offshore modules which are planned to be installed offshore need to be transported by cargo vessel. It means that offshore structure is not transported by installation vessel

[18] It depends to the DP manufacturer recommendations. Some of them recommend to conducting DP trial after arrival to a new field and some of them recommend doing DP-trial periodically like every month. Duration of DP trial for different vessel vary and normally takes between 2-6 hours.

[19] However, this vessel (Alfa Lift) is a submersible vessel as well.

and another vessel is assigned for this transportation. There are a couple of types of cargo vessel in the market as following:

1. Self-propelled cargo ship/barge.
2. None-propelled cargo barge etc.

All of above-mentioned vessel types can be semi-submersible vessel. Obviously, the self-propelled vessel is equipped with propulsion system which means that they can transport the objects by their own engine(s). However, none-propelled vessels need to be towed to the site or shore via tugboat(s). The number of tugboat(s) for towing is depends on a couple of factors:

I. Bullard pull capacity of tugboat(s).
II. Size and displacement of barge when it is loaded.
III. Risk of towage versus to the value of the modules.
IV. The distance which needs to be towed.
V. The weather condition in the route of towage and inside the field.

There are a couple of reason for transportation of modules to the field by the cargo vessel as following:

1. Installation vessel does not have enough deck space to load the cargo.
2. The load capacity of the deck of construction vessel is not sufficient.
3. The transportation by construction vessel is more expensive than the cargo vessel.
4. The installation vessel is involved in an operation in the field, and it is not feasible to halt the operation for transporting the modules from shore.

Figure 3-10 Self-Propelled Cargo Ship (Enercon E-Ship 1)

Figure 3-10 shows a self-propelled cargo ship. This ship is basically designed for transportation of onshore wind turbines and is equipped with 4 Flettener rotors.

Figure 3-11 None-Propelled Cargo Barge

Figure 3-11 shows a non-propelled cargo barge which is loaded with transition pieces. The photo shows that one tugboat is towing the barge and materials.

Figure 3-12 Heavy Load Carrier Semi-Submersible Ship

Figure 3-12 shows a semi-submersible and self-propelled ship during transportation of scrap ships.

Figure 3-13 Heavy Load Carrier During Loading 4 Topsides which are loaded on 2 Barge (SAL n.d.)

Figure 3-13 shows a semi-submersible and self-propelled ship during transportation of oil and gas modules.

Figure 3-14 SAL Trina Loading Transition Pieces

Figure 3-14 shows a cargo vessel type heavy lift carrier which is used for transportation of transition pieces from fabrication yard to feed the installation vessel either at port (indirect feeding) or inside the wind farm (directly feed to the construction vessel).

3.4.2.1 Problem of Current Cargo Vessels

There exist two major problems with existing cargo vessels. The current problem of the existing cargo vessel from a propulsion stance is that they are not equipped neither with positioning anchor winch (mooring system) nor DP system. Therefore, it is not possible to maintain the position of the vessel alongside the installation vessel (just tie up to the floating installation vessel is possible under some certain circumstances) or inside the field. As a consequent, the existing cargo vessel transport the cargo from fabrication yard to the port and discharge them inside the port, then in another operation, the materials are loaded on the installation vessel.

The problem with this method is that loading and offloading the material take two times and again the transportation from the feeder port to the site should be conducted by installation vessel.

The other possible option is that the cargo vessel ties up to the port and the jack up vessel position alongside the cargo vessel. Then the material can be discharged directly from cargo vessel to the jack up installation vessel. Again, in this condition, the construction vessel need to sail toward the port and then transport the material from port to the offshore site.

If the cargo vessel is not equipped with either the DP system or position anchor winches, they can just keep the position of vessel with large footprint which means the vessel position change and also the heading of the vessel change with wind, wave and current. In order to maintain the heading and location of the vessel, they should have been equipped with DP or anchor positioning winch. Therefore, the omission to implement the mooring system or the DP system compel the installation contractors to opt the pendulum configuration.

The other problem of current cargo vessel is that they are not designed for transportation of wind turbine components. The wind turbine components have special geometry, and they are bulky. Hence, vessels with optimum deck space and holds need to be deigned in order to transport more wind turbine components in order to slash the cost and mitigate the emission of transportation.

From a financial perspective, the charter rate of self-propelled heavy load/lift career is relatively low and can be between 15 000$ to 40 000$ daily. The reasons of low charter rate of heavy load/lift career are as following:

1. Lack of unique and special equipment onboard.
2. Low number of crew (max 25 Crew).
3. Lack of complex structure due to lack of crane.

3.5 Advantage and Disadvantages of DP mode

Regardless of types of the vessel, one has to assess what are the merits and demerits of dynamic positioning system in order to see if they are suitable for the cargo vessel, installation vessel or not.

There are some advantages and disadvantages with operating the vessel in DP mode. The advantages are listed in below:

- ☑ The manoeuvrability of the vessel in the DP mode is very flexible and precise.
- ☑ In addition to the high manoeuvrability of the vessel, in some fields, due to existence of subsea assets like cables, pipelines etc., the field owner do not allow the vessels to drop anchors. So, the only method of positioning is DP mode.
- ☑ Employing anchors in deep water is not a safe and effective means of positioning the vessel.
- ☑ Regardless of type of construction vessel, the cargo vessel can maintain the position via DP easily without any conflict. It means that conduction of simultaneous operation (SimOps) is so easy, if the cargo vessel run on DP.
- ☑ For maintaining the position of the vessel, there is no need for other vessel like AHT.

However, keeping the vessel in the DP mode has some disadvantages as following:

- ☒ The propulsion system should work around the clock which will result in large fuel consumption (the loads are discussed in the next sections).
- ☒ High fuel consumption leads to high CO_2 emission.
- ☒ For DP operation, DP officers need to be mobilized which they have high wage. So, the charter rate of vessel will increase in the DP mode.
- ☒ DP need more machineries to be in operation which means more maintenances are needed.

3.6 Comparison of Various Types of Installation Vessels

Table 3-2 compares different types of construction or installation vessel from seven different perspective. One can compare the advantages and disadvantages and select the right vessel based on the project demands and site specification.

Table 3-2 Pros and Cons of Various Types of Installation Vessels

Pros and Cons of Various Types of Installation Vessels					
Sr	**Essential Parameters**	**Non-Propelled Jack up**	**Jack up with DP System**	**Mooring Floating HLV**	**Mooring HLV with DP System**
1	**Fuel Consumption**	Low	Medium	Low	High
2	**Time of Readiness**	Very High	High	Medium	Low
3	**Dependency to Other Fleet**	Depend on: 1) AHT 2) Survey Vessel	Depend on: 1) Survey Vessel	Depend on: 1) AHT	Independent
4	**Impact of Weather Condition on Stability**	Wind	Wind	Wind Wave	Wind Wave
5	**Site Limitation**	1. Subsea asset 2. Water Depth 3. Seabed Condition	1. Subsea asset 2. Water Depth 3. Seabed Condition	Water Depth	None
6	**Port Limitation**	Length Draft Seabed	Length Draft Seabed	Length Draft	Length Draft
7	**Charter Rate [20,21]**	Medium 100K-180K$	High 150K-280K $	Low 80K-100K$	High 150K-300K$

[20] (Arantegui, Domínguez and Yusta 03.05.2018)

[21] (Dalgic, Lazakis and Turan 2018)

The market and availability of the vessel play colossal role, since sometimes, the clients are compelled to select the vessel based on availability and not mentioned factors in the following table.

3.7 Involved Construction Fleet In Installation of Wind Farms

Table 3-3 shows list of some wind parks which are developed from 2014 to mid-2018. The table shows the name and types of vessels that are used for the installation of the wind farms. Also, it shows how long the installation of foundations and wind turbines took place. As it shows, all of turbine machine were installed by jack up vessel in these wind farms. However, the foundations of 10 wind farms which are highlighted in blue were installed by heavy lift vessel.

Table 3-3 Involved Fleet in Installation of Foundation and Turbine in the NSR

Sr.	Offshore Wind Parks	Involved Fleet in Foundation Installation			Involved Fleet in Turbine Installation		
	Name of OWP	**Vessel Name**	**Propulsion System**	**(Duration) Year**	**Vessel Name**	**Propulsion System**	**(Duration) Year**
1	Aberdeen (EOWDC) (SB)[22]	Asian Hercules 3	Self-Propelled Not DP (HLV)	(4.54) 2018	Pacific Orca	Jack up DP2	(1.36) 2018
2	Nissum Bredning (G JKT)[23]	Grane/Matador3	DP2 HLV/ Non-Propelled (HLV)	(14.75) 2017	Crane on Barge	Barge	(13.25) 2017
3	Arkona (MP)	Fairplayer/Svanen	DP2 HLV /Self-Propelled Not DP (HLV)	(2.4) 2017	Sea Challenger	Jack up DP2	(1.5)2019
4	Rentel (MP)	Innovation	Jack up DP2	(1.33) 2017	Apollo	Jack up DP2	()2018

[22] This wind farm has suction bucket foundation. So, it is better not to compare the installation and timing with other projects.

[23] This Project has many innovations, so it is better not to compare with other project. it has gravity jacket foundation with concrete transition pieces as well using onshore cable inside pipe (source: https://youtu.be/5pp6l6xlIws)

Sr.	Offshore Wind Parks	Involved Fleet in Foundation Installation			Involved Fleet in Turbine Installation		
	Name of OWP	**Vessel Name**	**Propulsion System**	**(Duration) Year**	**Vessel Name**	**Propulsion System**	**(Duration) Year**
5	Pori Tahkoluoto (GB)	Vole au Vent	Jack up DP2	(2.4) 2017	Vole au Vent	Jack up DP2	(1.5) 2017
6	Ajos (GB)	Vole au Vent	Jack up DP2	(2.7) 2017	Vole au Vent	Jack up DP2	(1.5) 2017
7	Walney 4 (MP)	Aelous/Svanen	JU DP2 /Self-Propelled Not DP	(2.51) 2017	Scylla	Jack up DP2	()2017
8	Walney 3 (MP)	Aelous/Svanen	JU DP2 /Self-Propelled Not DP	(2.51) 2017	Scylla	Jack up DP2	(2.48) 2017
9	Galloper (MP)	Innovation	Jack up DP2	(1.64) 2016	Pacific Orca/Bold Tern	Both Jack up DP2	(5.41) 2017
10	Race Bank (MP)	Innovation/Neptune	Both Jack up DP2	(2.23) 2016	Sea Challenger	Jack up DP2	(2.55) 2017
11	Burbo Bank Ext. (MP)	Svanen	Self-Propelled Not DP (HLV)	(1.66) 2016	Sea Installer	Jack up DP2	(3.96) 2016
12	Nobelwind (MP)	Vole au Vent	Jack up DP2	(2.49) 2016	Vole au Vent	Jack up DP2	(3.20) 2016
13	Nordergrunde (MP)	Victoria Matthias	Self-Propelled Jack up	(4.39) 2016	Victoria Matthias	Self-Propelled Jack up	(7.28) 2016
14	Wikinger (JKT)	Giant 7/Taklift 4	Non-propelled HLV/Self-propelled HLV	(7.04) 2016	Brave Tern	Jack up DP2	(3.99) 2017
15	Dudgeon (MP)	Olev Strashnov	DP3 HLV	(1.84) 2016	Sea Installer	Jack up DP2	(3.63) 2017
16	Veja Mate (MP)	Scylla/Zaratan	Both Jack up DP2	(3.91) 2016	Bold Tern/ Scylla	Both Jack up DP2	(3.34) 2017
17	Rampion (MP)	Pacific Orca/Discovery	Both Jack up DP2	(2.86) 2016	Discovery/Adventure	Both Jack up DP2	(2.55) 2017
18	Nordsee One (MP)	Innovation	Jack up DP2	(2.33) 2015	Victoria Matthias	Self-Propelled Jack up	(3.76) 2017

Sr.	Offshore Wind Parks	Involved Fleet in Foundation Installation			Involved Fleet in Turbine Installation		
	Name of OWP	Vessel Name	Propulsion System	(Duration) Year	Vessel Name	Propulsion System	(Duration) Year
19	Sandbank (MP)	Pacific Orca	Jack up DP2	(2.64) 2015	Adventure	Jack up DP2	(2.5) 2016
20	Gemini (MP)	Aelous/Pacific Osprey	Both Jack up DP2	(1.43) 2015	Aelous/Pacific Osprey	Both Jack up DP2	(2.52) 2016
21	Kentish Flats Ext. (MP)	Neptune	Jack up DP2	(1.47) 2015	Neptune	Jack up DP2	(3.8) 2015
22	Gode Wind I & II(MP)	Innovation	Jack up DP2	(1.63) 2015	Sea Challenger	Jack up DP2	(2.97) 2015
23	Luchterduinen (MP)	Aelous	Jack up DP2	(1.84) 2014	Aelous	Jack up DP2	(1.51) 2015
24	Butendiek (MP)	Svanen/Javelin	Self-Propelled Not DP (HLV)/DP HLV	(2.79) 2014	Bold Tern	Jack up DP2	(3.41) 2014
25	Borkum Riffgat (MP)	Olev Strashnov	DP3 HLV	(2.97) 2012	Bold Tern	Jack up DP2	(2.83) 2013
26	Belwind (MP)	Svanen	Self-Propelled Not DP (HLV)	(2.6) 2006	JB-114	Non-propelled Jack up	(6) 2006
27	Nordsee Ost (JKT)	Victoria Matthias	Self-Propelled Jack up	(9.24) 2014	Victoria Matthias	Self-Propelled Jack up	(7.69) 2014
28	Rhyl Flats (MP)	Svanen	Self-Propelled Not DP (HLV)	3.96 2008	Lisa A	Non-propelled Jack up	7.6 2009

Source: (Arantegui, Domínguez and Yusta 03.05.2018)

Table 3-4 shows the average time of installation of wind turbine as well as foundation based on Table 3-3. This duration is not just installation duration. It means it is the time that the vessel commenced installation in the field until installation of last turbine. So, it includes time of sailing, positioning, waiting on weather (WOW), mechanical failure, waiting on client (WOC) and so forth.

Table 3-4 Duration of Installation of Foundation and Turbine with Various Vessels

Average Duration of Installation with Various Vessels					
Sr	**Components**	**Jack up DP2 (Day)**	**Jack Up Non-Propelled (Day)**	**HLV DP (Day)**	**HLV Mooring (Day)**
1	**Foundation Installation**	2.24	14.15	2.50	2.8
2	**WT Installation**	2.82	5.85	Not Utilized	Not Utilized

The above table shows how efficient the vessel types were during installation of above-mentioned projects. However, the vessel types play a colossal role in duration of project, but there are other factors which have profound impact on the duration and cost of projects as following:

1. Planning and Management of project.
2. Sea state during installation operation and waiting on weather.
3. Vessel types and vessel stability.
4. Mechanical break-down of equipment.
5. Labour experience.
6. Number of wind turbines in the wind park.
7. Size and weight of wind turbines.
8. Distance from mobilization/installation/feeder port.
9. Water depth at wind farm.
10. Seabed characteristic.
11. Method of assembly (part by part, bunny ear, star configuration etc.).
12. Foundation type.
13. Transition piece installation method.
14. Logistic configuration.
15. Utilized tools and equipment like pile handling and driving equipment.

Having considered above, a combination of parameters play role in duration of either installation or decommissioning operations.

3.8 Availability of Cargo Vessel in the Oil and Gas Industry and Wind Industry

As it is stated earlier, in the majority of oil and gas projects, the structures are not transported offshore via heavy lift vessel. One of the reasons is the size of the oil and gas structure are larger than the vessel deck. Therefore, it is not possible to transport the oil and gas module in many cases with installation vessel.

Furthermore, the oil and gas industry are mature industry, so, different fleets are designed, developed and existed for any phase of the project development. However, project planning in the wind industry is mostly in a way to transport the wind turbines components with the jack up vessel. Since the size of wind turbine components are cumbersome and large, they can load out between 1 to 8 set of wind turbine components excluding the transition pieces and foundation onboard the installation jack up vessel. Then after installation of the wind turbine(s), the vessel has to return to the port to load out another set(s) of turbine component and return to the field for further installation. This method is one of the most expensive method for transportation of components, if the number of wind turbine is more than the deck space of the vessel.

The omission to transport the wind turbine components with transportation vessel can be lack of suitable transportation vessel for the bulky wind turbine components. One of the main components that shall be carried with high precision are blades. The blades of wind turbine are long and cannot be transported in two or more sections. Therefore, the blades should be transported in on piece. Moreover, the tower is as long as blade approximately. But in some projects, the towers are made of several segments for easier transportation and installation. The main concern with transportation of wind turbine component is not the weight of these components rather is the size and geometry of them. This omission or oversight to construct a suitable vessel for transportation of wind turbine components made transportation a bottleneck in this industry which the authors strive to give solution for the transportation of the components. The solution not only can be applied for the Decom Tools project, but also has great advantages for the installation phase of offshore wind parks too.

Furthermore, an algorithm has been devised and generated in order to identify the portion of different activities including offshore transportation and installation as well as calculation of fuel consumption and cost estimation for a decommissioning project. Findings of this simulation shows that approximately more than 45% of offshore operation is belong to the loading and transportation of wind turbine components whereas less than 40 % is attributed to the installation of components. Waiting on weather is heavily depends on duration of construction, the commencement and end of operation. When the operation is executed during winter, fall or unworkable weather condition, then waiting on weather will be increased.

3.9 Various Logistic Configurations

3.9.1 Feeder Configuration

To minimize cost and reduce CO_2 emission resulting from decommissioning of offshore wind parks, several scenarios of marine operation and logistic can be devised. One of the most efficient logistic scenarios is mobilization of construction vessel along with transportation vessel in the field[24]. This logistic configuration is called feeder configuration in that the construction vessel remains at site for disassembly and lifting operation and the transportation vessels (feeder), carry the materials to ashore. The construction vessel can be heavy lift vessel, wind turbine installation vessel (Jack-up vessel), semi-submersible vessel etc. This configuration is coveted and common in the oil and gas industry.

Figure 3-15 shows utilization of this combination during decommissioning of Lely wind farm[25] in the Netherlands. As it shows, they have used four transportation barges and one heavy lifting crane (sheer leg crane barge) for the decommissioning of this wind park. This wind park had 4 number of 500KW wind turbines. Each wind turbine had hub height of 39m with rotor dimeter of 40.77m (The Wind Power 2020). Since the size of mobilized transportation barges are small, the contractor decided to mobilize 4 numbers of barges to carry all the material. The other reason to mobilize small barges is that in the Lely wind farm, the water depth is about 4,5m. Furthermore, the distance of OWP from port is just about 1km (The Wind Power 2020).

Figure 3-16 show installation of monopile of Walney Extension wind farm with a heavy lift vessel by the name of Svanen which maintained its position by using position anchor winches. Figure 3-17 and Figure 3-19 show two different vessel that are used for transportation of the wind turbine components to the field or port.

Figure 3-17 shows that monopiles of Hornsea 1 wind farm which were constructed in the Rostock and Esbjerg were transported to Teesport in order to be shipped by the installation vessel to the field. Some part of the transportation has been carried out by feeder configuration and some part by pendulum configuration. Since the cargo vessel is not equipped with either mooring system or DP, the direct loading of the materials from the cargo vessel to the

[24] If the wind park has more than 10 numbers of wind turbines or the distance to the port is considerable.

[25] The Lely wind farm was erected in 1992 and decommissioned in 2016. It was a two-blade wind turbine and without TP and tower was made of two segments. The disassembly of 4 wind turbine took 3 days and the entire piles are extracted by vibratory hammer. The monopile had diameter of 3,7m, length of 27m and weight of 84 tons. Ful removal of wind turbines and cables took 21 days (offshoreWIND.biz 201).

installation vessel is not doable at offshore site which compel the installation vessel to position in the port for loading operation.

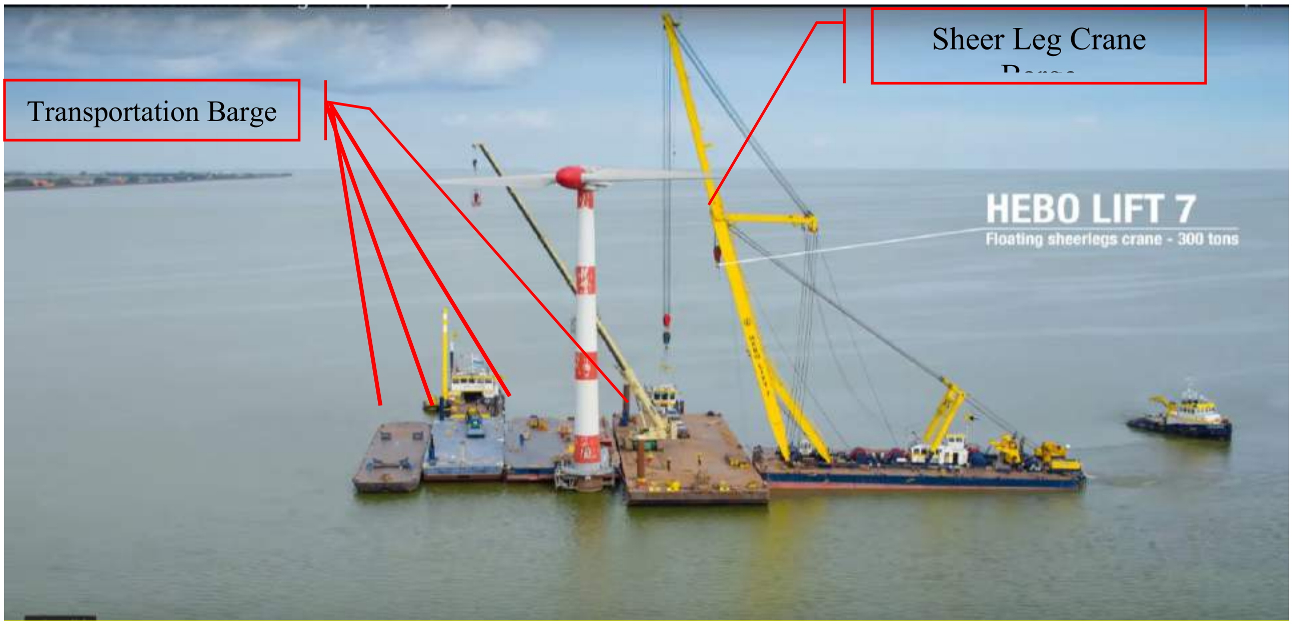


Figure 3-15 Feeder Configuration In Decommissioning of Lely Wind Farm

Source: (Dieseko Group - ICE, PVE & Woltman n.d.)

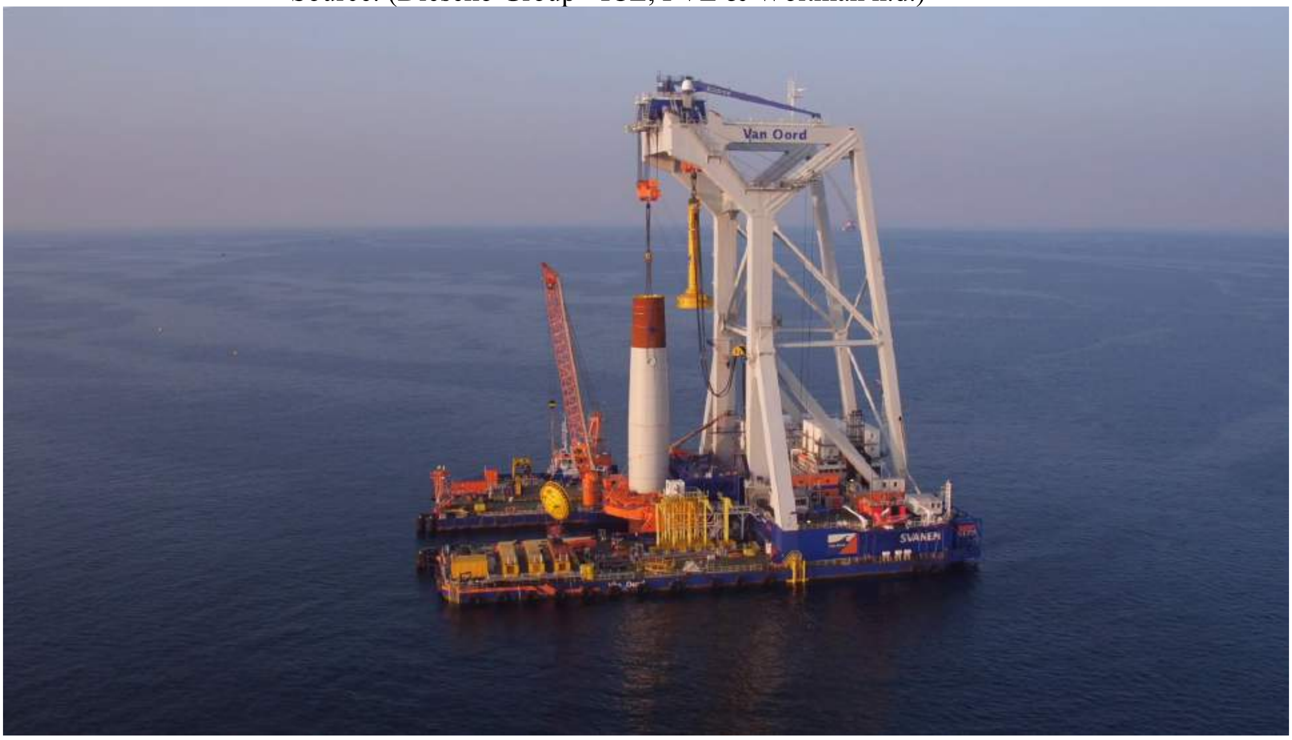


Figure 3-16 Feeder Configuration During Installation of Walney Extension (Van Oord 2017)

Figure 3-19 shows Enercon E-Ship 1 which is designed to transport the onshore wind turbine from wind turbine factory to the suitable location (port or onshore location). This vessel is not designed to transport the components to offshore wind farm.

The last components which need to be installed is the blades which are loaded on the weather deck of this vessel. Loading the blades on the weather deck prevent access to the holds for lifting and installation of nacelle and other components. Therefore, by using this loading arrangement, the vessel cannot remain offshore alongside the installation vessel as feeder vessel.

Figure 3-17 Loading the Cargos from Cargo Vessel to The Installation Vessel

Source: (SAL n.d.)

Figure 3-18 Transportation barge is loaded with Monopile & TP

Figure 3-19 Enercon E-Ship1 (Cargo Ship) is loaded with Blades

Figure 3-20 shows that due to boom length and the SWL of port crane, the monopile (MP) and Transition pieces (TP) were loaded on the portside of the ship, then after rotation of the vessel (Figure 3-21), other set of monopile and TP were loaded on the starboard side of the vessel (Figure 3-22).

Figure 3-20 Aura Heavy Load Carrier Loaded with 2 Monopiles+2 TP

Source: (Bladt Industries 202)

Figure 3-21 Aura Heavy Load Carrier Loaded with 2 Monopiles+2 TP

Source: (Bladt Industries 202)

Figure 3-22 Aura Heavy Load Carrier Loaded with 2 Monopiles+2 TP

Source: (Bladt Industries 202)

Therefore, in the feeder configuration, at least two vessels need to work during decommissioning operation. The first vessel is installation vessel in order to disassemble and lift the wind turbine components, and the second vessel is cargo vessel to transport the components.

Figure 3-25 show this configuration during installation of TPC wind farm in Taiwan. Figure 3-24 shows load out of jacket foundations on the cargo vessel (or heavy load career) and Figure 3-25 shows that a cargo barge loaded with pile are moored to the installation vessel for the installation of pre-piled foundation of TPC wind farm. This combination is another example of feeder configuration.

Figure 3-23 Load of Jacket Foundation with Sheer Leg Crane Barge for TPC OWF

Source: https://youtu.be/Z7fSCIuvIYU

Figure 3-24 Transportation Of Wikinger Wind Farm Jacket To The Field By A Heavy Load Career

Source: (Royal Boskalis 2017) (Royal Boskalis 2017)

Figure 3-23 and Figure 3-24 shows that for the load out of the jacket on the cargo vessel, a crane barge or port crane is needed. This is one of the problems of the feeder configuration. It means for loading and offloading the materials onto the cargo vessel, another vessel or port crane or onshore crane is needed. However, some of existing cargo vessels in the market are equipped with in-house crane(s). It should be noted that if the foundation of wind turbine is jacket or gravity base (GSB), transportation with jack up installation vessel is impossible. So, in these two types of foundation feeder configuration should be adopted.

Figure 3-25 and Figure 3-26 demonstrates installation of monopile in feeder configuration. The cargo vessel/ barge is alongside the installation vessel at field and feed the installation vessel.

Figure 3-25 Installation of Piles for Pre-Piled Jacket of TPC OWF

Source: (SteelGuru Business News 2020)

It should be noted that most of cargo vessels are not equipped with neither DP nor position anchor winches (PAW). Therefore, the only method to maintain the position of the cargo vessel in the field is to moor (tie up) the cargo vessel to the construction vessel. If the construction vessel is a jack up vessel, normally vessels are not allowed to tie up to the jack up vessels since the legs and stability of the jack up vessels are not designed to withstand the external forces which are exerted by other fleets. Therefore, the cargo barge can tie up to the floating vessel just and not to the jack up vessel. This is one of the reasons that in the installation of the offshore wind parks the pendulum configuration has been adopted mostly.

Figure 3-26 shows that spud crane barge is for lifting and installation operation, cargo vessel kept the position by dropping the bow anchor as well as mooring to the small support vessel at the stern.

Figure 3-27 shows installation of offshore high voltage substation in the feeder configuration. As it stated before, most of jacket foundation, gravity base structure as well as topsides need to be installed in feeder configuration since they are large size structure. In addition, the installation of mentioned structures is not possible to be executed by jack up vessel since they are heavy. Therefore, for such installation, a cargo vessel is assigned for the transportation into the field and installation vessel remain in the field for the installation.

Figure 3-26 Installation of Frylan OWF in Feeder Configuration

Source: (Ocean Energy Resources 2020)

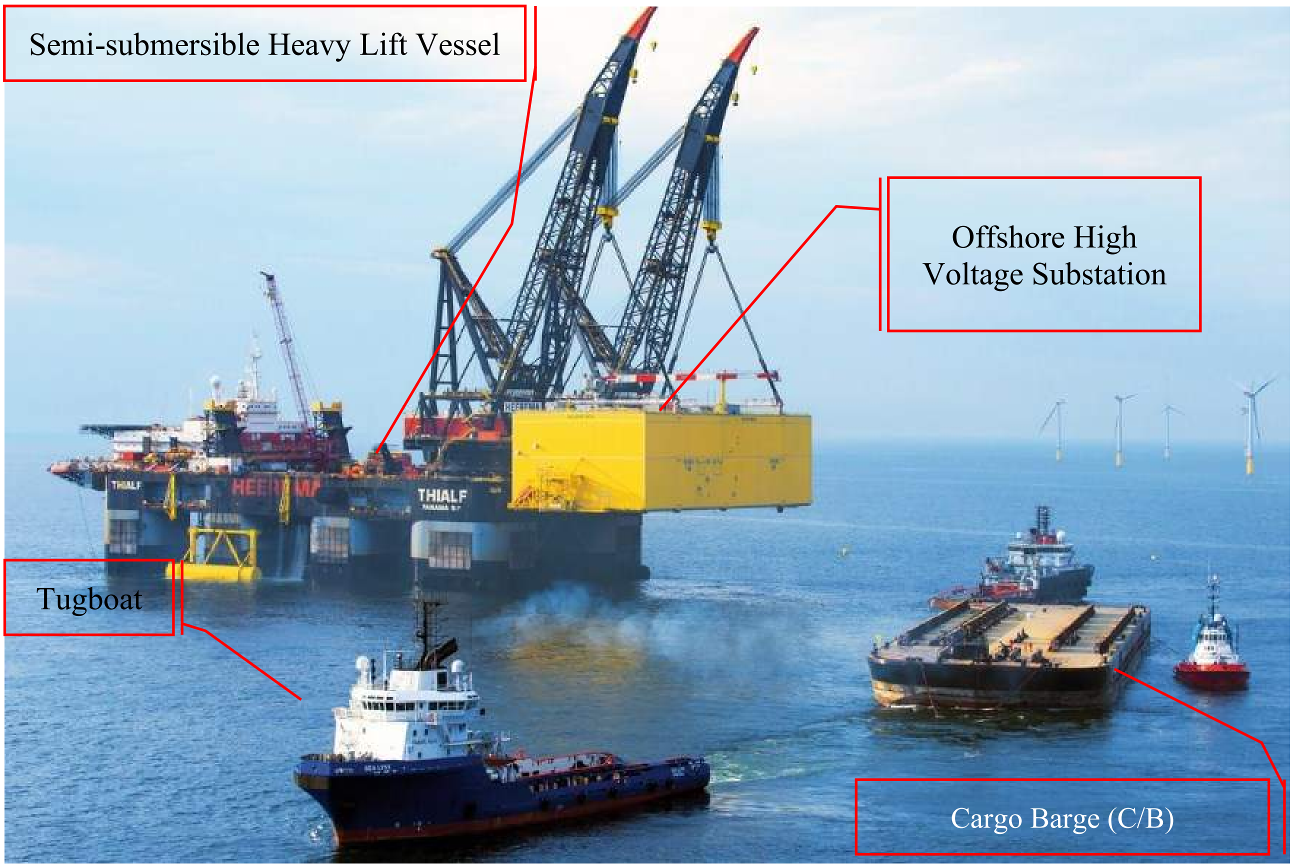


Figure 3-27 Installation of Topside of OHVS

3.9.2 Pendulum Configuration

In this configuration, one vessel is used for both cargo transportation as well as wind turbine (or foundation) installation. In other words, the installation vessel pick-up the wind turbine component from the specific port, transport offshore and then install them. As soon as completion of installation of loaded components, it returns to the port for the further transportation and installations. So far, this configuration is coveted in the wind industry. According to the Table 3-3, Jack up vessels are most used vessel type for transportation and installation of wind turbine. Transportation of components with jack up vessel mainly depends on the following factors:

1. Depends on the size of wind turbine since they occupy deck space.
2. Weight of wind turbines since they impact the centre of gravity of vessel during sailing.
3. Depends on the weight of components, since it impacts the variable deck load (VDL). VDL delimit the distribution of load on the deck while the vessel's legs are penetrated into the seabed.

However, in this logistic configuration, just one vessel is used for both transportation and installation purpose. But it should be considered that this type of vessel is one of the most expensive vessels which consume considerable amount of fuel too. To put it more simply, the transportation of component which can be carried out by cheaper vessels is done with the most expensive vessel which contribute to increase in the project cost. Furthermore, the geometry of the jack up vessel is similar to the barge which increase the hull resistance. The higher hull resistance contributes to higher energy demand for the propulsion system. It means that this type of vessel consumes considerable amount of fuel due to their hull geometry. To analyze this configuration, we would like to draw your kind attention to the following figures.

Figure 3-28 Installation of OWP with Pendulum Config. (4 Set of WT in each Campaign)

Figure 3-28 shows two jacks up vessels install the turbines and the towers. This configuration which two vessels work simultaneously is called tandem configuration.

Figure 3-29 shows that the transition pieces are loaded on the jack up vessel. Since the jack up vessel is a none-self-propelled vessel, the towage is done by a tugboat.

Figure 3-29 Installation of OWP with Pendulum Config. (4 Set of Transition Pieces with Non-propelled JU) (Van Oord 2014)

Figure 3-30 Installation of Rotor (Star configuration) with Pendulum Configuration

3.9.3 Reverse Consolidation Configuration

In this configuration, the materials are transferred to one port for storage and some shore-based process (shore-based process can be disassembly or cutting process). The next stage is to transfer the materials with vessels or onshore transportation system such as train or trucks to other ports or places for further process like recycling. Again, in this configuration having a suitable transportation vessel is necessary. The transportation of materials from offshore site to staging port and to other ports and locations does not need any installation vessel. Therefore, in this configuration a heavy load career (Cargo barge) is needed.

3.9.4 Accumulative Transport Configuration

In this configuration, the transportation vessel travels to different port for offloading the various materials. For example, in the first campaign, after disassembly of blades of all wind turbines, transportation of all the blades will take place to the port that have infrastructure for the blade shredding and recycling. In the second run, the vessel transfers all the nacelles of one wind park to a port that have workshop and infrastructure for disassembly and function test of components. Again, in this configuration, just installation vessel needs to be employed for disassembly and lifting. The transportation will be conducted with heavy load career vessel which is cheaper.

3.10 Comparison of Various Logistic Configuration

3.10.1 Required Fleet for Various Logistic Configuration

According to above mentioned explanation for different logistic configurations, Table 3-5 shows the necessity of vessel types in different configuration. However, in the following table, the comparison is made for the similar vessels in various configuration.

Table 3-5 Required Vessel Types in Various Configuration

Sr.	Logistic Configuration	Required Vessel		Remark
		Installation Vessel	Cargo Vessel	
1	Pendulum	Required	Not Required	Transportation take place with installation vessel
2	Feeder	Required	Required	
3	Accumulative	Required	Required	Transportation can take place with installation vessel or cargo vessel
4	Reverse Consolidation	Required	Required	

It is evident that in pendulum configuration less vessels need to be employed in order to complete the operations. From a project management stance, this configuration does not have complexity. Therefore, planning and project management can be easier since one vessel need to be arranged for cargo loading, transportation and installation. But it can be argued that transportation of components which can be done by a cheaper vessel need to be conducted by installation vessel which is much more expensive vessel. Also, the overall duration of operation as well as CO_2 emission need to be assessed and compared.

3.10.2 Time-Cost-Consumption-Emission Analysis of Logistic Configurations

In this section, the aim of authors is to show the difference between pendulum and feeder configurations in terms of duration of marine operations, cost, fuel, and CO_2 emission. This calculation is called time-cost-consumption-emission analysis. In this analysis, in the pendulum configuration, the vessel which is used for the installation of offshore wind farm is used for the disassembly of them. In addition, sequences of the disassembly of a set of the wind turbine are exactly reverse to installation. Having this assumption, the decommissioning take place exactly reverse to the installation.

However, in the analysis of feeder configuration, two different types of vessels have been studied and compared in this document. In the first feeder configuration, the same vessel which was used for the installation of wind farm has been used along with the Decom Tools vessel which the designed is presented in the further sections of this document.

Furthermore, in the second feeder configuration, a heavy lift vessel along with the Decom Tools vessel will be studied. All the calculation is based on specification of offshore wind park and specification of vessels. However, some uncertainties such as waiting on weather, waiting on client and mechanical breakdown is assumed as unplanned activities.

For the jack up vessel, 25% of the duration of offshore operation is considered as waiting on weather which is under category of unplanned activities and for heavy lift vessel 35% of offshore operation is considered as waiting on weather. Three different wind parks selected as case studies in order to verify the comparison results.

3.10.2.1 First Case Study-Nobelwind Offshore Wind Farm

Nobelwind is a wind farm consist of 50 number of 3.3MW wind turbine. The wind farm is located approximately 47 kilometres off the coast at Oostende and has a capacity of 165 MW.

The jack up vessel by the name of Vole au Vent which is equipped with DP2 has been installed this wind farm from 20 October 2016 till 3 April 2017 (Installation took 166 days). On each voyage 6 sets of tower, rotor and nacelle were transported by this jack up vessel. It means for complete installation of the wind farm the jack up has been sailed 9 times from port to site.

Figure 3-31 and Figure 3-32 shows the load out and installation of this wind park.

3.10.2.1.1 Time-Cost Analysis of Nobelwind OWP Decommissioning with Pendulum Configuration (Reverse to the Installation)

The maximum sailing speed of the Vole au Vent vessel is 10 knots. In the calculation, the average service speed of the jack up is considered 6 knots (60% of the maximum speed of the vessel), then just approximately 3.17 days was the sailing time of the vessel[26].

Figure 3-31 Installation of Nobelwind Farm by Vole au Vent Jack up Vessel (Jan De Nul Group 2017)

Figure 3-32 Load Out of Turbine Blades onto the Vole au Vent Jack up Vessel (Mulder 2019)

[26] Nine times load out resulted in 18 times going and coming back.

This vessel is one of the largest installation jack-up vessel which we can consider charter rate of 200 000$ daily[27]. It means just the transportation cost was about 634 449$. Table 3-6 shows, the duration, portion, and cost of loading, transportation and installation of wind turbine excluding transition pieces and foundation for Noblewind farm with pendulum configuration. If the disassembly take place exactly reverse of the installation, then the same offshore cost or even more will be incurred to the project. The more cost will be due to extraction of monopile, removal of marine growth and cables retrieval which take more time than installation.

Table 3-6 Results of Pendulum Configuration in Decommissioning of Nobelwind OWF

Results of Pendulum Configuration in Decommissioning of Nobelwind OWF (Jack up for T & I))			
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Positioning	27.72	25.1%	$ 5,543,055.56
Figures of In-Field Transit	0.76	0.7%	$ 151,187.90
Figures of Sailing	3.17	2.9%	$ 634,449.24
Figures of Offshore Construction	41.15	37.3%	$ 8,229,166.67
Figures of Offloading	14.06	12.7%	$ 2,812,500.00
Figures of Unplanned Activities	23.45	21.3%	$ 4,689,997.03
Grand Total	**110.30**	**100.0%**	**$ 22,060,356.40**

According to Table 3-6, we can interpret and conclude the following:

- Approximately 25% of the project is just related to positioning the jack up vessel which means making the jack up vessel ready for operation.
- 12.7% of the operation time is just for being at port for offloading the items.
- 3.6% is for sailing time which includes in-field sailing (between turbines) and sailing from port to site (9 times inward + 9 times outward) and,
- 37.3% of the offshore operation is disassembly and lifting activities
- It should be noted that unplanned activities mean waiting on weather (WOW), waiting on client (WOC) and mechanical breakdown. The portion of unplanned activities is 21.3% of offshore time.

[27] The charter rate of jack up vessel varies between 150000$ to 250000$. The average charter rate of 200000$ is considered in the entire calculation of this document.

Conclusion: From a financial perspective, the overall cost of offshore operation of decommissioning of Nobelwind OWF with pendulum configuration is about **22,060,356.40 $**, considering the daily charter rate of construction vessel 200 0000$.

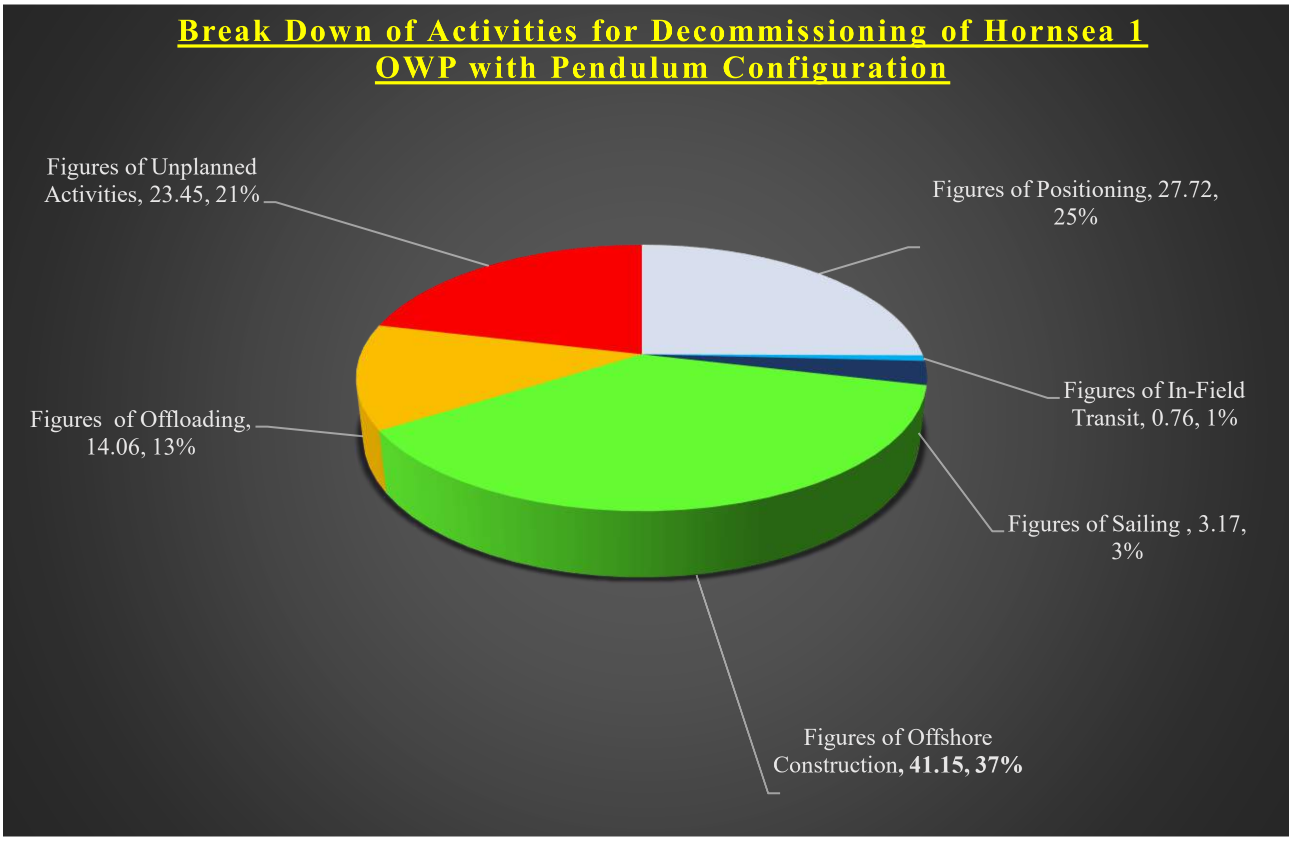


Figure 3-33 Break Down of Noblewind offshore Wind Farm Decommissioning with a Jack up

3.10.2.1.2 Time-Cost Analysis of Nobelwind OWP Decommissioning with Feeder Configuration (Jack Up + Decom Tools Vessel)

In order to achieve the objectives of Decom Tools project, the feeder logistic configuration has been studied in order to see the changes in term of fuel consumption, CO_2 emission and offshore operation duration. Table 3-7 shows the cost and duration of offshore operation when the same jack up vessel that is used for the installation is utilized for disassembly of wind turbines. In addition, the Decom Tools vessel is assumed for the transportation of components. The day rate of Decom Tools vessel for transportation operation is considered 40000$[28].

So, if the disassembly and removal of wind turbine rotor, nacelle and tower take place exactly reverse to the installation but with feeder logistic configuration (Decom Tools vessel transport

[28] The charter rate of the cargo vessel varies between 30000$ to 50000$. The charter rate of the Decom Tools vessel during transportation analysis is considered 40000$ in the entire document. However, for the other modes of operation of Decom Tools vessel, the charter rate is different.

the cargos to the port), a considerable amount of saving in terms of time, fuel, cost and CO_2 emission will be achieved.

Table 3-7 Results of Feeder Configuration (Jack up+ Decom Tools vessel) in Decommissioning of Nobelwind OWF

Results of Feeder Configuration in Decommissioning of Nobelwind OWF (Jack up + Decom Tools Vessel)			
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Daily Charter Rate ($)**
Figures of Positioning	27.72	31.2%	$ 5,543,055.56
Figures of In-Field Transit	0.35	0.4%	$ 151,187.90
Figures of Sailing	0.76	0.9%	$ 634,449.24
Figures of Offshore Construction	41.15	46.3%	$ 8,229,166.67
Figures of Unplanned Activities	18.89	21.3%	$ 2,812,500.00
Figures of Decom Tools Vessel	103.15	N/A	$ 4,689,997.03
Grand Total	**88.86**	**100.0%**	**$ 22,060,356.40**

Conclusion: In this configuration, the decommissioning of wind turbine excluding transition pieces and foundation take 88.86 days which is 21 days less than pendulum configuration. Cost of offshore operation will be **22,060,356.40 $** if the decommissioning take place by using a jack up vessel (similar to the pendulum configuration) and Decom Tools Vessel. In other words, compared to pendulum configuration, 162,221.6$ will be saved in this configuration.

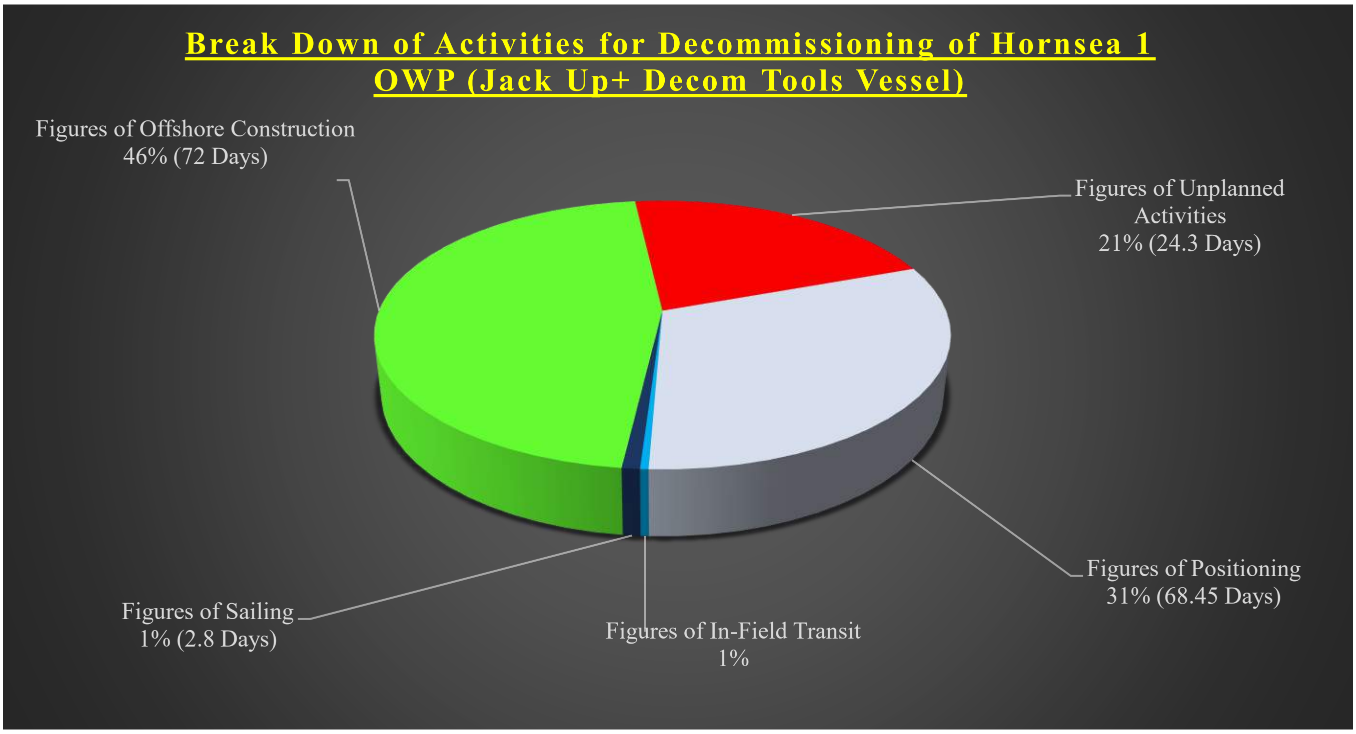


Figure 3-34 Break Down of Noblewind offshore Wind Farm Decommissioning with Jack up + HLC

Referring to Table 3-7, we can interpret and conclude the following:

- Duration of decommissioning is 88.86 days approximately which has reduction with respect to pendulum configuration for 21 days.
- Approximately 27.72 days of the offshore operation is just related to positioning the jack up vessel which means making the jack up vessel ready for operation. So, the duration of positioning in the feeder and pendulum configurations is the same.

Important Note: the duration of positioning can change if either the spec of wind farm change or the spec of installation vessel change. It varies with the number and size of turbine, the water depth, depth of leg penetration etc. In other words, logistic configuration cannot change duration of positioning.

- Having considered that the jack up vessel does not go to the port for offloading the components, therefore, sailing's duration reduced considerably from 3.17 days to 0.76 days. This sailing time is minimized remarkably. It means the 18 times sailing from port to site reduced to two times.
- Duration of disassembly and removal will be the same as pendulum configuration (41.15 days), but the percentage of this item increase since the overall duration of the project is decreased.

Important Note: The duration of disassembly and lifting depends on the number of wind turbines in the field and methods of disassembly. Therefore, logistic configuration does not change the duration of disassembly, lifting and removal.

- It should be noted that unplanned activities here mean waiting on weather (WOW), waiting on client (WOC) and mechanical breakdown. Waiting on weather is assumed 25% of sailing, installation and offloading. Waiting on client and mechanical breakdown is considered 2% of above-mentioned activities.

3.10.2.1.3 Time-Cost Analysis of Nobelwind OWP Decommissioning with Feeder Configuration (HLV + Decom Tools Vessel)

The other possible logistic configuration is to use heavy lift vessel (HLV) for removal and disassembly of wind turbine rotor, nacelle and tower and load them onboard a cargo vessel for further transportation to port. By using this configuration, we can omit the duration of positioning of the jack up vessel. Table 3-8 shows the result of using a heavy lift vessel and the cargo vessel (here the Decom Tools vessel is considered as cargo vessel with a day rate of 40000$).

Table 3-8 Results of Feeder Configuration (HLV + Decom Tools Vessel) in Decommissioning of Nobelwind OWF

Results of Feeder Configuration in Decommissioning of Nobelwind OWF (HLV + Decom Tools Vessel)			
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Sailing	0.25	0.4%	$ 50,353.11
Figures of In-Field Transit	0.35	0.6%	$ 70,494.36
Figures of Offshore Construction	41.15	71.9%	$ 8,229,166.67
Figures of Unplanned Activities	15.45	27.0%	$ 3,089,505.23
Figures of Decom Tools Vessel	77.65	N/A	$ 3,105,953.85
Grand Total	**57.20**	**100.0%**	**$ 14,545,473.22**

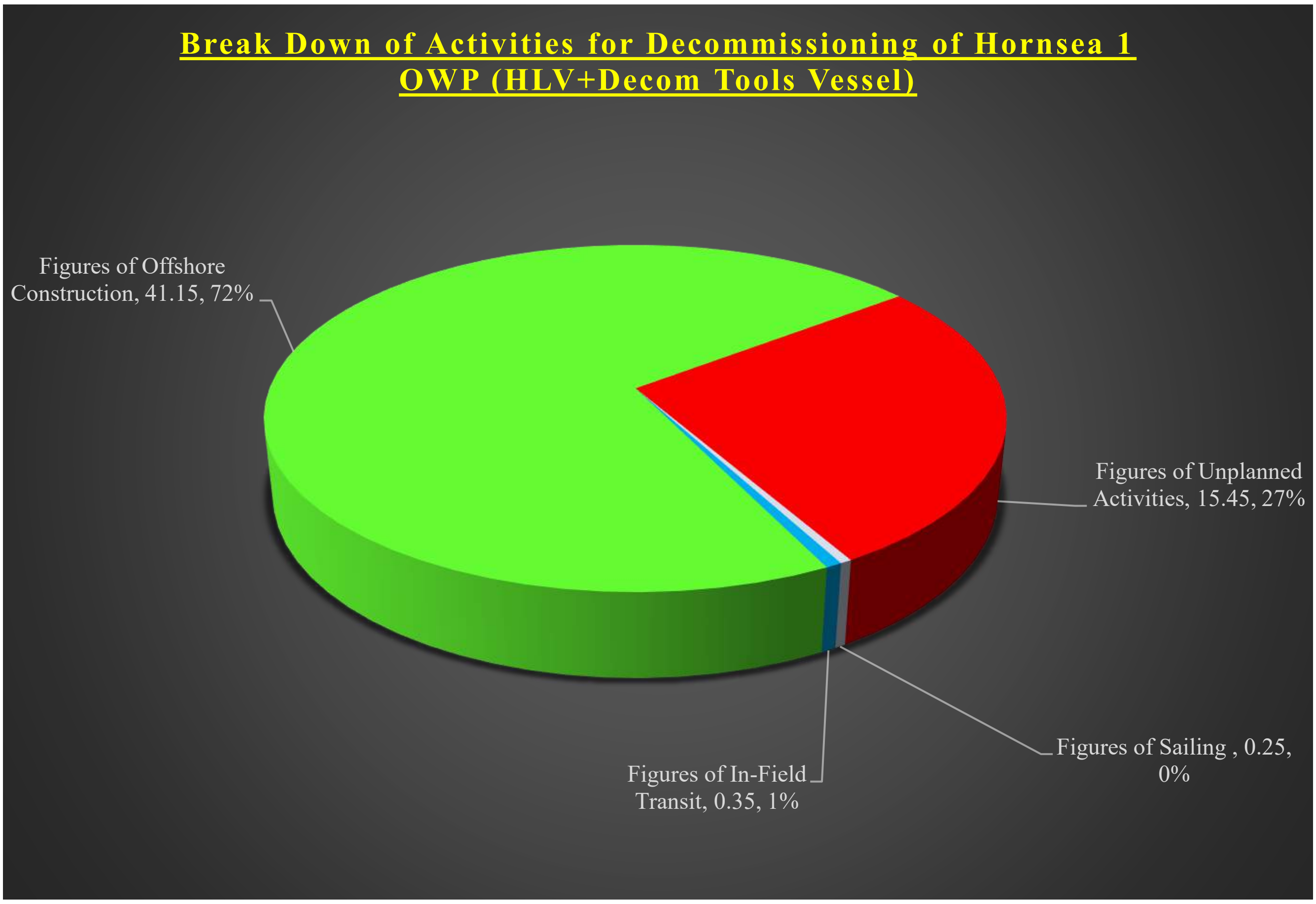


Figure 3-35 Break Down of Noblewind offshore Wind Farm Decommissioning with HLV + HLC

Having considered that heavy lift vessel is floating and is not a fixed vessel like jack up vessel, then both wind and wave forces as environmental loads impact the stability of the vessel. Therefore, in this configuration, the waiting on weather is considered 35% of sailing, installation and offloading time, which in the jack up vessel, it was considered 25%. Having considered this fact, we can interpret the Table 3-8 as following:

- The duration of positioning which means jacking up/down the legs and ballasting/deballasting will be omitted (it was 27.72 days for jack up). It means this type of vessel does not need time for preparation except the DP trial which is between 2-6 hours. As soon as arrival to the field and conduction of the DP trial, they can start disassembly and lifting operations.
- Duration of sailing excluding in-field sailing will be a little bit less than the jack up vessel (the average speed of the HLV is 8.4 knots, 60% of the maximum speed which is 14 knots).
- Also, duration of offshore disassembly will be the same as jack up vessel (since the number of wind turbine and lifts are the same).
- Waiting on weather considered as 35% of sailing, installation and offloading duration as explained before.

Conclusion: In this configuration, the decommissioning of wind turbines excluding transition pieces, foundation and cables take 57.20 days. As a consequence, the cost of offshore operation will be **$ 14,545,473.22** if the decommissioning take place by using a heavy lift vessel and the designed cargo vessel (Decom Tools Vessel). Considering the charter rate of heavy lift vessel 200000$ and the Decom Tools vessel 40000$.

3.10.2.1.4 Time-Cost-Consumption-Emission Comparison of Various Logistic Configurations for Decommissioning of Nobelwind OWP

In order to summarize the pros and cons of each logistic configuration in decommissioning of Noblewind offshore wind park, the comparison has been made. Table 3-9 compares fuel consumption, CO_2 emission, cost and duration of offshore operation for all three configurations. Furthermore, the difference of each variable for various configurations has been calculated based on base scenario. Having considered that for the installation of wind turbines of this wind park, the pendulum configuration was opted, therefore, base scenario for the decommissioning is the pendulum configuration. Not only the base scenario is the same logistics configuration, but only does it mean the same installation vessel is considered for disassembly and removal. It means that we have to calculate how much the variables[29] will be in the base scenario, then try to find an optimal, realistic and practical solution in order to optimize the variables. Calculation is based on the technical specification of vessel, wind farms specification and the

[29] Variable here means duration of project, project cost, fuel consumption and CO2 emission.

assumed unplanned activities. The green cells show the best or lowest figure, the red cells show the worst figure, and the yellow cells show the mediocre value.

As it shows, the best configuration in terms of fuels saving, CO_2 emission, project cost and project duration is feeder configuration with utilizing a heavy lift vessel and the designed cargo vessel (Decom Tools Vessel). In this case, duration of offshore operation will be 48% less than base scenario, the cost will be about 34% less than base scenario, fuel consumption is 26% less than base scenario and CO_2 emission will be 27% less than the base scenario.

Table 3-9 Comparison of Duration, Cost, fuel Consumption and CO2 Emission of Various Logistic Configuration in Decommissioning of Nobelwind OWP

50 WT	Comparison Table for Disassembly of Wind Turbines		OWP: Nobelwind
Configuration	**Pendulum**	**Feeder**	
Parameters	**DP2 Jack Up**	**Jack Up + Decom Tools**	**HLV + Decom Tools**
Duration (Day)	**110.30**	**88.86**	**57.20**
	Base Scenario	**-21**	**-53**
		19%	**48%**
Cost ($)	**$ 22,060,356.4**	**$ 21,898,134.8**	**$ 14,545,473.2**
	Base Scenario	**$ (162,221.6)**	**$ (7,514,883.2)**
		0.74%	**34.07%**
Fuel (Tons)	**1360.05**	**1520.41**	**1005.94**
	Base Scenario	**160.35**	**-354.11**
		-12%	**26%**
CO2 Emission (Tons)	**4352.16**	**4679.66**	**3187.88**
	Base Scenario	**327.50**	**-1164.28**
		-8%	**27%**

Furthermore, the second optimum scenario is feeder configuration with utilizing a jack up vessel with the Decom Tool vessel in term of cost and duration of project. In this case, duration of offshore operation will be 19% less than base scenario, the cost will be about 0.74% less than base scenario.

Furthermore, from fuel consumption and emission stance, it can be seen in the Table 3-9 that in the feeder configuration by using the Decom Tools vessel and the jack up vessel, the fuel consumption is 12% more than pendulum configuration and the CO_2 emission is 8% more than pendulum configuration.

Therefore, in all three logistic configurations, the design of Decom Tools contributes to reduction of project duration. However, fuel consumption and CO_2 emission in the feeder configuration with combination of jack up vessel and Decom Tools vessel is slightly more than pendulum configuration. However, in the feeder configuration with combination of HLV and

Decom Tools vessel considerable saving in terms of time, cost, fuel consumption and emission can be achieved.

3.10.2.1.5 Conclusion of Comparison of Various Logistic Configurations for Decommissioning of Nobelwind OWP

The best logistic configuration for decommissioning of Noblewind wind farm is feeder configuration by using a heavy lift vessel and the designed cargo vessel (Decom Tools vessel) in the sense that all the parameters namely offshore duration, cost, fuel consumption and emission is less than the base scenario. Furthermore, the objectives of the Decom Tools project can be met with this logistic configuration and the designed vessel.

In the Table 3-9, the green cells show the most optimum configuration, and the red cells indicates the highest and worst configuration. The yellow cells show the mediocre configuration. As it shows, the second-best scenarios can be either pendulum configuration or feeder configuration with a combination of jack up vessel and the Decom Tools vessel.

From cost and duration perspective, the combination of jack up vessel and the Decom Tools vessel is better since in this configuration the duration of the operation is 19% less and the cost is about 0.74% less than pendulum configuration.

From fuel consumption and emission stance, the pendulum configuration is better than the combination of jack up vessel and the Decom Tools vessel since it consumes 12% less and emit CO_2 8% lower.

Figure 3-36, Figure 3-37, Figure 3-38 and Figure 3-39 depicts the duration, cost, consumption and emission of decommissioning of the Nobelwind wind farm with three different logistic configuration.

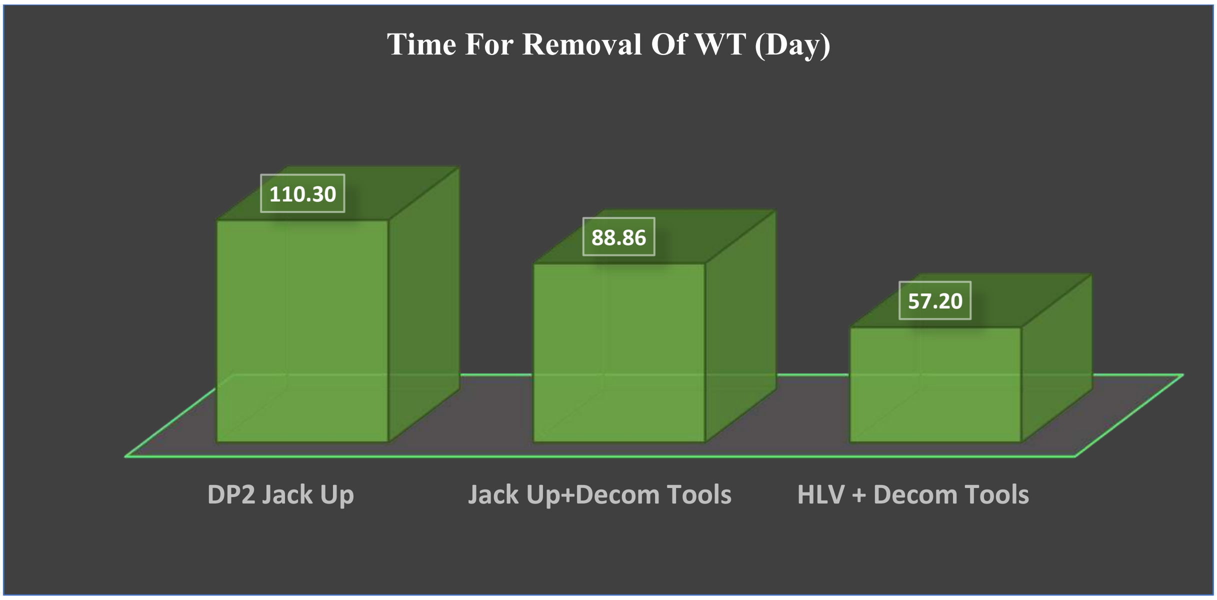


Figure 3-36 Duration of Various Logistic Configuration in Decommissioning of Noblewind OWP

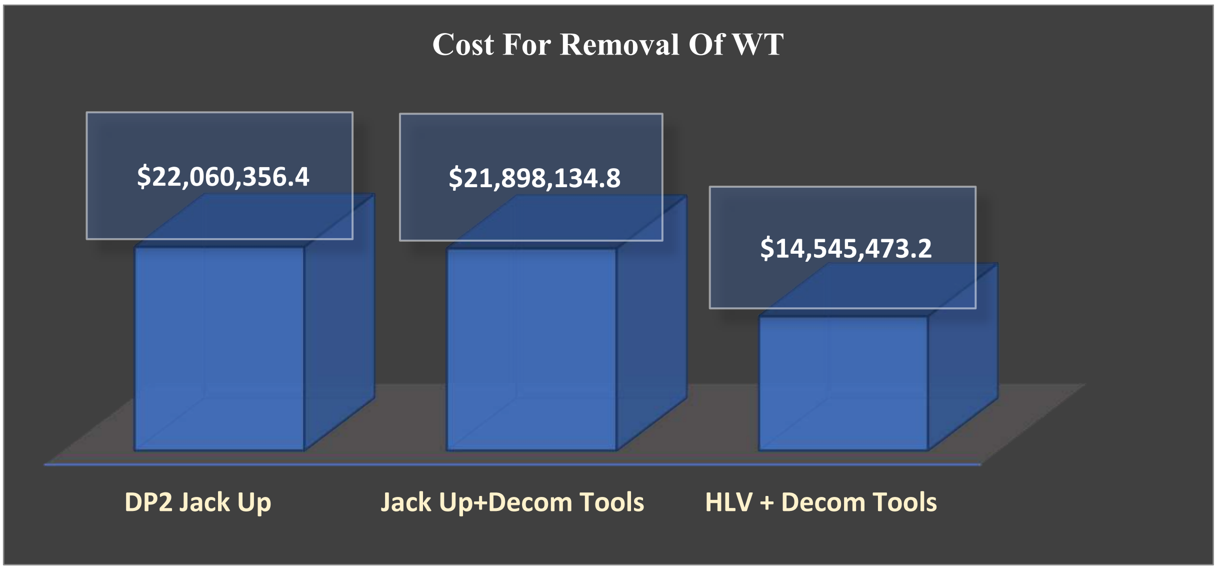


Figure 3-37 Cost of Various Logistic Configuration in Decommissioning of Noblewind OWP

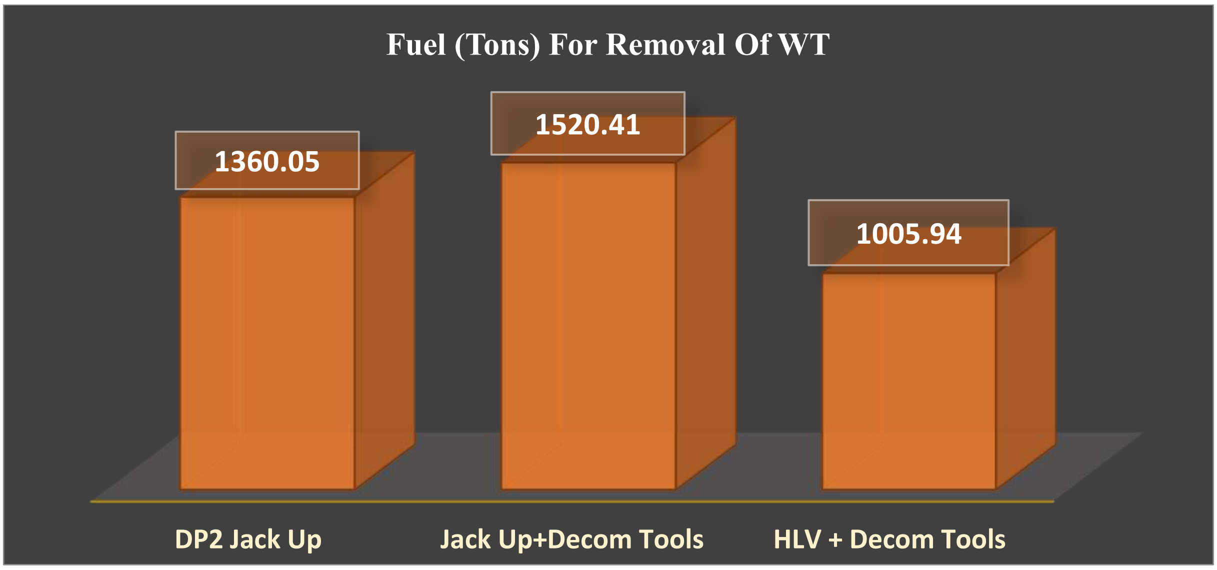


Figure 3-38 Fuel Consumption of Various Logistic Configuration in Decommissioning of Noblewind OWP

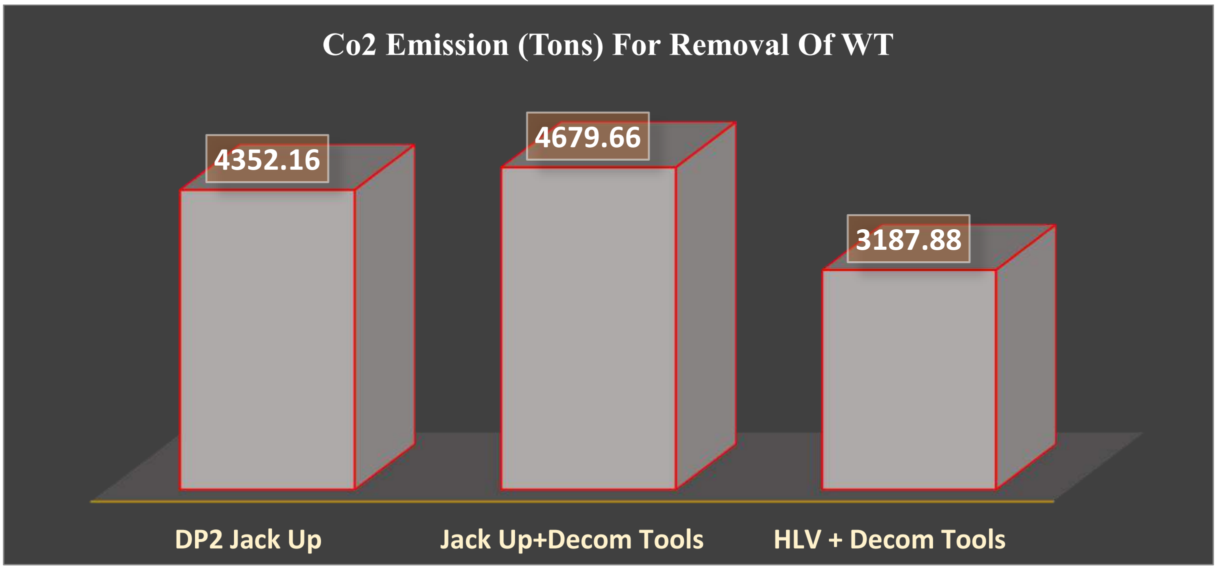


Figure 3-39 CO2 Emission of Various Logistic Configuration in Decommissioning of Noblewind OWP

3.10.2.2 Second Case Study-Hornsea One Offshore Wind Farm

This wind farm consists of 174 Siemens Gamesa SWT-7.0-154 turbines and is the world's largest offshore wind farm to date[30] (Fred. Olsen Windcarrier 2020). Hornsea One is located 120km from shore (Yorkshire, England) which is the furthest offshore wind farm has ever been built (Fred. Olsen Windcarrier 2020). Bold Tern which is a DP2 Jack-up vessel transported and installed the towers, nacelles, and rotors of this wind park with pendulum configuration. It started sailing to the field on 4 February 2019 and 91 set of wind turbines excluding foundation were completely installed on 25 September 2019 with pendulum configuration. It means transportation and installation of 91 set of wind turbines excluding foundation took 234 days. During installation, on each voyage, 4 sets of nacelle, rotor and tower were loaded on the vessel. The fuel consumption of the vessel based on its technical specification is as following:

- Transit speed of 10 knots [t/24h]: 45
- Elevated, standby [t/24h]: 5-6
- Elevated, crane work [t/24h]: 6-8 (Fred. Olsen Windcarrier 2020) (Fred. Olsen Windcarrier 2020)

3.10.2.2.1 Time-Cost Analysis of Hornsea 1 OWP Decommissioning with Pendulum Configuration

The logistic configuration for the installation was pendulum configuration. Therefore, the base scenario for the decommissioning will be pendulum configuration with the same installation vessel. Having considered the jack up vessel and wind farm specification, the result of developed program demonstrated the figures which are shown in the Table 3-10 for pendulum configuration.

Table 3-10 Results of Pendulum Configuration in Decommissioning of Hornsea 1 OWF

Results of Pendulum Configuration in Decommissioning of Hornsea 1 OWF (Jack up for T & I)			
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Positioning	56.24	25.2%	$ 11,248,611.11
Figures of In-Field Transit	1.89	0.8%	$ 378,347.73
Figures of Sailing	17.25	7.7%	$ 3,449,724.02
Figures of Offshore Construction	74.89	33.5%	$ 14,977,083.33
Figures of Offloading	25.59	11.5%	$ 5,118,750.00
Figures of Unplanned Activities	47.48	21.3%	$ 9,496,579.37
Grand Total	**223.35**	**100.0%**	**$ 44,669,095.57**

[30] November 2020

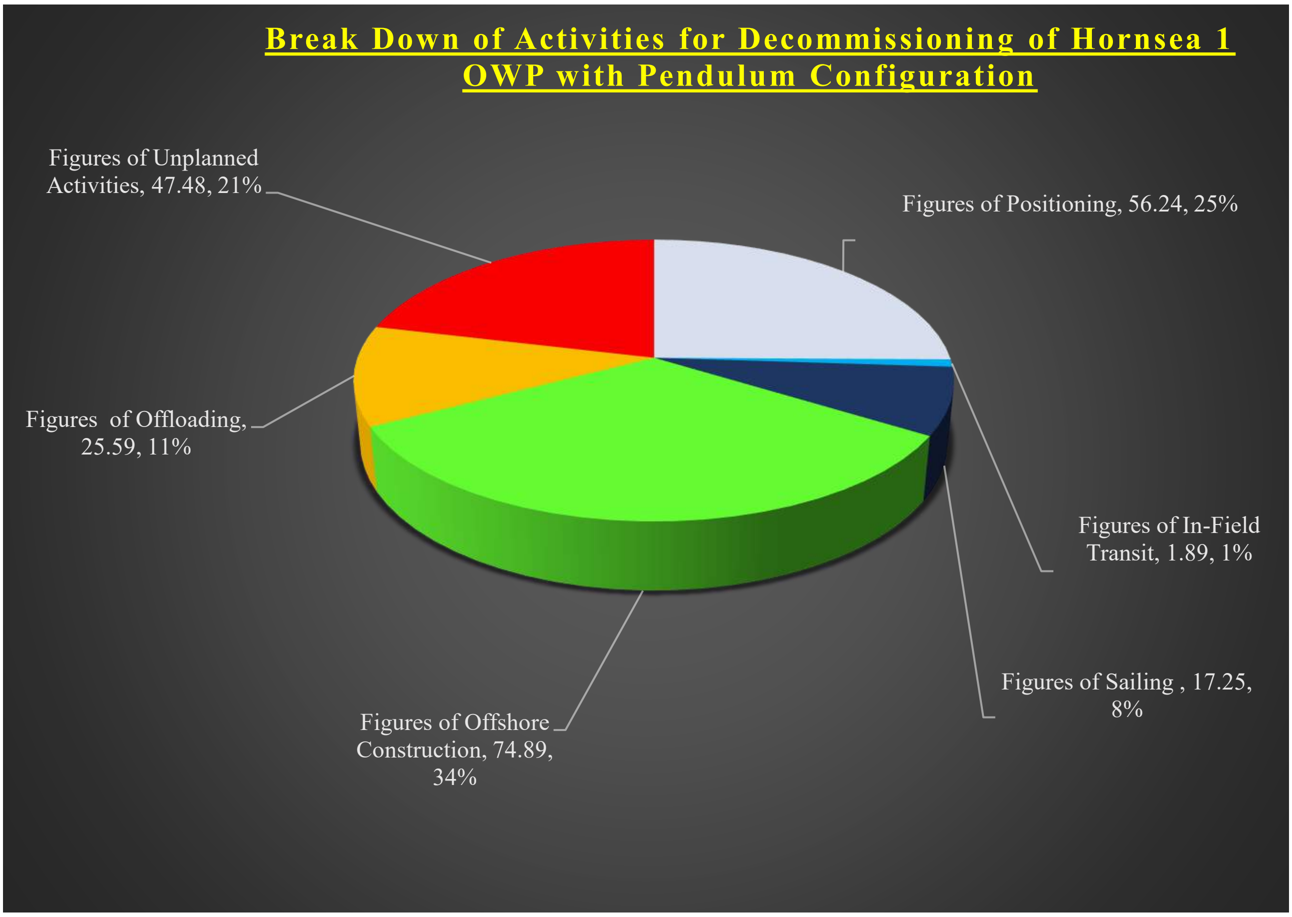


Figure 3-40 Break Down of Hornsea 1 offshore Wind Farm Decommissioning with a Jack up

According to Table 3-10 and Figure 3-40, we can interpret and conclude the following:

- The duration of decommissioning of this wind farm in this configuration calculated 223 days.
- Approximately 25.2% (56.24 Days) of the project is just related to positioning the jack up vessel which means making the jack up vessel ready for operation.
- 11.5% (25.59 days) of the operation time is just for being at port for offloading the items.
- 7.7% (17.25 days) is for sailing time between port and wind farm (24 times inward + 24 times outward).
- In-field sailing (between turbines) constitute 0.8% of overall offshore operation.
- 33.5% (74.89 days) of the offshore operation is construction time.
- It should be noted that unplanned activities mean waiting on weather (WOW), waiting on client (WOC) and mechanical breakdown. For the jack up vessel, the waiting on weather (WOW) is considered 25% and waiting on client and mechanical breakdown is assumed 2% of workable time.

Conclusion: From a financial perspective, the overall cost of offshore operation of decommissioning of Hornsea 1 OWF with pendulum configuration is about **44,669,095.57 $**, considering the daily charter rate of construction vessel 200 0000$.

Time-Cost Analysis of Hornsea 1 OWP Decommissioning with Feeder Configuration (Jack up + Decom Tools Vessel)

In this configuration, the jack up vessel which was used for installation of this OWP is considered for disassembly and lifting of turbines components. Furthermore, the Decom Tools vessel which is designed as a part of this research is considered for transportation of disassembled items to port or decommissioning yard for further disassembly, recycling etc.

Table 3-11 shows the results of decommissioning by this configuration. As you can see in this configuration, the duration of offshore operation is reduced by 24% or 53 days.

The daily charter rate of jack up vessel is considered 200 000$ and charter rate of the Decom Tools vessel is considered 40 000$.

Table 3-11 Results of Feeder Configuration in Decommissioning of Hornsea 1 OWF (Jack Up+ Decom Tools vessel)

Results of Feeder Configuration in Decommissioning of Hornsea 1 OWF (Jack up + Decom Tools)			
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Positioning	56.24	33.1%	$ 11,248,611.11
Figures of Sailing	0.75	0.4%	$ 149,988.00
Figures of In-Field Transit	1.89	1.1%	$ 378,347.73
Figures of Offshore Construction	74.89	44.1%	$ 14,977,083.33
Figures of Unplanned Activities	36.12	21.3%	$ 7,223,588.15
Figures of Decom Tools Vessel	186.82	N/A	$ 7,960,136.16
Grand Total	**169.89**	**100.0%**	**$ 41,937,754.49**

According to Table 3-11 and Figure 3-41, we can interpret and conclude the following:

- The duration of decommissioning of this wind farm in this configuration calculated 169.89 days which is 53 days (24%) less than pendulum configuration.
- Approximately 33.1% (56.24 Days) of the project is just related to positioning the jack up vessel which means making the jack up vessel ready for operation.
- 0.75% (1.89 days) is for sailing time between port and the wind farm. The sailing time reduced from 17.25 days to 1.89 days.

- In-field sailing (between turbines) constitute 0.4% of overall offshore operation.
- 44.1% (74.89 days) of the offshore operation is construction time.

Important Note: The duration of disassembly and lifting does not change with change of logistic configuration.

- It should be noted that unplanned activities mean waiting on weather (WOW), waiting on client (WOC), mechanical breakdown etc. For the jack up vessel, the waiting on weather (WOW) is considered 25% and waiting on client and mechanical breakdown is assumed 2%. For the Decom Tools vessel as it explained before, the waiting on weather is considered 35% of working time and WOC is considered 2%.

Conclusion: The overall cost of decommissioning of this wind park with this logistic configuration is **41,937,754.49$** considering 200 000$ for the charter rate of jack up vessel and 40000$ for the charter rate of Decom Tool vessel.

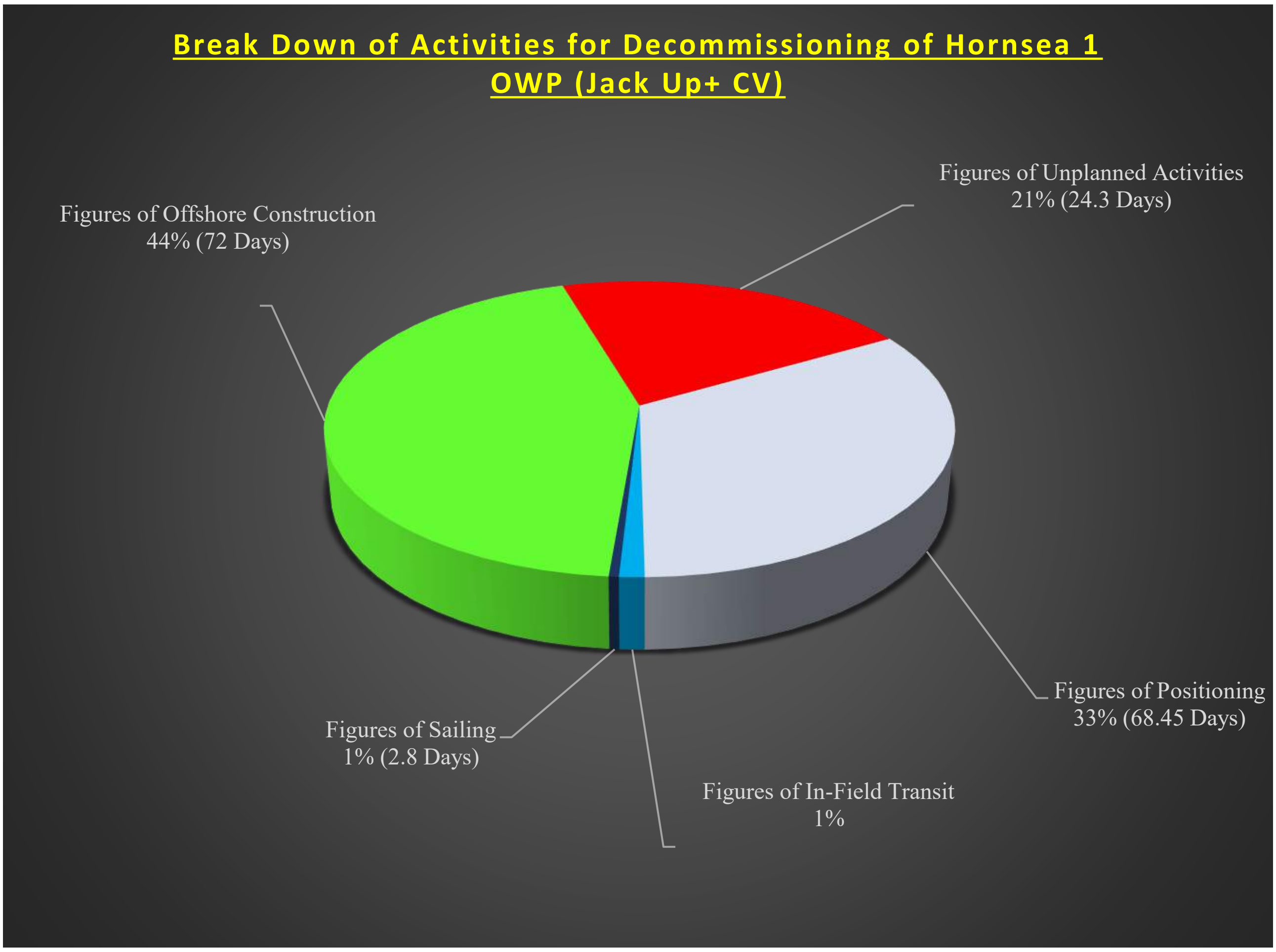


Figure 3-41 Break Down of Hornsea 1 offshore Wind Farm Decommissioning with a Jack Up+ Decom Tools Vessel

3.10.2.2.2 Time-Cost Analysis of Hornsea 1 OWP Decommissioning with Feeder Configuration (DP2 HLV + Decom Tools Vessel)

Another calculation with the developed program has been made for another logistic configuration. In this configuration, combination of a heavy lift vessel along with the designed heavy load carrier is doing decommissioning of this wind farm. In this configuration, the HLV remains in the field just for disassembly and lift of wind turbine components and the heavy load carrier (Decom Tools Vessel) transport the disassembled components to shore. The result of this program for this configuration is shown in Table 3-12 and Figure 3-42.

Table 3-12 Results of Feeder Configuration in Decommissioning of Hornsea 1 OWF (HLV+HLC)

Results of Feeder Configuration in installation of Hornsea 1 OWF (HLV + Decom Tools Vessel)			
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Sailing	0.64	0.6%	$ 128,561.14
Figures of In-Field Transit	0.75	0.7%	$ 149,988.00
Figures of Offshore Construction	74.89	71.7%	$ 14,977,083.33
Figures of Unplanned Activities	28.22	27.0%	$ 5,644,584.02
Figures of Decom Tools Vessel	145.52	N/A	$ 5,883,469.50
Grand Total	**104.50**	**100.0%**	**$ 26,783,685.99**

According to Table 3-12 and Figure 3-42, we can interpret and conclude the following:

- The duration of decommissioning of this wind farm in this configuration calculated 104.5 days which is 119 days less than pendulum configuration. With jack up vessel, about 56.24 days of the project is belonged to positioning the jack up vessel which this duration is not applied for the heavy lift vessel.
- 0.64 days is the sailing time between port to wind farm.
- In-field sailing (between turbines) takes 1.89 days.
- Disassembly and lifting operation constitute 74.89 days (70.6%). The duration will not be changed by changing of logistic configuration.
- It should be noted that unplanned activities mean waiting on weather (WOW), waiting on client (WOC) and mechanical breakdown in this research. For the heavy lift vessel, the waiting on weather (WOW) is considered 35%[31] and waiting on client and

[31] Since the DP2 HLV is a floating vessel, it has all 6 motions. Therefore, in addition to the wind other environmental load such as wave, swell, current etc will impact the workability of the vessel. So, in the North Sea, the waiting on weather for HLV is considered 35%.

mechanical breakdown is assumed 2%. Therefore, in this case the duration of bad weather is 26.7 days and mechanical break down and WOC is 1.53 days.

Conclusion: The overall cost of decommissioning of this wind park with this logistic configuration is **$26,783,685.99** considering 200 000$ for the charter rate of the heavy lift vessel and 40000$ for the charter rate of Decom Tool vessel

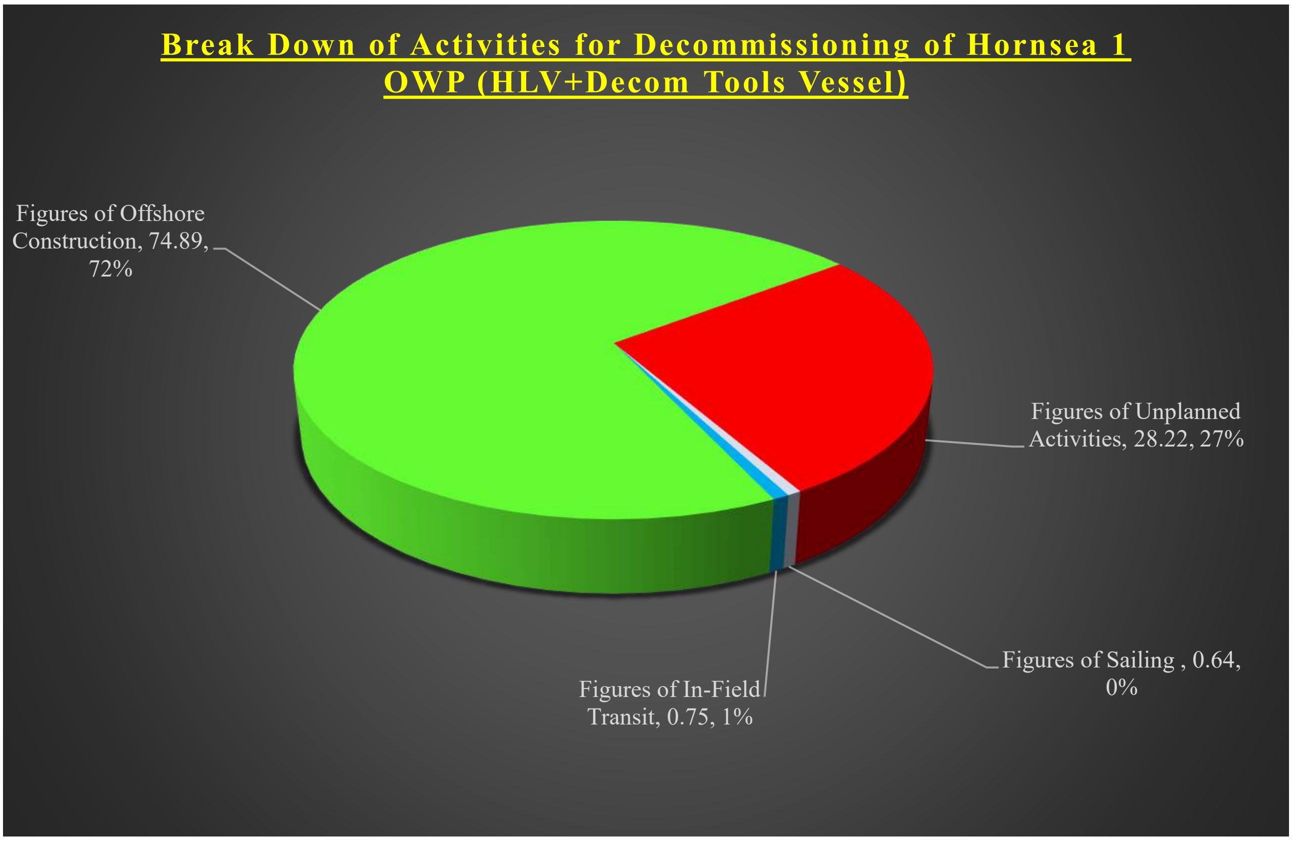


Figure 3-42 Break Down of Hornsea 1 offshore Wind Farm Decommissioning with a HVL + Decom Tools Vessel

3.10.2.2.3 Time-Cost-Consumption-Emission Comparison of Various Logistic Configurations for Decommissioning of Hornsea 1 OWP

In order to summarize the pros and cons of each logistic configuration in decommissioning of Hornsea 1 offshore wind park, the comparison has been made. Table 3-13 compares fuel consumption, CO_2 emission, cost and duration of offshore operation for all three configurations. Furthermore, the difference of each variable for various configurations has been calculated based on base scenario. Having considered that for the installation of wind turbines of this wind park, the pendulum configuration was opted, therefore, base scenario for the decommissioning is the pendulum configuration. Not only the base scenario is the same logistics configuration, but only does it mean the same installation vessel is considered for disassembly and removal.

It means that we have to calculate how much the variables[32] will be in the base scenario, then try to find an optimal, realistic and practical solution in order to optimize the variables. Calculation is based on the technical specification of vessel, wind farms specification and the assumed unplanned activities. The green cells show the best or lowest figure, the red cells show the worst figure, and the yellow cells show the mediocre value.

Table 3-13 Financial, Duration and CO2 Emission Comparison of Various Logistic Configuration in Decommissioning of Hornsea 1 offshore Wind Park

OWP: Hornsea 1	Comparison Table for Disassembly of 91 Wind Turbines		
Configuration	Pendulum	Feeder	
Parameters	DP2 Jack Up	Jack Up+Decom Tools	HLV + Decom Tools
Duration (Day)	223.35	169.89	104.50
	Base Scenario	-53	-119
		24%	53%
Cost ($)	$44,669,095.6	$ 41,937,754.5	$ 26,783,686.0
	Base Scenario	$ (2,731,341.1)	$ (17,885,409.6)
		6.11%	40.04%
Fuel (Tons)	2697.51	2531.69	2049.33
	Base Scenario	-165.82	-648.17
		6%	24%
CO2 Emission (Tons)	8648.20	7742.04	6482.45
	Base Scenario	-906.16	-2165.75
		10%	25%

As it shows, the best configuration in terms of fuels saving, CO_2 emission, project cost and project duration is feeder configuration with utilizing a heavy lift vessel and the designed cargo vessel, Decom Tools Vessel. In this case, duration of offshore operation will be 53% less than base scenario (119 days), the cost will be about 40% less than base scenario $ 17,885,409.6, fuel consumption is 24% less than base scenario and the CO_2 emission will be 25% less than the base scenario. Furthermore, the second optimum scenario is again feeder configuration with

[32] Variable here means duration of project, project cost, fuel consumption and CO2 emission.

utilizing a jack up vessel with the Decom Tools vessel. In this case, duration of offshore operation will be 24% less than base scenario, the cost will be about 6.11% less than base scenario, the fuel consumption around 6% less than the base scenario and CO_2 emission will be 10% less than the base scenario which was the pendulum configuration.

Figure 3-43, Figure 3-44, and Figure 3-46 depicts the duration, cost, fuel consumption as well emission of decommissioning of Hornsea 1 respectively.

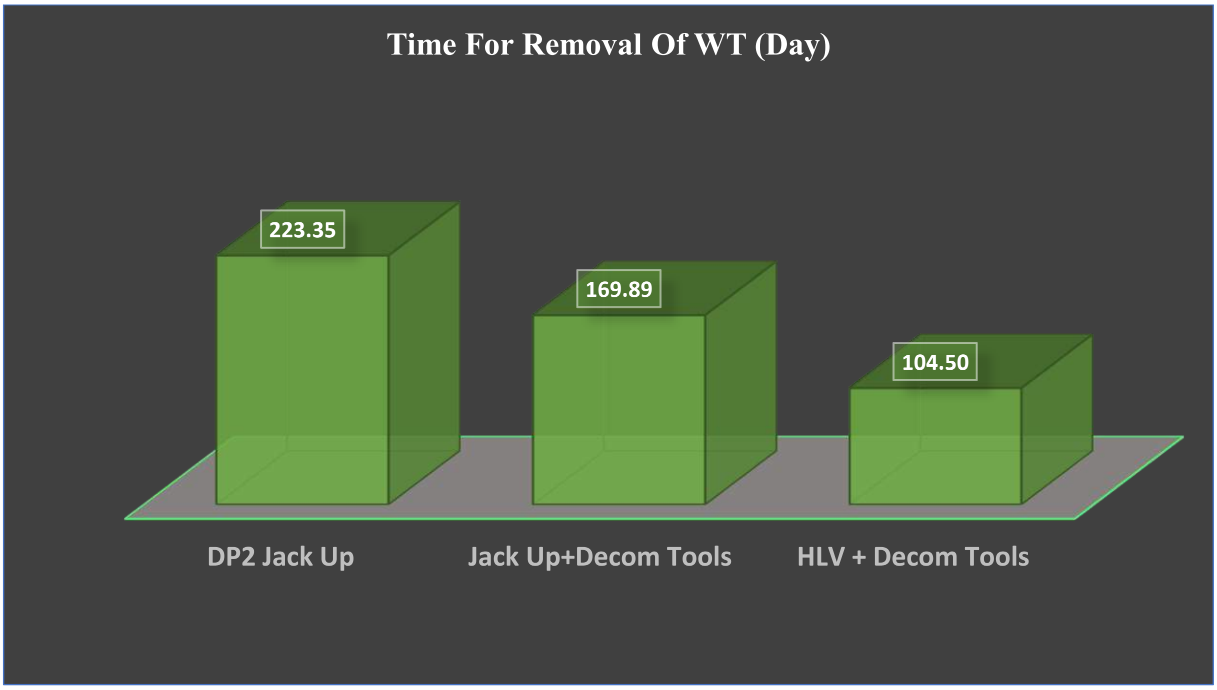


Figure 3-43 Duration of Decommissioning of Hornsea 1 OWP

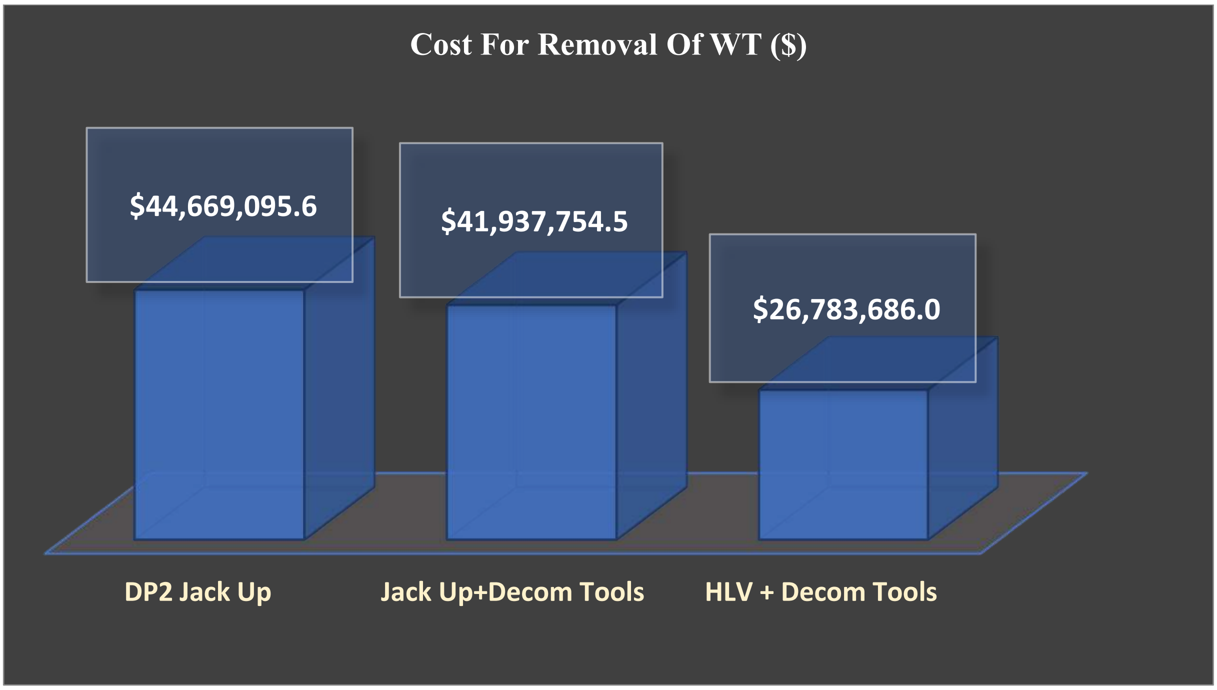


Figure 3-44 Cost of Various Logistic configuration for Decommissioning of Hornsea1 OWP

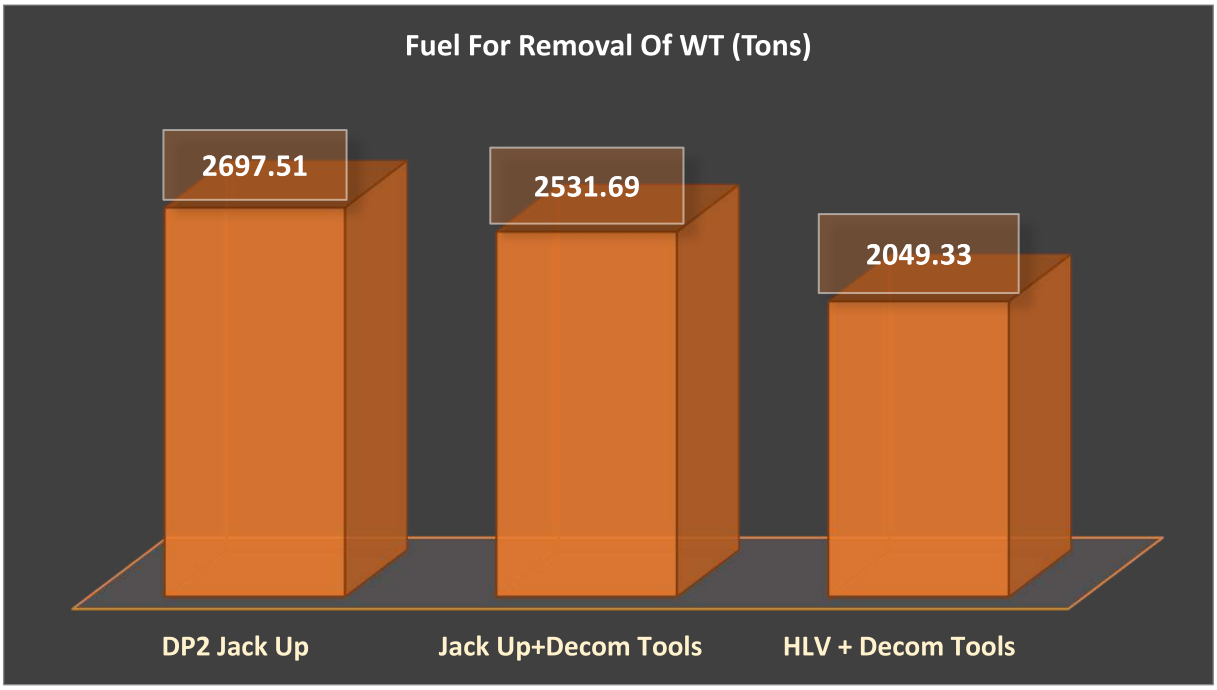


Figure 3-45 Fuel Consumption of Various Logistic configuration for Decommissioning of Hornsea1 OWP

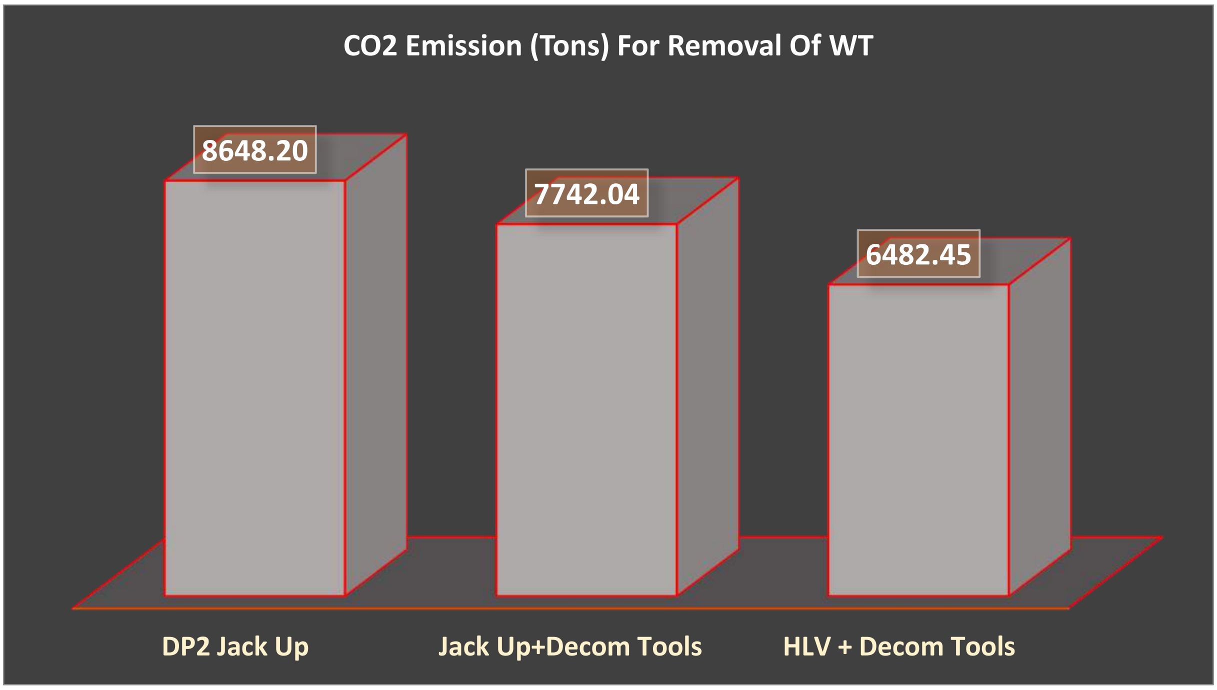


Figure 3-46 CO2 Emission of Various Logistic configuration for Decommissioning of Hornsea 1 OWP

3.10.2.2.4 Conclusion of Comparison of Various Logistic Configurations for Decommissioning of Hornsea 1 OWP

The best logistic configuration for decommissioning of Hornsea 1 wind farm is feeder configuration by using a heavy lift vessel and the designed cargo vessel in the sense that saving in terms of time, fuel consumption, project cost and emission will be achieved. In addition, all the objectives of the Decom Tools can be met with this logistic configuration and the designed vessel for transportation of component to shore.

3.10.2.3 Third Case Study-Hohe See & Albatros Offshore Wind Farm

Hohe See wind farm is located around 95 kilometres north of Borkum and around 100 kilometres north-west of Helgoland in the water depth of 40 meter. It consists of 71 numbers of 7.0 megawatts Siemens wind turbine with hub height of 105 meter and the rotor diameter of 154 meter. While (Hohe See Extension) Albatros lies 105 kilometres from both Borkum and Helgoland coast and consists of 16 number of above-mentioned turbines. Figure 3-47 shows the schematic of these two wind farms. Brave Tern and Blue Tern which are two DP2 Jack-up vessel installed this wind park with tandem[33] configuration. According to official website of the transportation and installation contractor, half of the wind turbines were installed by Brave Tern and another half by Blue Tern (Fred. Olsen Windcarrier 2019). Figure 3-48 shows installation of this wind parks by these two fleets. On 5 April 2019, Brave Tern (a jack up DP2 Vessel) installed first turbine on Hohe See and the last turbine installation completed on the 12 August 2019. After completion of installation of Hohe See turbines, installation of first turbine on the Hohe See extension commenced on 21 August 2019 and the last turbine emplaced on 20 September 2019. The installation of a total of 87 Siemens Gamesa SWT-7.0-154 turbines at the Hohe See completed on 20 September 2019 which means installation took 169 days (Fred Olsen n.d.) (Fred. Olsen Windcarrier 2019). Having considered that in installation of these two wind farms, two jack-up vessels which have almost similar specification have been involved, we can assume that if just one vessel used for installation of this wind farm, the duration would take 302 days (however, it cannot be so accurate estimation).

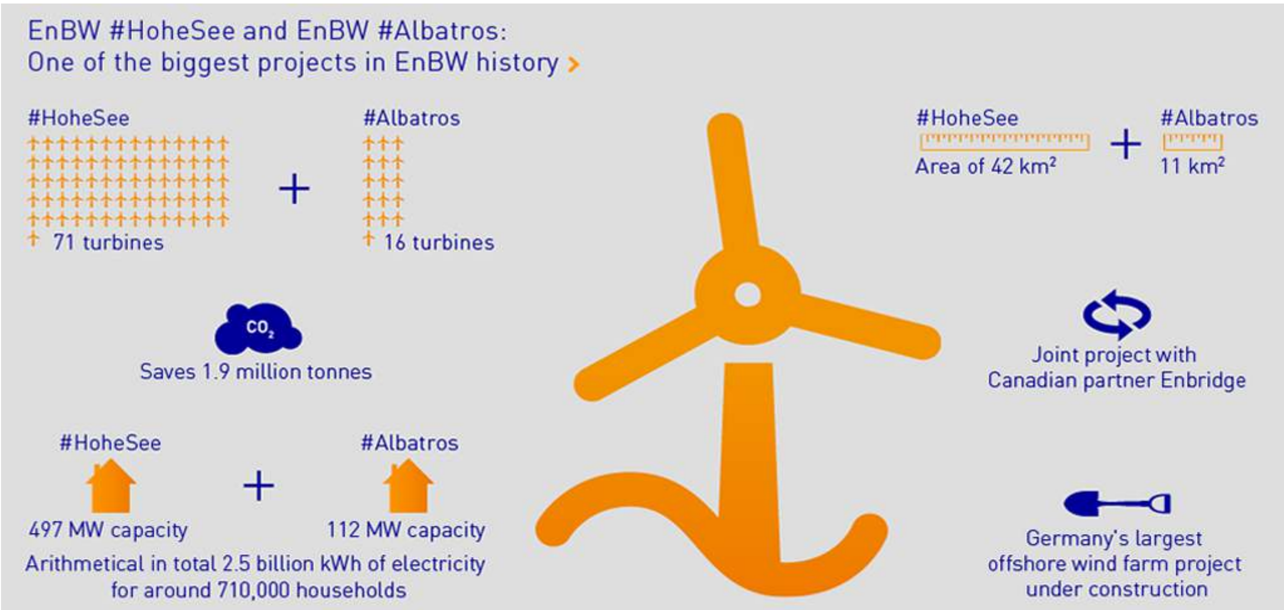


Figure 3-47 Facts and Figures about Hohe See and Albatros Wind Farm (EnBw n.d.)

[33] Tandem configuration means two installation vessels simultaneously installed the wind park turbines.

Figure 3-48 Tandem Installation of Hohe See Wind Farm in Germany

Note: In the tandem configuration (when two or more vessels work simultaneously), both vessels face bad weather at the same time. The duration of waiting on weather will be the same for both vessels in the same OWP, depending on the vessel's stability. Then in case of employing same equipment and equal number and qualification of crew, the duration of operation will be the same approximately.

3.10.2.3.1 Time-Cost Analysis of Hohe See & Albatros OWP Decommissioning with Pendulum Configuration (Reverse to the Installation)

The logistic configuration for the installation was pendulum configuration. Therefore, the base scenario for the decommissioning will be pendulum configuration with the same installation vessel. Having considered the jack up specification and wind farm specification, the result of developed program demonstrated the following figures for pendulum configuration.

Table 3-14 Results of Pendulum Configuration in Decommissioning of Hohe See OWF (Jack up DP2)

Results of Pendulum Configuration in Decommissioning of Hohe See OWF (Jack up DP2)			
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Positioning	51.80	25.6%	$ 10,360,940.48
Figures of In-Field Transit	1.81	0.9%	$ 361,717.06
Figures of Sailing	9.37	4.6%	$ 1,874,850.01
Figures of Offshore Construction	71.59	35.4%	$ 14,318,750.00
Figures of Offloading	24.47	12.1%	$ 4,893,750.00
Figures of Unplanned Activities	42.94	21.3%	$ 8,588,702.04
Grand Total	**201.99**	**100.0%**	**$ 40,398,709.59**

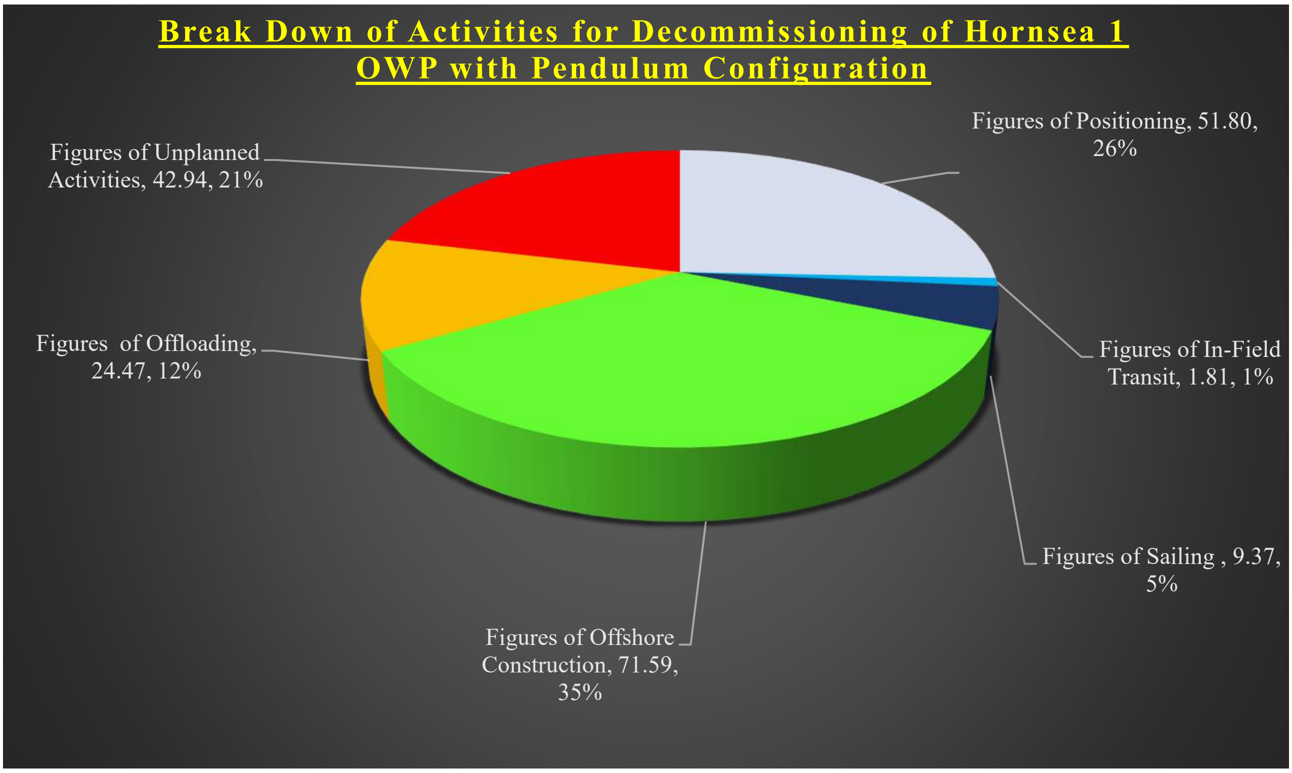


Figure 3-49 Break Down of Hohe See offshore Wind Farm Decommissioning with the Jack Up Vessel

According to Figure 3-49 and Table 3-14, we can interpret and conclude the following:

- The duration of decommissioning of this wind farm in this configuration calculated 202 days approximately with one vessel (Installation took place 169 day with two vessels).
- Approximately 25.6% (51.80 Days) of the project is just related to positioning the jack up vessel which means making the jack up vessel ready for operation.
- 12.1% (24.47 days) of the operation time is just for being at port for offloading the items.
- 4.6% (18.47 days) is for sailing time from port to site (15 times inward + 15 times outward) and,
- 35.4% (72.9 days) of the offshore operation is installation time
- It should be noted that unplanned activities mean waiting on weather (WOW), waiting on client (WOC) and mechanical breakdown. For the jack up vessel, the waiting on weather (WOW) is considered 25% and waiting on client and mechanical breakdown is assumed 2%.

It should be noted that the daily charter rate of the construction vessel (the day rate of jack up which should be used for disassembly is considered 200000$).

3.10.2.3.2 Time-Cost Analysis of Hohe See OWP Decommissioning with Feeder Configuration (Jack Up vessel + Decom Tools Vessel)

In this configuration, the jack up vessel which was used for installation of this OWP is considered for disassembly and lifting of turbines components. Furthermore, a heavy lift carrier (cargo vessel) which is designed as a part of this research (the Decom Tools vessel) is considered for transportation of disassembled items to port or decommissioning yard for further disassembly, recycling etc. Table 3-15 shows the results of decommissioning by this configuration. As you can see in this configuration, the duration of offshore operation is reduced to 160 day which means 24% reduction in duration of offshore operation.

Table 3-15 Results of Feeder Configuration in Decommissioning of Hohe See OWF (Jack up DP2 + Decom Tools Vessel)

Results of Feeder Configuration in Decommissioning of Hohe See OWF (Jack up DP2 + Decom Tools Vessel)			
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter (%)**
Figures of Positioning	51.80	32.4%	$ 10,360,940.48
Figures of In-Field Transit	0.62	0.4%	$ 361,717.06
Figures of Sailing	1.81	1.1%	$ 124,990.00
Figures of Offshore Construction	71.59	44.8%	$ 14,318,750.00
Figures of Unplanned Activities	33.97	21.3%	$ 6,794,927.34
Figures of Decom Tools Vessel	179.13	N/A	$ 7,208,775.04
Grand Total	**159.81**	**100.0%**	**$ 39,170,099.91**

According to Table 3-15 and Figure 3-50, we can interpret and conclude the following:

- The duration of decommissioning of this wind farm in this configuration calculated 159.81 days which is 42 days (21%) less than pendulum configuration.
- Approximately 32% (51.8 Days) of the project is just related to positioning the jack up vessel which means making the jack up vessel ready for operation.
- 0.4% (0.62 days) is for sailing time from port to site (1 time inward + 1 time outward).
- Infield transits constitute 1.1% of the offshore operation. In this mode. The service speed of the vessel is 1 knot.
- 44.8% (71.6 days) of the offshore operation is construction time (the time of disassembly).
- It should be noted that unplanned activities mean waiting on weather (WOW), waiting on client (WOC), mechanical breakdown etc. For the jack up vessel, the waiting on

weather (WOW) is considered 25% and waiting on client and mechanical breakdown is assumed 2%. This time is calculated 34 days approximately.

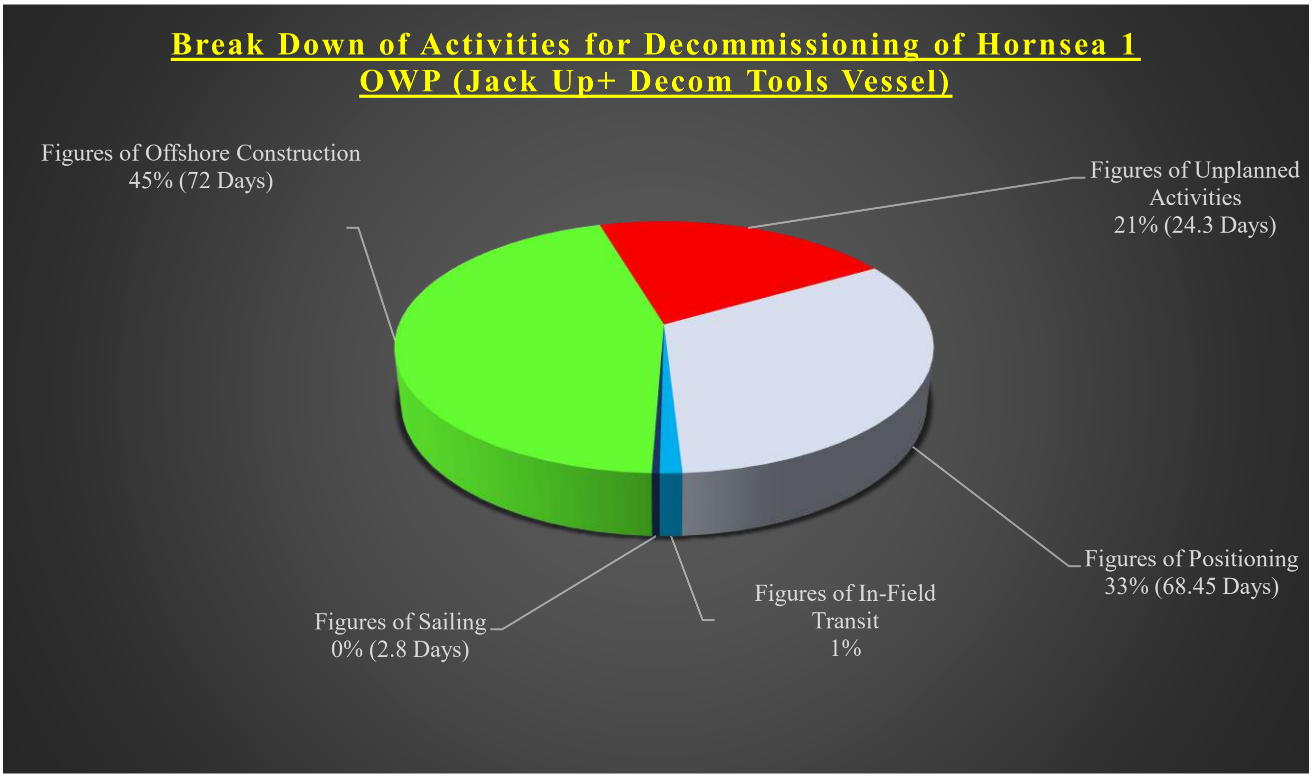


Figure 3-50 Break Down of Hohe See offshore Wind Farm Decommissioning with a Jack Up + Decom Tools Vessel

Important Note: The duration of disassembly and lifting does not change with change of logistic configuration.

- It should be noted that unplanned activities mean waiting on weather (WOW), waiting on client (WOC), mechanical breakdown etc. We consider unplanned activities 15% of sailing and installation time.

Conclusion: The overall cost of decommissioning of this wind park with this logistic configuration is **$39,170,099.91**, considering 200 000$ as charter rate of the jack up vessel and 40000$ as charter rate of Decom Tool vessel.

3.10.2.3.3 Time-Cost Analysis of Hohe See OWP Decommissioning with Feeder Configuration (DP2 HLV+Decom Tools Vessel)

Another calculation with the developed program has been made for another logistic configuration. In this configuration, combination of a heavy lift vessel along with the designed heavy lift carrier (Decom Tools vessel) assumed to carry out decommissioning of this wind farm. In this configuration, the HLV remains in the field just for disassembly and lift of wind turbine components and the heavy load carrier (Decom Tools vessel) transport the disassembled components to shore. The result of this program for this configuration is shown in Table 3-16 and Figure 3-51

According to Figure 3-51 and Table 3-16, we can interpret and conclude the following:

- The duration of decommissioning of this wind farm in this configuration calculated 99.67 days which is 102 days (51%) less than pendulum configuration. With jack up vessel, about 52 Days of the project is belonged to positioning the jack up vessel which this duration is not applied for the heavy lift vessel.
- 0.54 days is for sailing time from port to site.
- Figure of infield transit remain the same as other configuration 1.89 days.
- Disassembly and lifting operation constitute 71.59 days. This duration will not be changed by changing of logistic configuration.

It should be noted that unplanned activities mean waiting on weather (WOW), waiting on client (WOC), mechanical breakdown etc. For the heavy lift vessel, the waiting on weather (WOW) is considered 35% and waiting on client and mechanical breakdown is assumed 2%. Since the jack up vessel is a stable vessel while is positioned, the waiting on weather for jack up vessel is considered 25% and for heavy lift vessel, the waiting on weather is considered 35%. This time is calculated 26.92 days for this logistic configuration.

Again, in this calculation, the charter rate of heavy lift vessel is considered 200000$ and the charter rate of the Decom Tools vessel is considered 40000$. Therefore, the cost of decommissioning is calculated based on above-mentioned charter rates.

Table 3-16 Results of Feeder Configuration in Decommissioning of Hohe See OWF (HLV DP2 + HLC)

Results of Feeder Configuration in Decommissioning of Hohe See OWF (HLV DP2 + Decom Tools Vessel)			
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Sailing	0.54	0.5%	$ 107,134.29
Figures of In-Field Transit	0.62	0.6%	$ 124,990.00
Figures of Offshore Construction	71.59	71.8%	$ 14,318,750.00
Figures of Unplanned Activities	26.92	27.0%	$ 5,383,823.49
Figures of Decom Tools Vessel	137.35	N/A	$ 5,493,860.75
Grand Total	**99.67**	**100.0%**	**$ 25,428,558.52**

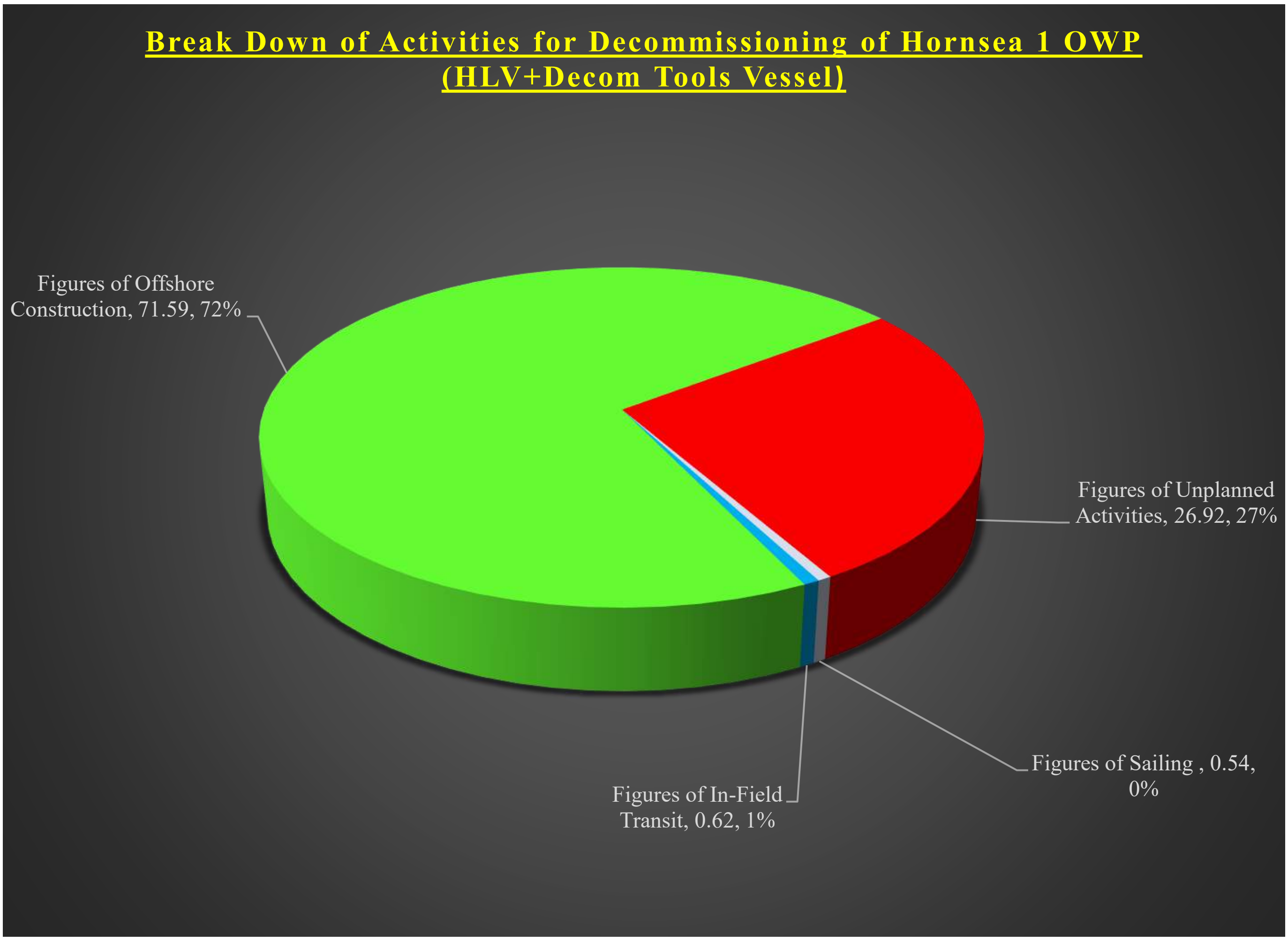


Figure 3-51 Break Down of Hohe See offshore Wind Farm Decommissioning with a HLV DP2+ Decom Tools Vessel

3.10.2.3.4 Time-Cost-Consumption-Emission Comparison of Various Logistic Configurations for Decommissioning of Hohe See OWP

In order to summarize the pros and cons of each logistic configuration in decommissioning of Hohe See offshore wind park, the comparison has been made by the developed program. Table 3-17 compares fuel consumption, CO_2 emission, cost and duration of offshore operation for all three configurations. Furthermore, the difference of each variable for various configurations has been calculated based on base scenario. Having considered that for the installation of wind turbines of this wind park, the pendulum configuration was opted, therefore, base scenario for the decommissioning is the pendulum configuration. Not only the base scenario is the same logistics configuration, but only does it mean the same installation vessel is considered for disassembly and removal. It means that we have to calculate how much the variables will be in the base scenario, then try to find an optimal, realistic and practical solution in order to optimize the variables.

Table 3-17 Financial, Duration and CO2 Emission Comparison of Various Logistic Configuration in Decommissioning of Hohe See OWP

Hohe See & Albatros	Comparison Table for Disassembly of 87 Wind Turbines		
Configuration	**Pendulum**	**Feeder**	
Parameters	**DP2 Jack Up**	**Jack Up+Decom Tools**	**HLV + Decom Tools**
Duration (Day)	**201.99**	**159.81**	**99.67**
	Base Scenario	**-42**	**-102**
		21%	**51%**
Cost ($)	**$ 40,398,709.6**	**$ 39,170,099.9**	**$25,428,558.5**
	Base Scenario	**$ (1,228,609.7)**	**$ (14,970,151.1)**
		3.04%	**37.06%**
Fuel (Tons)	**2640.74**	**2764.66**	**1935.87**
	Base Scenario	**123.92**	**-704.86**
		-5%	**27%**
CO2 Emission (Tons)	**8466.20**	**8513.65**	**6130.80**
	Base Scenario	**47.45**	**-2335.41**
		-1%	**28%**

Calculation is based on the technical specification of vessel, wind farms specification and the assumed unplanned activities.

The green cells show the best or lowest figure, the red cells show the worst figure, and the yellow cells show the mediocre value. As it shows, the best configuration in terms of fuels saving, CO_2 emission, project cost and project duration is feeder configuration with utilizing a heavy lift vessel and the designed heavy load carrier. In this case, duration of offshore operation will be 51% less than base scenario, the cost will be about 37% less than base scenario, fuel consumption is 27% less and the CO_2 emission will be 28% less than the base scenario.

Furthermore, the second optimum scenario from project cost and offshore duration perspective, is again feeder configuration with utilizing a jack up vessel with the designed heavy lift carrier (the Decom Tools vessel).

In this case, duration of offshore operation will be 21% less than base scenario and the cost is about 3% less than pendulum configuration. On the other hand, the fuel consumption is about 5% more and CO_2 emission is 1% more than the base scenario.

Figure 3-52, Figure 3-53, Figure 3-54 and Figure 3-55 show respectively the duration, cost, fuel consumption and emission of decommissioning of Hohe See & Albatros wind farm with three different logistic configurations.

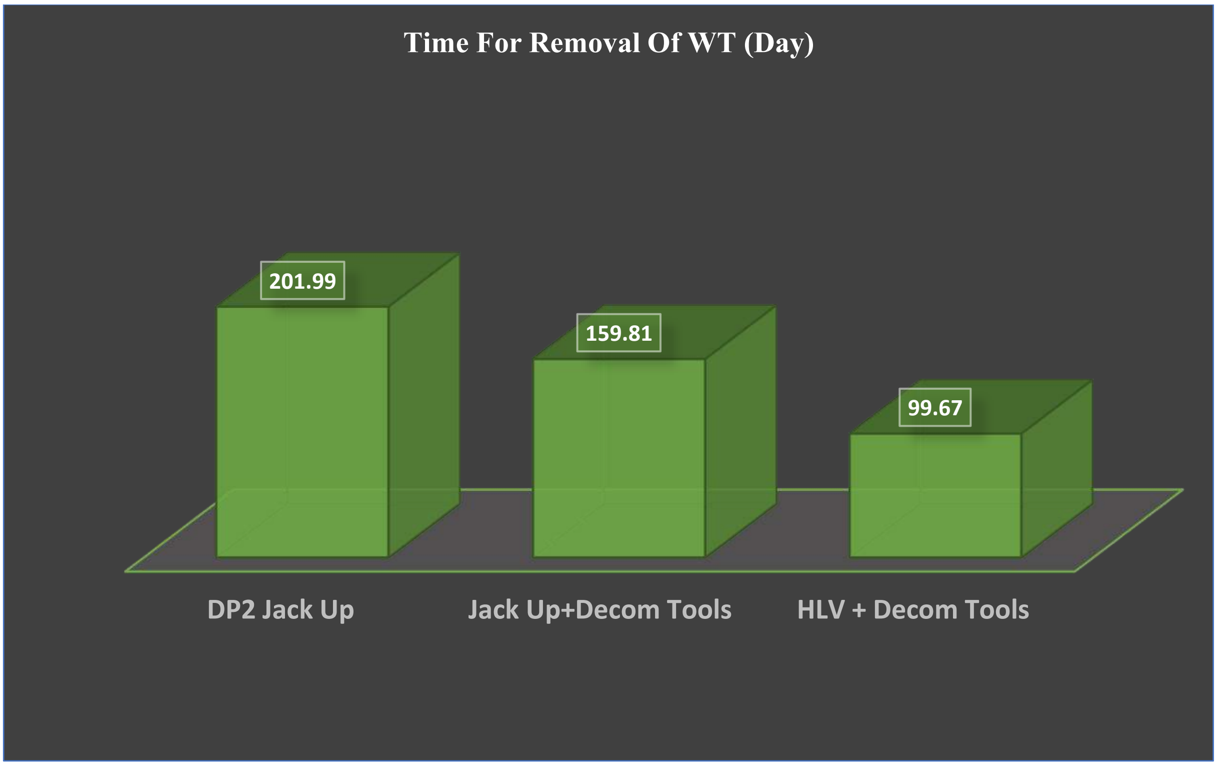


Figure 3-52 Duration of Decommissioning of Hohe See OWP

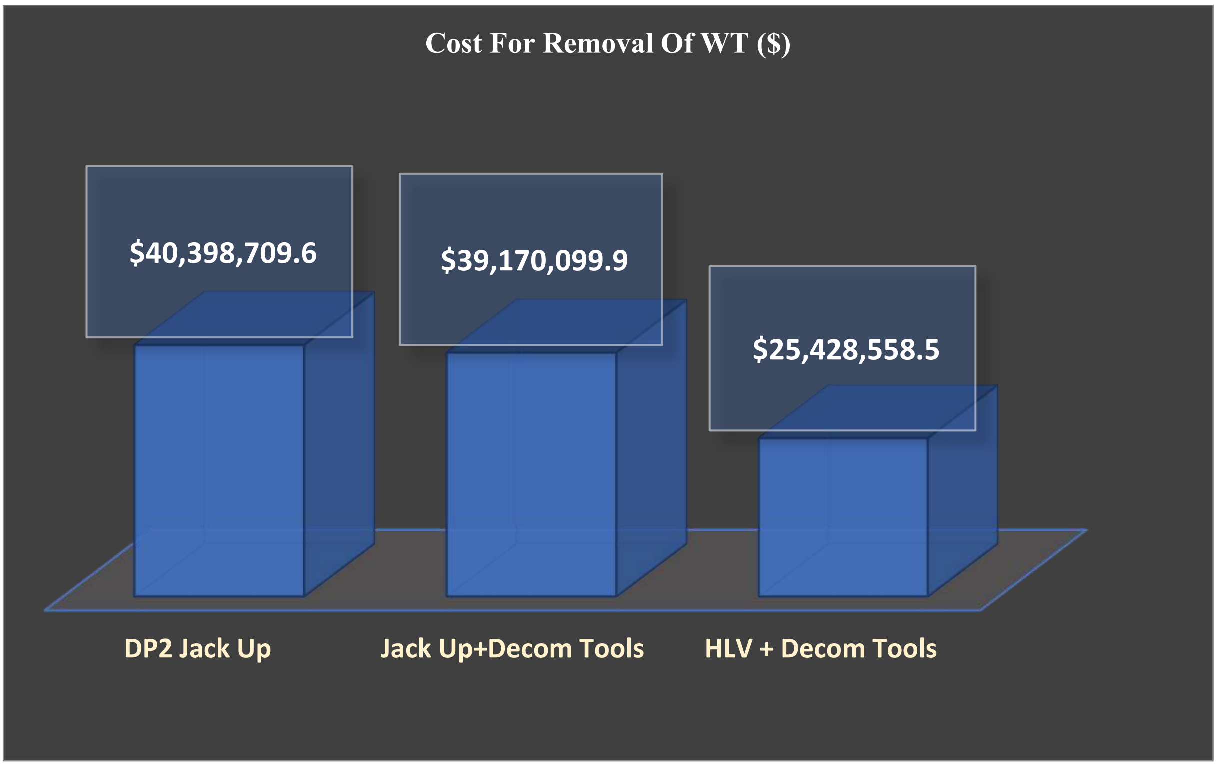


Figure 3-53 Cost of Decommissioning of Hohe See OWP

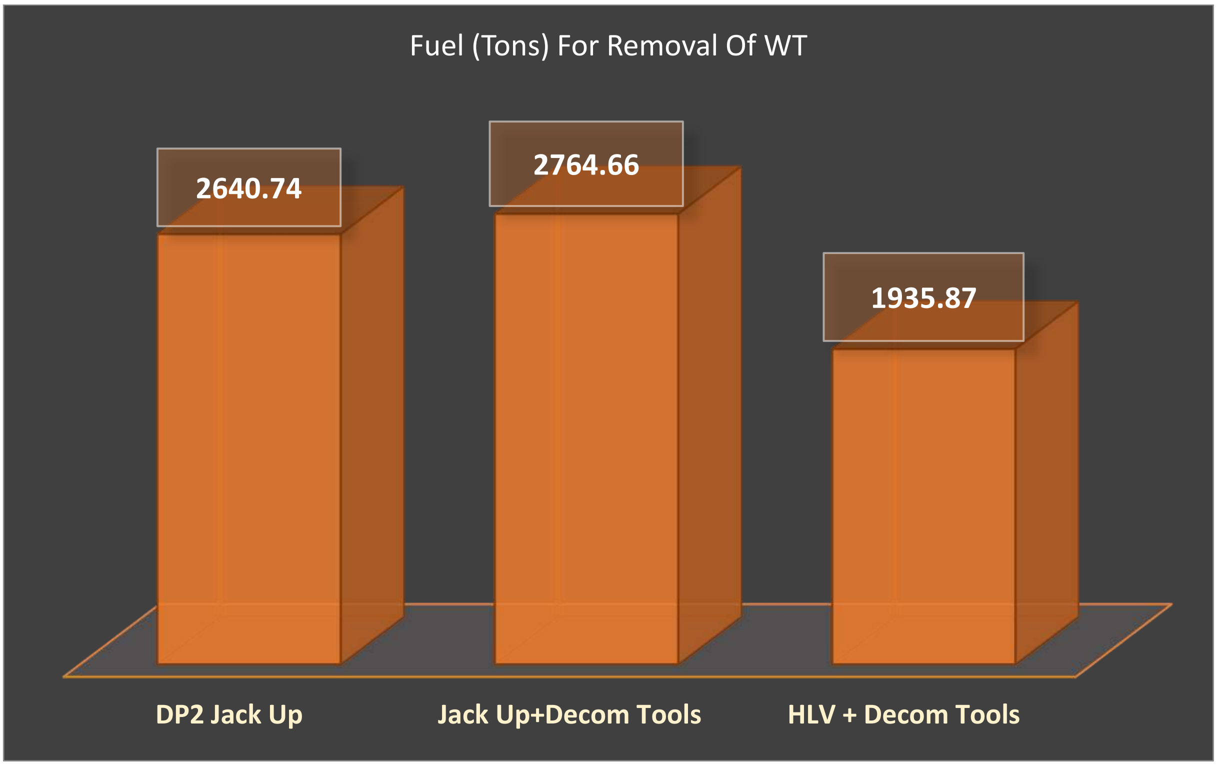


Figure 3-54 Fuel Consumption of Decommissioning of Hohe See OWP

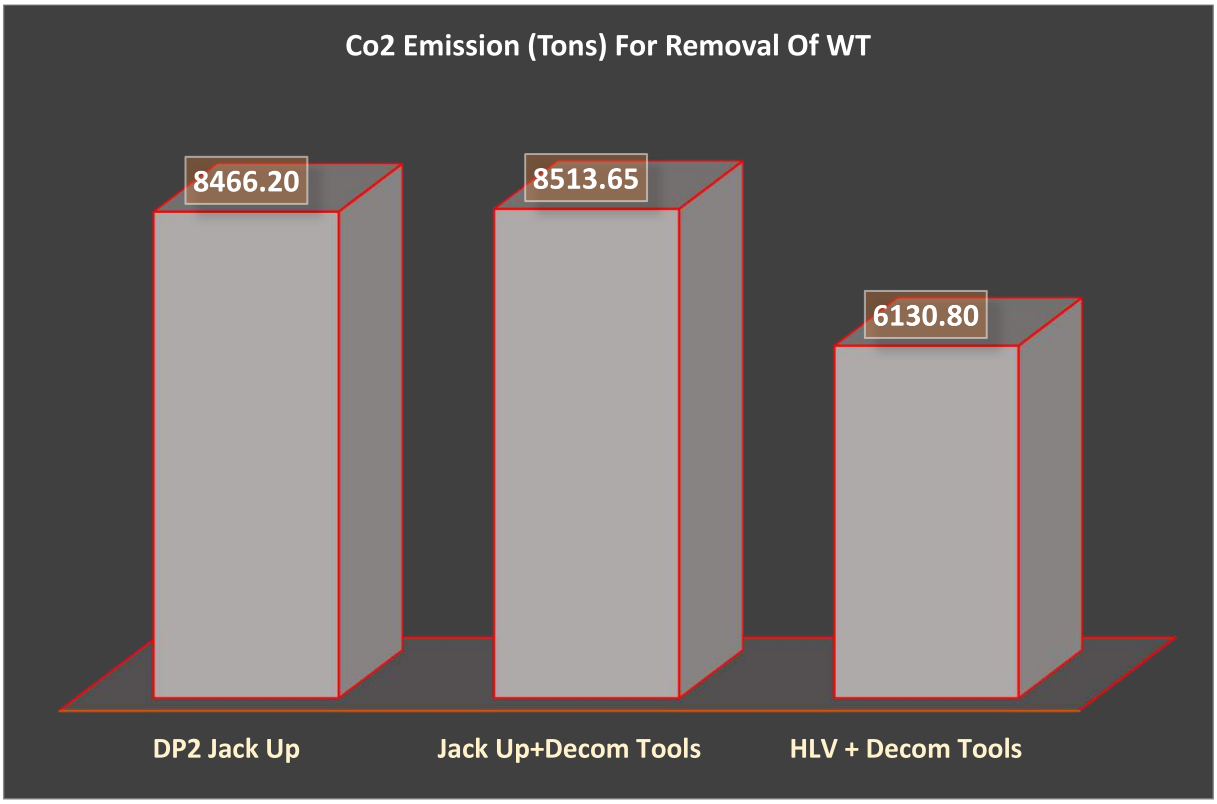


Figure 3-55 CO2 Emission of Decommissioning of Hohe See OWP

3.10.2.3.5 Conclusion of Comparison of Various Logistic Configurations for Decommissioning of Hohe See OWP

The best logistic configuration for decommissioning of Hohe See wind farm is feeder configuration by using a heavy lift vessel and the designed cargo vessel (the Decom Tools vessel) in the sense that saving can be achieved in terms of offshore operation duration, offshore cost, fuel consumption as well as CO_2 emission. Furthermore, all objectives of the Decom Tools can be met with this logistic configuration and the designed vessel during disassembly and transportation of component to shore.

3.10.3 Conclusion of Time-Cost-Consumption-Emission Analysis

In all three cases the optimum logistic configuration is feeder configuration with combination of a heavy lift vessel for disassembly and lifting of rotor, nacelle and tower and the designed cargo vessel (Decom Tools Vessel) in order to transport the components from site to nearest decommissioning yard or port.

Table 3-18 Comparison of Vital Variables of Decommissioning in all Three OWPs

Variables	OWP	Pendulum	Jack Up+ Decom Tools Vessel	HLV+ Decom Tools Vessel
Duration	Noblewind	Base Scenario	19%	48%
	Hornsea 1		24%	53%
	Hohe See		21%	51%
	Average		**21.33%**	**50.67%**
Cost	Noblewind	Base Scenario	0.74%	34%
	Hornsea 1		6.11%	40%
	Hohe See		3%	37%
	Average		**3.28%**	**37%**
Fuel	Noblewind	Base Scenario	-12%	26%
	Hornsea 1		6%	24%
	Hohe See		-5%	27%
	Average		**-3.66**	**25.67%**
Emission	Noblewind	Base Scenario	-8%	27%
	Hornsea 1		10%	25%
	Hohe See		-1%	28%
	Average		**0.33%**	**27%**

The average saving in this configuration with respect to reverse installation which was pendulum configuration in all three cases study are listed in the Table 3-18.

1. **Time saving: 50.67%**

2. **Cost Saving: 37%**
3. **Fuel Consumption:25.67%**
4. **CO_2 emission saving: 27%**

According to the above results and Table 3-18, by design of the Decom Tools vessel and utilization of the feeder configuration with combination of a heavy lift vessel and the Decom tools vessel, the objectives of the Decom Tools project can be achieved.

Table 3-18 shows the value of duration, cost, fuel consumption and emission of all three case studies. The yellow and the green cells shows the average of this parameters in these case studies.

- ❖ In conclusion, the best configuration is a combination of fleet including a heavy lifting vessel (HLV) with designed cargo vessel (Decom Tools vessel).
- ❖ In the decommissioning of Noblewind and Hohe See offshore wind park, the fuel consumption and emission in the logistic configuration by using a jack up vessel and the Decom Tools vessel is more than pendulum configuration. The reasons why fuel consumption as well as emission in these two wind farms are higher than pendulum configuration correlate with the distance of wind farm and the number of wind turbines in a wind farm. Therefore, for the calculation of time, cost, fuel consumption and emission, the factors such as number of wind turbines, the size of them, spec of the vessels, water depth and so forth impact. Consequently, the time-cost-consumption-emission study should be conducted case by case in order to make the right decision.
- ❖ Interestingly same research has been done by Seaway Heavy lifting company in the Netherland which the result is comparable with our findings. Their result can be found in this Link.

4 Ship Propulsion System

4.1 Introduction to Propulsion System

Together with the manoeuvring equipment, the propulsion system of a vessel is undoubtedly the most important system on board. The design and dimensioning of the various propulsion systems depend on various factors, which are described below. Propulsion system always provides the necessary power to keep the ship on the desired course or location at the desired speed. Over 97% of today's ships are equipped with diesel engines. However, in the offshore industry, most of the vessels are equipped with electrical propulsion system. In this propulsion type, electricity is generated by generators. Generators are coupled to the engines which these engines are powered by diesel, then the electrical energy is distributed to the network for various consumers. It should be noted that all the vessels that are equipped with DP, need electrical propulsion system.

In the Figure 4-1 the main components of propulsion system are described.

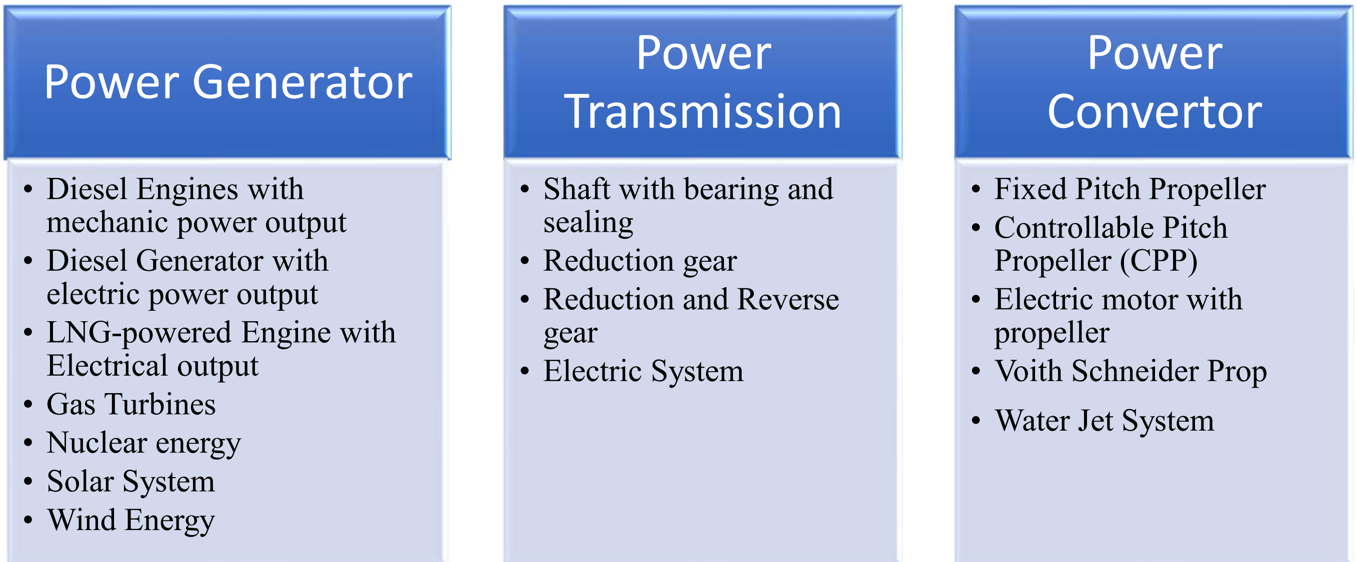


Figure 4-1 Main Components of Propulsion System

In addition to the technological advancement, regulation outlining the measure that need to be taken by ship in yards and ship owners. The shipping industry is under increasing pressure to act upon the Paris Agreement and reduce greenhouse gas (GHG) emissions. The substantial emission reductions which must be achieved over the next decades are expected to drive technology development and, in particular, the introduction of low-carbon fuels. Furthermore, authorities are increasingly paying attention to the consequences of hazardous NO_X, SO_X and particle emissions at the local level.

Prior to selection of the propulsion system for the designed ship, we review all the available, reasonable and feasible propulsion systems in the market. Then the best decision will be made for the design vessel.

4.2 Engine Types

Internal combustion engines are heat engines in which the thermal energy is generated directly in the engine by burning the fuel and partially converted into mechanical energy (rotation of the crankshaft). The most common types of combustion engines are 2 stroke and 4 stroke engines.

4.2.1 4-Stroke Engines

With 4-stroke engines, each cylinder only burns every 2 revolutions. Each of the four work sequences "intake", "compression", "expansion" and "extension" requires a piston movement from bottom dead centre (BDC) to bottom dead centre (TDC) or vice versa, i.e. half a crankshaft rotation. The four work sequences each form a so-called cycle. For gas exchange, four-stroke engines have a valve control system with one or two intake and exhaust valves per cylinder.

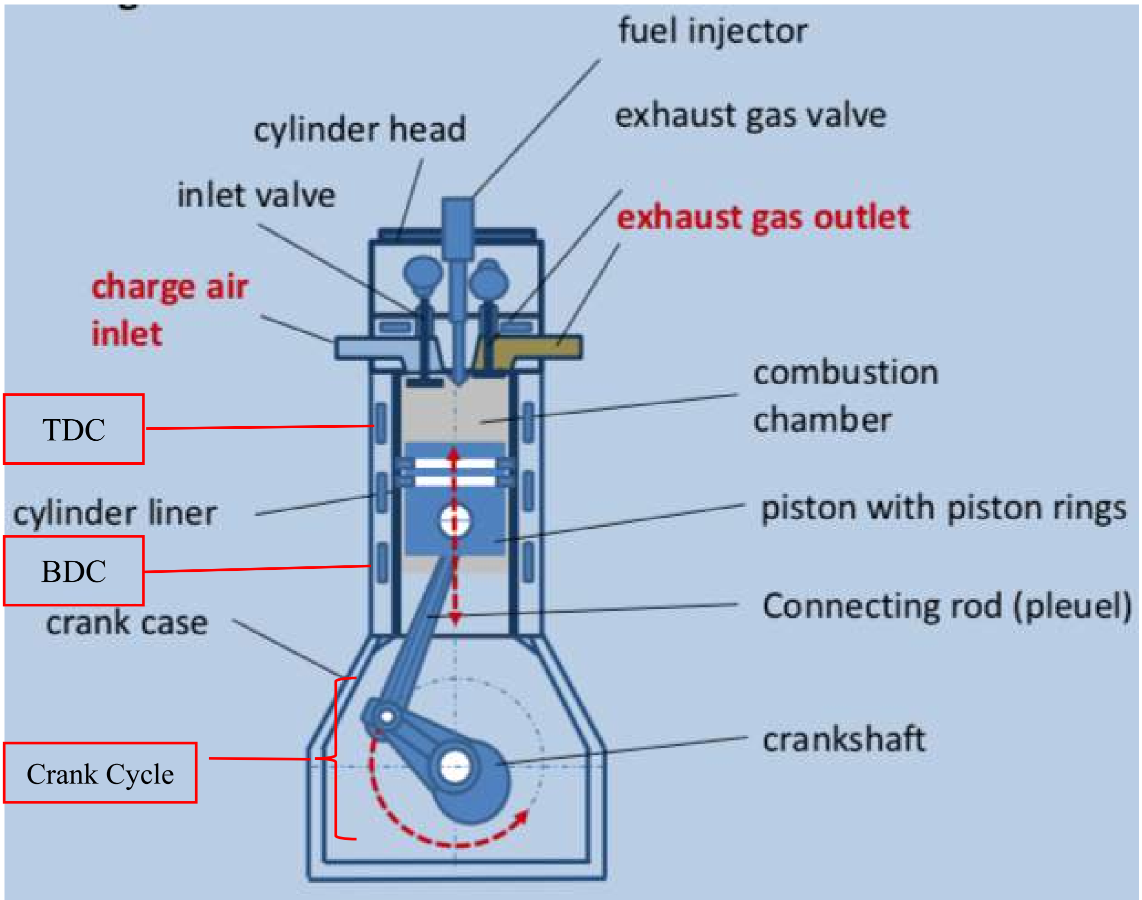


Figure 4-2 Cross Section of 4 Stroke Diesel Engine

In the four-stroke engine makes use of four distinct piston strokes for its operating cycle (see Figure 4-2 and Figure 4-3). This internal combustion engine's cycle requires two passes within the cylinder, completing two 360° revolutions of the crankshaft and the piston. The four stroke engines are the most common and popular engines in the market.

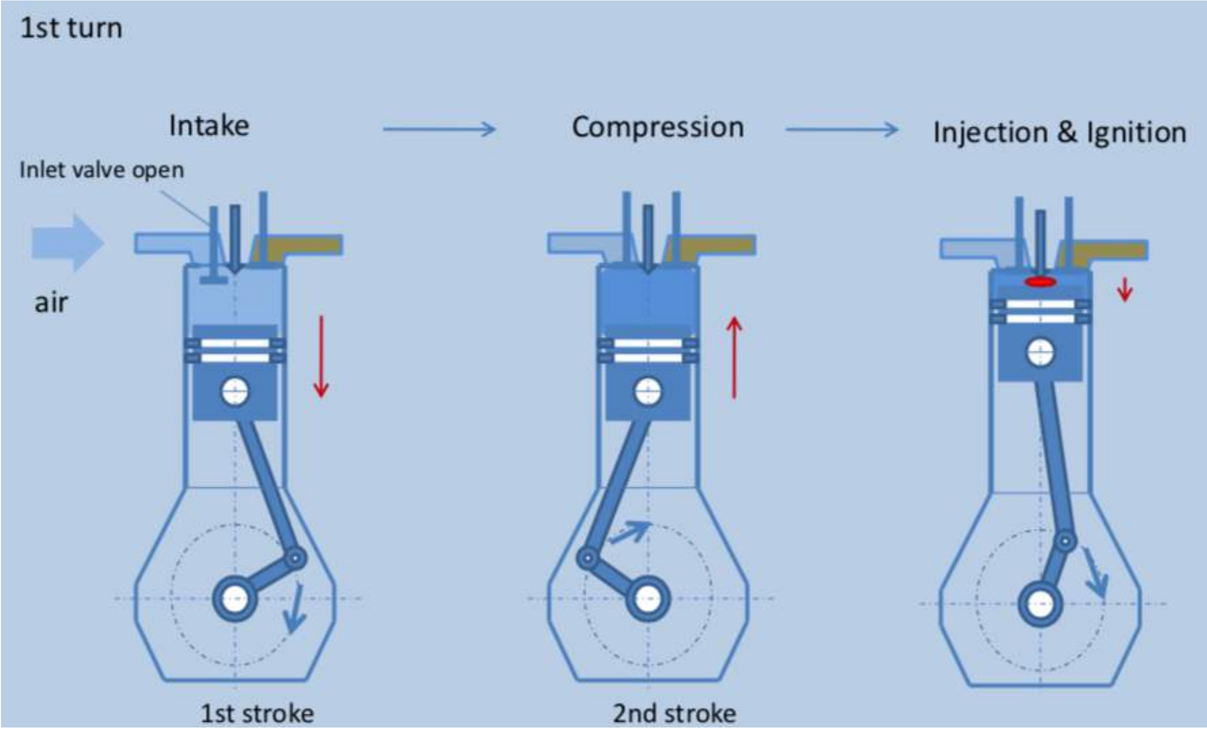


Figure 4-3 First and Second Stroke of 4-Stroke Engine

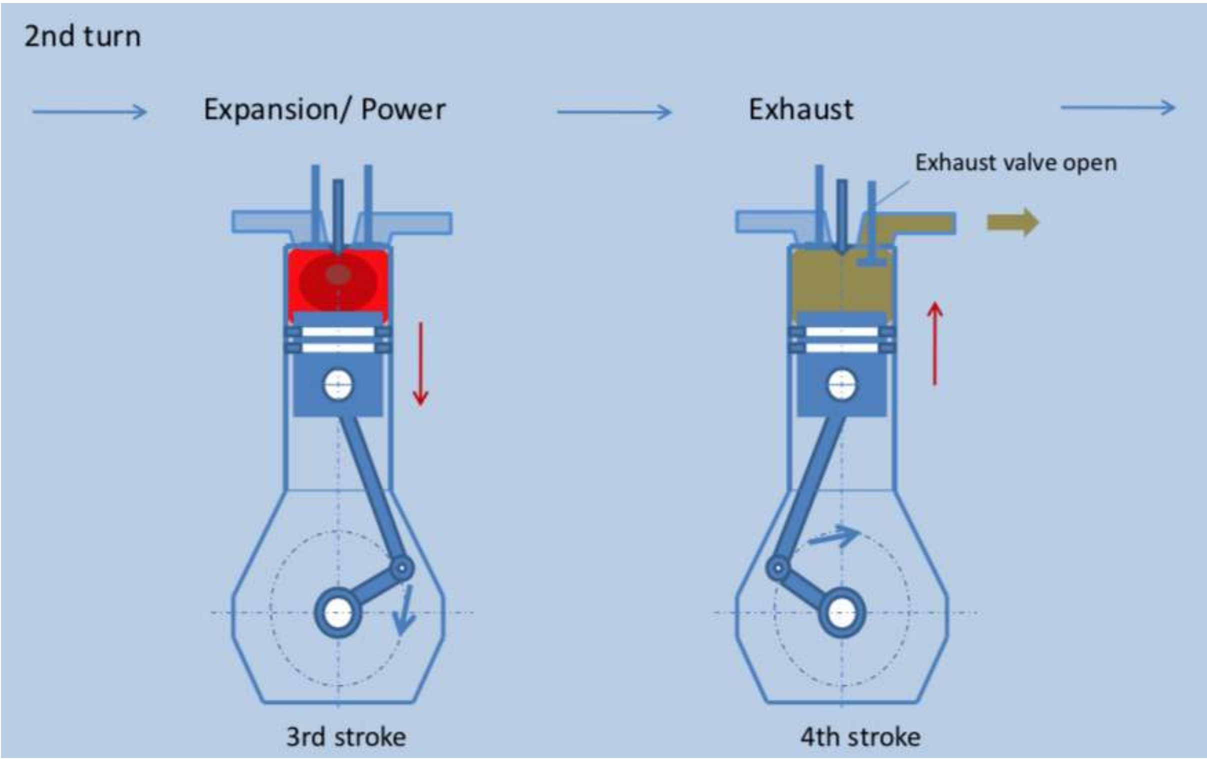


Figure 4-4 Third and Fourth Stroke of 4-Stroke Engine

4.2.2 2-Stroke Engines

The process of two-stroke engines is the same as a four-stroke, but combustion complete in one revolution of the crankshaft only. The engine is designed in such a way that the Induction, Compression, Power, and Exhaust steps could occur simultaneously between the two-stroke cycles. This innovation allows for greater efficiency within the process.

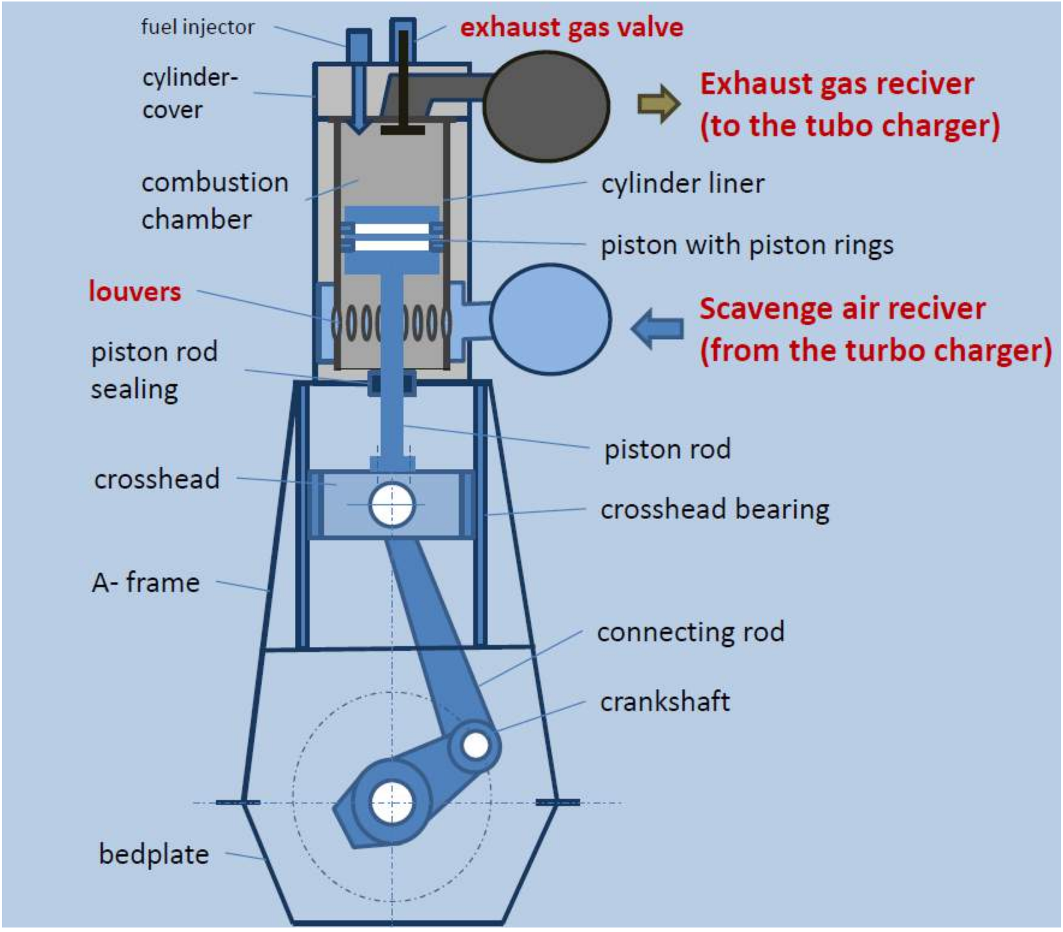


Figure 4-5 Cross Section of 2-Stroke Crosshead Engine

4.3 Efficiency of Four Stroke Versus Two-Stroke Engine

1. Large 2 stroke cross head engines are most efficient combustion engines in the universe.
2. Large 2 stroke cross head engines are today the most powerful combustion engines in the world. (> 80.000 kW)
3. 2- stroke cross head engines are able to rotate in both directions.
4. 2 stroke cross head engines are slow speed engines. (approx. 120 rpm), therefore, it is possible to use without gearbox. Having considered that that energy dissipation occurs in the gearbox, so it means that this type of the engines has higher efficiency.
5. 2-stroke cross head engines deliver a high drive torque which pave the way to install propeller(s) with a larger diameter.
6. In the best condition, the 2-stroke crosshead engine is able to run with a maximum efficiency of 50 – 51% at 100% load at 100% speed. However, the best 4-stroke diesel engines have a maximum efficiency of 45%.

   The thermal energy balance of slow speed 4 stroke cross head engines and 2 stroke cross head engine which shows the mechanical output as well as energy dissipation are shown in the Figure 4-6 and Figure 4-7respectively.

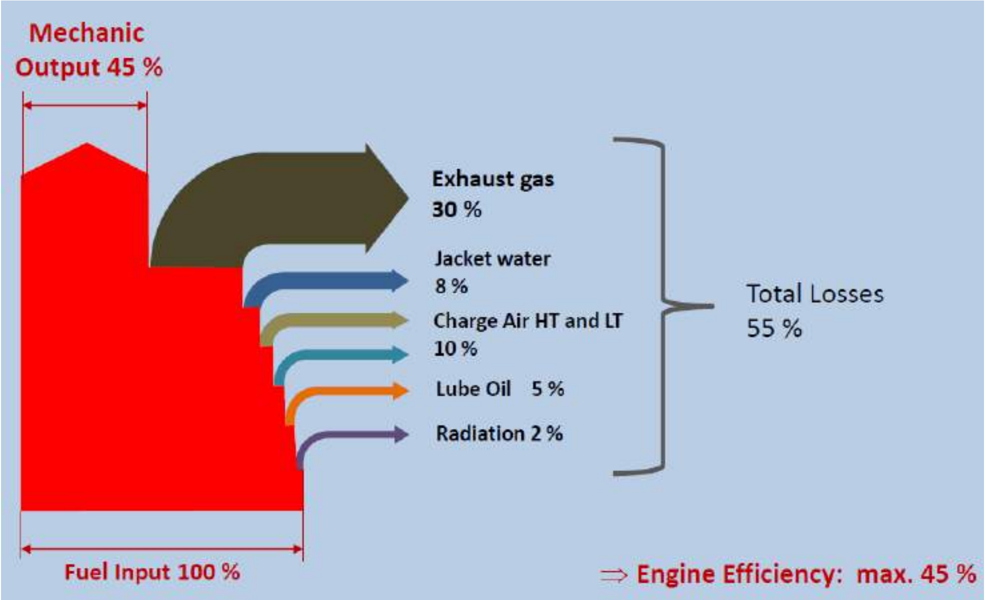


Figure 4-6 Thermal energy balances or Sankey-diagram of 4-Stroke Cross Head Engine (Meyer 2019)

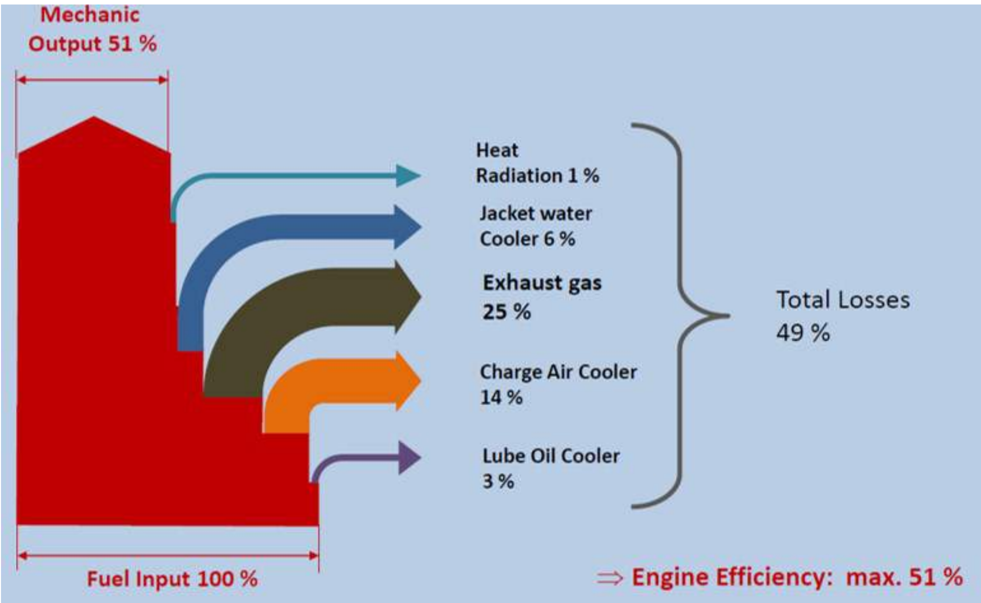


Figure 4-7 Thermal energy balances or Sankey-diagram of 2-Stroke Cross Head Engine (Meyer 2019)

Moreover, Efficiency of engine can be calculated based on following equation.

$$\boldsymbol{Energy\ Effiecieny\ of\ Engine\ (\eta\ engine) = \frac{Mechanical\ Power\ Output}{Supplied\ amount\ of\ Energy} = 45\%\ to\ 51\%}$$

In general, it can be stated that the highest efficiency in propulsion is achieved when the largest possible quantity of water is moved with the smallest possible acceleration.

But in selection of engine, just the efficiency of the engine should not be considered. Of course, having more efficient engine pave the way for lower consumption as well as less emission, but the availability of them should be considered too. 2-stroke cross head engines are normally large engines which cannot be used onboard the small vessel or the vessels that have DP system.

4.4 Parameters to Select a Suitable Propulsion System

In selection of right propulsion system, several parameters play role as following:

- Ship type /duty,
- Propulsion dynamic/ manoeuvrability,
- Ship speed,
- Space in the engine room,
- Required power,
- Environmental consideration,
- Fuel consumption,
- Routes of voyage (region of operation),
- Regulation and laws (EU-Harbours, US Costal, IMO …),
- Capital and operational expense,
- Ship Dimension and,
- Hull Design.

4.5 Hull Resistance

The most important influential factor for the ship propulsion layout is the hull resistance. The hull resistance is affected by ship design factors as well as external factors:

- Ship dimensions.
- Hull shape.
- Displacement.
- Ship weight.
- Design draught.
- Length / block coefficient.

External Factors:

- Shallow Water Influences
- Salinity (Water Density)
- Heavy Weather Conditions

The hull resistance is calculated by MAXSURF for the design of the Decom Tools vessel. MAXSURF has several modules which one of them is MXSURF Resistance. With this module of MAXSURF, the vessel resistance can be calculated.

4.6 Ship Resistance Coefficient

The ship resistance can be calculated with the following equations. The correlation between the speed, power and the resistance are calculated at the end of this section by MAXSURF.

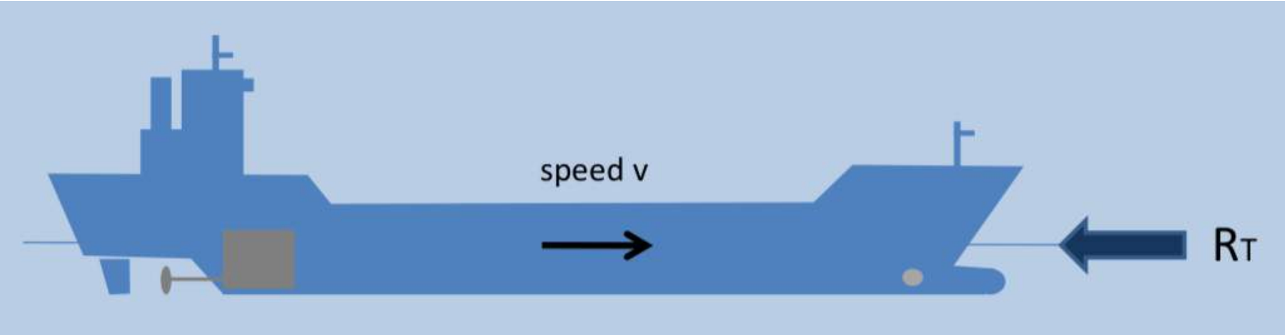


Figure 4-8 Ship Resistance VS Speed

$$R_T = 0.5 * C_{T*} v^2 * \rho_w * s$$

Where:

- R_T = Total Ship Resistance [N]
- S = wet ship hull area [m2]
- ρ_w= water density [Seawater = 1025 kg/m3]
- C_T = Ship resistance coefficient [Dimensionless]

Having considered above, based on the above formula and output of MAXSURF, according to Figure 4-9, the Decom Tools resistance coefficient is shown for the various speed.

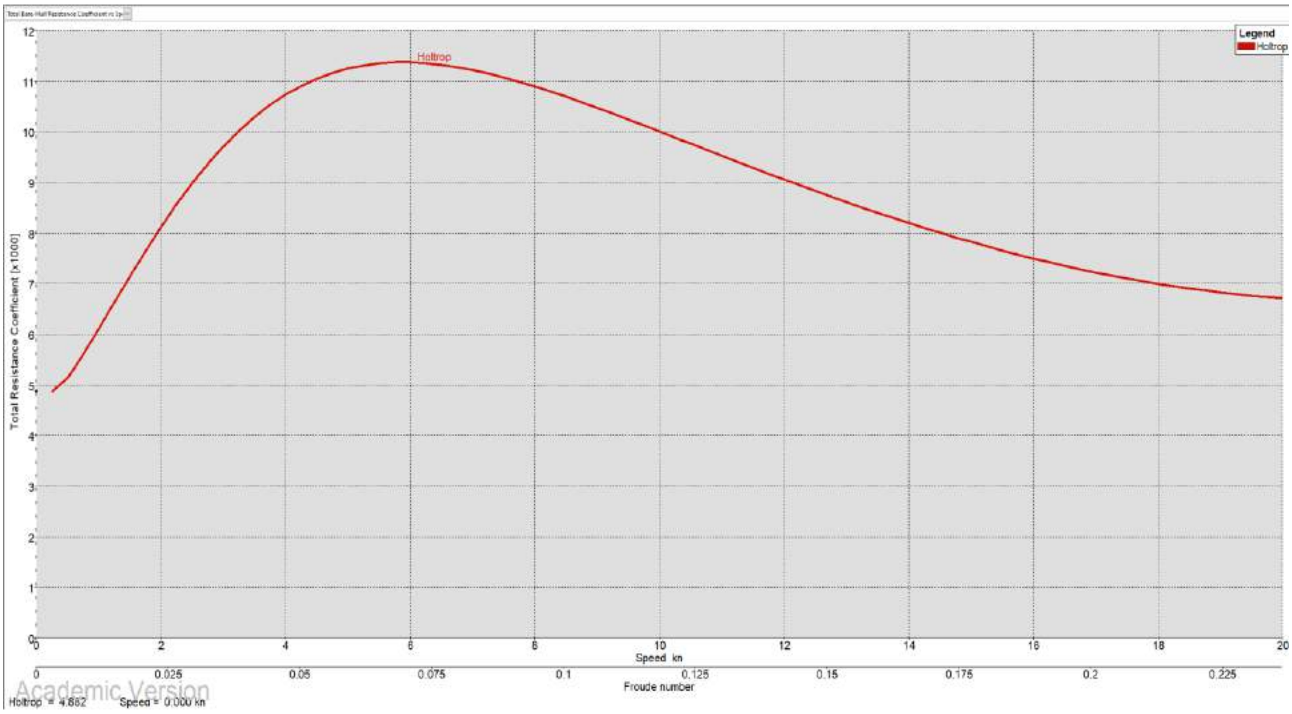


Figure 4-9 Decom Tools Resistance Coefficient

The propeller trust F_T has to be equivalent to the ship hull resistance R_T to run the ship with a constant speed.

$$F_T = R_T$$

To sail the distance S, work W_T has to be done:

$$W_T = F_T * S$$

The necessary thrust power (work /time) for the propulsion system to sail within time:

$$P_E = R_T * V_{Ship} \text{ (KW)}$$

Where:

P_E is Net Propulsion Power (P_E) requirement according to the ship speed:

$$R_T = Ship\ Resistance * v_{ship}^2$$

Where:

R_T is total Ship Resistance [N]

$$P_E = Ship\ Resistance * v_{ship}^3$$

Conclusion: The ship speed has a very high impact to the required propulsion power!

4.7 Selection of Propeller Type

There are various types of the propeller in the market. Here in this section, some of the most common types of propellers are introduced. Selection of propeller is heavily depending on the type of the vessel, the function of the vessel, the size of the vessel, the distance that the vessel has to sail and so forth.

4.7.1 Fixed Propeller

A fixed-pitch propeller is the simplest propeller type. It consists of a series of blades around a hub attached to the end of the rotating propeller shaft. Its popularity derives from its relatively low OPEX and CAPEX. One of the most significant problems is low manoeuvrability of the vessel with this type of propeller. For reversing, the motor must be reversed (change of direction of rotation) or a reversing gear must be provided. Figure 4-10 shows a fixed propeller.

Figure 4-10 Fixed Propeller

4.7.2 Tandem Propeller

In this arrangement, two propellers are mounted on a single shaft turning in the same direction. Tandem propellers are fixed so as to reduce loading on a single propeller as it can lead to cavitation. Here the thrust is divided between the two propellers. In normal loading, they are not of much use but in heavy loading, they produce better loading than a single propeller (Singh 2018).

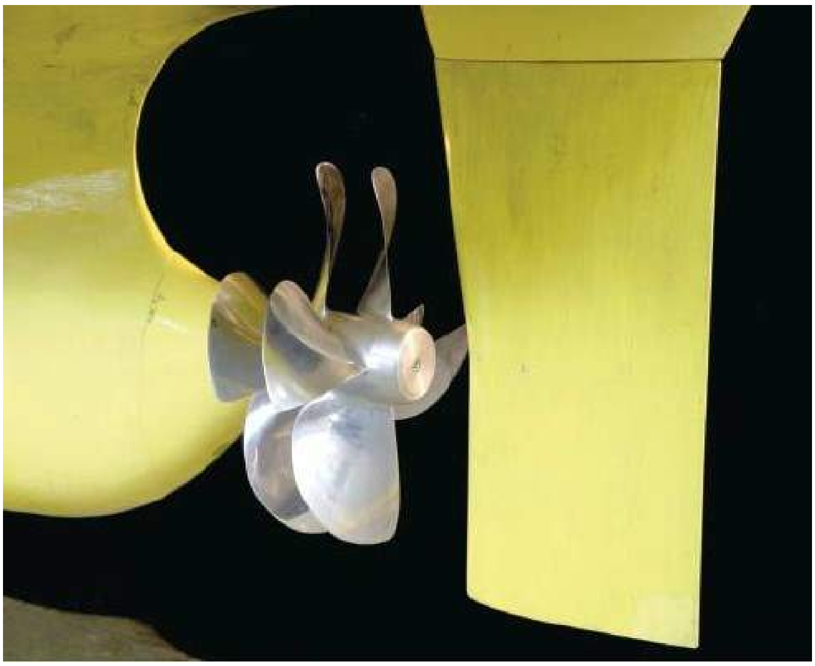


Figure 4-11 Tandem Propeller

4.7.3 Overlapping propeller

It has the same advantage as a tandem propeller as the load is divided between two propellers. There are two propellers with their shafts placed at a horizontal distance less than the diameter of either propeller. They have higher hull efficiency because they work in a region of a higher wake. Sometimes the mutual interaction between the propellers may, however, result in more cavitation (Singh 2018).

Figure 4-12 Overlapping Propeller

4.7.4 Controllable Pitch Propeller

In this type of propeller, the blades are not directly fixed to the boss but attached to separate spindles. The spindles can be turned about the axis and so the pitch of the propeller can be altered. These are mainly used in ships requiring full power at varying speeds and resistances. Some advantages over the conventional fixed propeller are as following.

- They provide better acceleration, stopping and manoeuvring properties.
- Non reversing propulsion machinery may be used thereby reducing its cost, weight and space occupied.
- At all loading conditions, the full power of machinery can be used.
- The speed of the ship can be varied without altering the speed of the main engine.
- Speed can be directly controlled from navigation bridge.
- It is easy to replace damaged blades.

Some disadvantages are:

- The control mechanism is very complex.
- It has high initial cost.
- Maintenance costs are also high (Singh 2018).

Figure 4-13 Pitch Controllable Propeller

4.7.5 Comparison Of Fixed-Pitch Propeller and Controllable-Pitch Propeller

Table 4-1 shows the feature of fixed-pitch propeller and controllable pitch propeller.

Table 4-1 Fixed Pitch Propeller VS Controllable-Pitch Propeller

Fixed-Pitch Propeller	Controllable-Pitch Propeller
For change of direction of thrust the sense of rotation of the shaft has to be changed by reversing the engine itself (starting air) or by reversible gearbox	For reversing thrust direction just pitch is hydraulically changed, number of operations is unlimited, shaft rotation (and RPM) remains unchanged
Minimum ship's speed governed by lowest possible engine RPM, mostly quite high	Minimum ship's speed can be adjusted without technical restrictions
After stopping engine propeller rotates a long time in water flow preventing the engine from restarting	Reversing thrust, especially crash stop, can be initiated without delay
Stopped propeller does barely not impede water flow to and effectiveness of rudder	Rapidly reduced pitch or zero pitch may restrict water flow to rudder resulting in possible loss of steerability
Stopped propeller does not generate ISR	Even at zero pitch ISR is constantly generated
During mooring and unmooring the propeller is not constantly turning (safe)	Propeller turns continuously (danger)

4.7.6 Electrical Propulsion System

4.7.6.1 Azimuth Thruster

Most of the advanced electrical propeller are azimuth. It means that the propeller can rotate to wide range of angels which provide a high manoeuvrability to the vessel. In other words, even large vessel can enter the port or pass the harbour lock quickly and safely. More importantly they can easily manoeuvre inside offshore wind park between the wind turbines. A ship with electrical propulsion does not need rudders, long shaft lines or stern transversal thrusters. ABB is one of the leaders of electrical propulsion system. ABB declares that their electrical propulsion system reduces the cost including fuel consumption and life cycle cost of a ship up to 20%. Consumption of less fuel lead to reduction of emission. In addition, this kind of propulsion system does not have gearbox which result in less dissipation of energy. Therefore, less need for lubricants reduces the potential risk of leakage too. Different models with wide range of application are produced by ABB. The following figure shows the various model of electrical propeller.

Figure 4-14 ABB Electrical Propeller (ABB 2021)

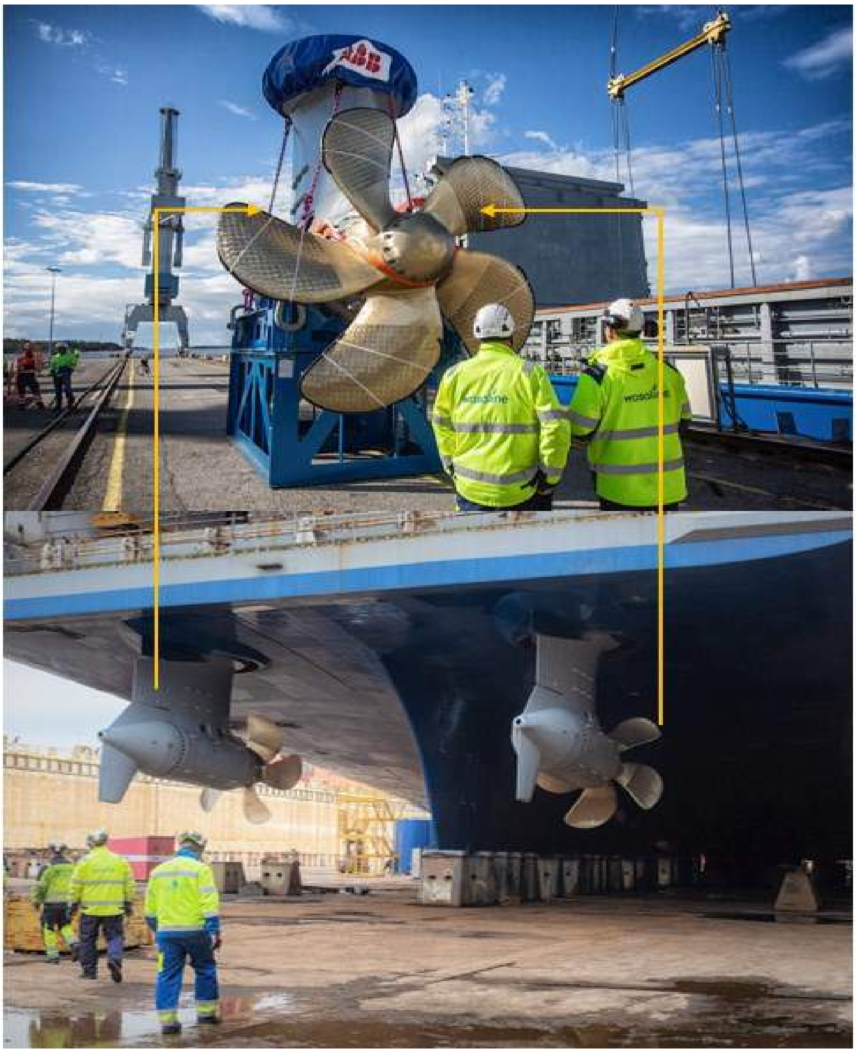


Figure 4-15 ABB Azipod Propeller Installed on a Ferry

Electrical propeller is gearless steerable propulsion system where the electric drive motor is in a submerged pod outside the ship hull. ABB propulsion system is called Azipod® which can rotate 360 degrees to increase manoeuvrability and operating efficiency, with the proven ability to cut fuel consumption by up to 20% compared to traditional shaft line propulsion systems. The following figure shows one of installed ABB Azipod propeller on a new constructed ferry in Finland. Each of the propellers is about 5 meters in height.

4.7.6.2 Voith Schneider Propulsion System

Voith Schneider propulsion system is another type of electrical propulsion system. It means that propellers are not connected to the engine directly or via gearbox. Though the electricity generated by engines and generators should feed this propulsion system. The Voith Schneider propeller generates thrust by means of profiled blades that protrude from the vessel bottom and rotate around a vertical axis. The blades are mounted in a rotor casing which is flush with the bottom of the vessel (Voith n.d., 4). Figure 4-16 shows the cross section of VSP.

The Voith Schneider Propeller (VSP) combines propulsion and steering in one unit, thus allowing prompt, safe and precise manoeuvring, even under adverse conditions. The magnitude of thrust is determined by the rotational speed of the rotor casing; The blade angle determines the direction of thrust. The Voith Schneider Propeller (VSP) is a propulsion system allowing stepless, highly accurate and fast control of thrust in terms of magnitude and direction (Dr. Jürgens and Beu n.d.).

Figure 4-16 Cross Section of Voith Schneider Propeller

4.7.6.3 Advantage of Voith Schneider Propulsion Systems

- The very rapid and precise thrust variation according to cartesian coordinates makes the VSP an ideal propulsion system for efficient dynamic positioning even in extremely rough weather conditions.
- Redundancy of the entire propulsion system, which guarantees full control of the vessel even with only one power train in operation.
- It offers additional roll stabilization[34], which reduces the roll motion of the ship shaped while it is stationary, avoiding the installation of an additional anti-rolling system (like active tanks). It implies that a VSP is a cheaper option compared to a solution of thrusters + active anti-rolling system (Seasteading 2010).

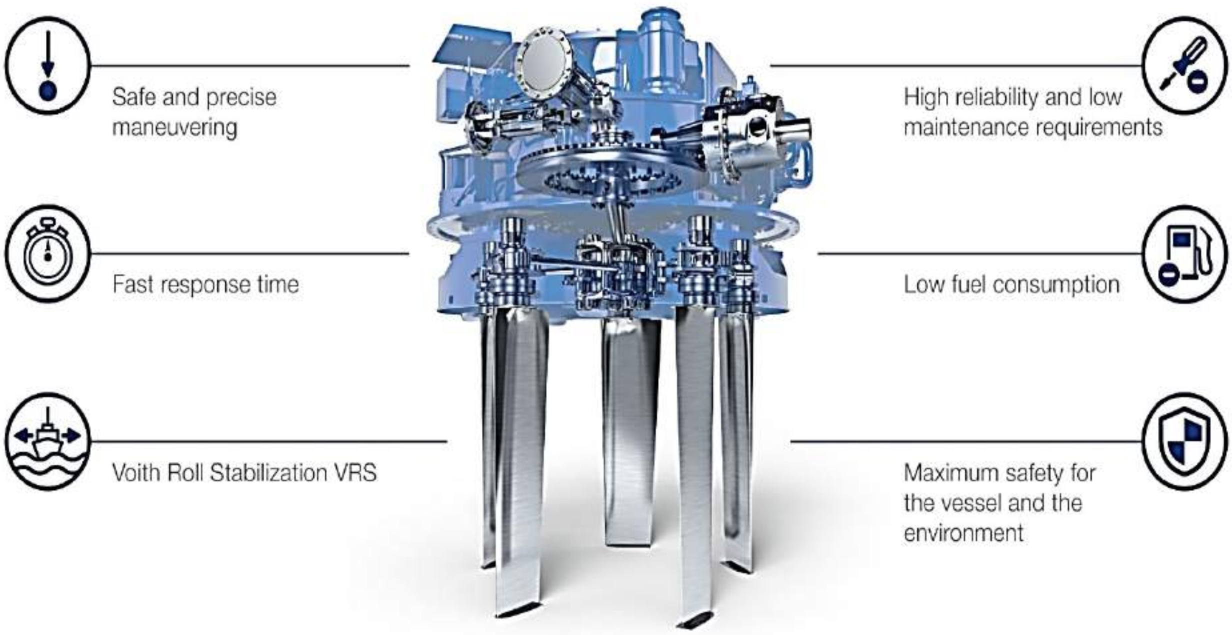


Figure 4-17 Advantage of Voith Schneider Propeller (Voith Schneider n.d.)

4.7.6.3.1.1 Various Size of Voith Schneider Propulsion System

Nowadays, the Voith Schneider produce huge propulsion system for large vessel. Figure 4-18 shows the various size of this type of propulsion system. They produce wide range of propeller for different ship size.

[34] The Voith Schneider Propeller offers additional roll stabilization for OSVs, which reduces the roll motion of the PSV while it is stationary. This additional function has been proven by Voith in theoretical computations with the University of Hamburg-Harburg, during model tank tests and full-scale measurements in the North Sea (Voith Schneider 2019)

Propeller type / size	Control system ME/ECA*	Control system EC**	VRS*** option	Blade orbit diameter A [mm]	Blade length B**** [mm]	Housing heigt C [mm]	Housing diameter D [mm]	Number of gearsteps	Weight without oil [abt. kg]	Oil filling [abt. l]	Max. propeller input power [kW]
VSP 12		x		1200	912	1185	1660	1	3800	380	260
VSP 16		x		1600	1215	1372	2145	1	6700	680	540
VSP 18		x		1800	1512	1480	2405	1	9500	1000	780
VSP 21	x			2100	1766	1755	2815	1 or 2	16000	1600	1000
VSP 26	x			2600	1965	1980	3435	2	27500	2700	1500
VSP 28	x	x	x	2800	2355	2168	3790	2	38500	4300	2000
VSP 30	x			3000	2666	2380	4000	2	47000	4000	2450
VSP 31	x	x	x	3100	2666	2300	4200	1	48000	4000	2500
VSP 32	x	x	x	3200	2666	2371	4250	2	50000	5200	2600
VSP 36	x	x	x	3600	2872	2985	4765	2	75000	7700	3900

Figure 4-18 Voith Schneider Propulsion System Size

4.7.6.3.1.2 Application and Arrangement of Voith Schneider Propeller

Today, Voith Schneider propellers are in use all over the world wherever precise and safe manoeuvring is significant. In the wind industry as well as oil and gas industry a number of vessels such as cable laying vessel (CLV), pipeline installation vessel as well as jack up installation vessel are equipped with Voith Schneider propulsion system namely North Sea Giant[35], Bold Tern and Brave Tern (Fred. Olsen Windcarrier 2020). In addition, many of the offshore support vessels including Seaway Moxie are equipped with VSP for quick and safe manoeuvrability (Subsea 7 n.d.).

Figure 4-19 Seaway Moxie Installation Support Vessel with VSP

[35] The vessel is equipped with 3 numbers of VSP at aft and 2 numbers of VSP at forward (North Sea Shipping 2018).

Figure 4-20 Voith Schneider Propulsion System on Jack Up Installation Vessel

Moreover, the following figures shows the various types of vessels that are equipped with VSP. The yellow colour shows the arrangement of the VSP on the ship.

Figure 4-21 North Sea Giant (Cable Laying and Pipelaying Vessel)

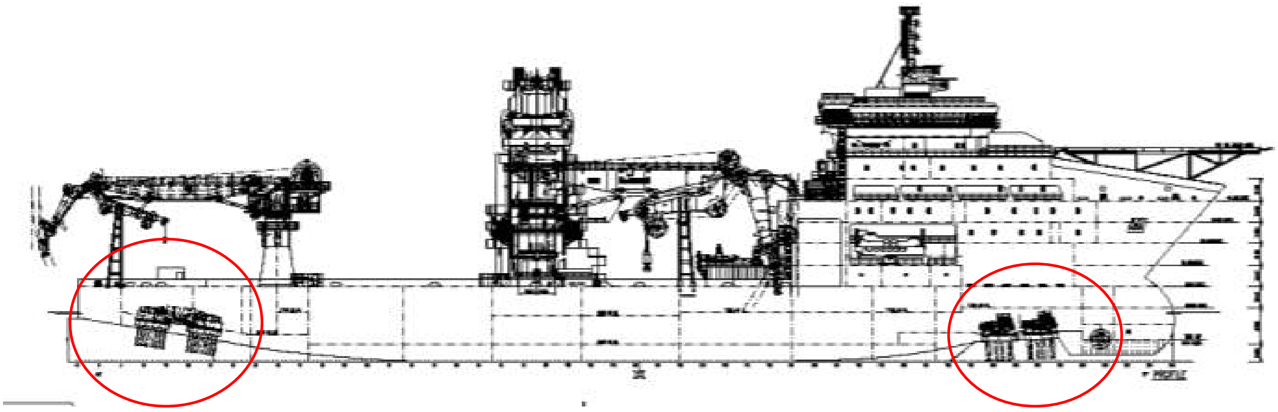


Figure 4-22 Arrangement of Voith Schneider Propeller on North Sea Giant

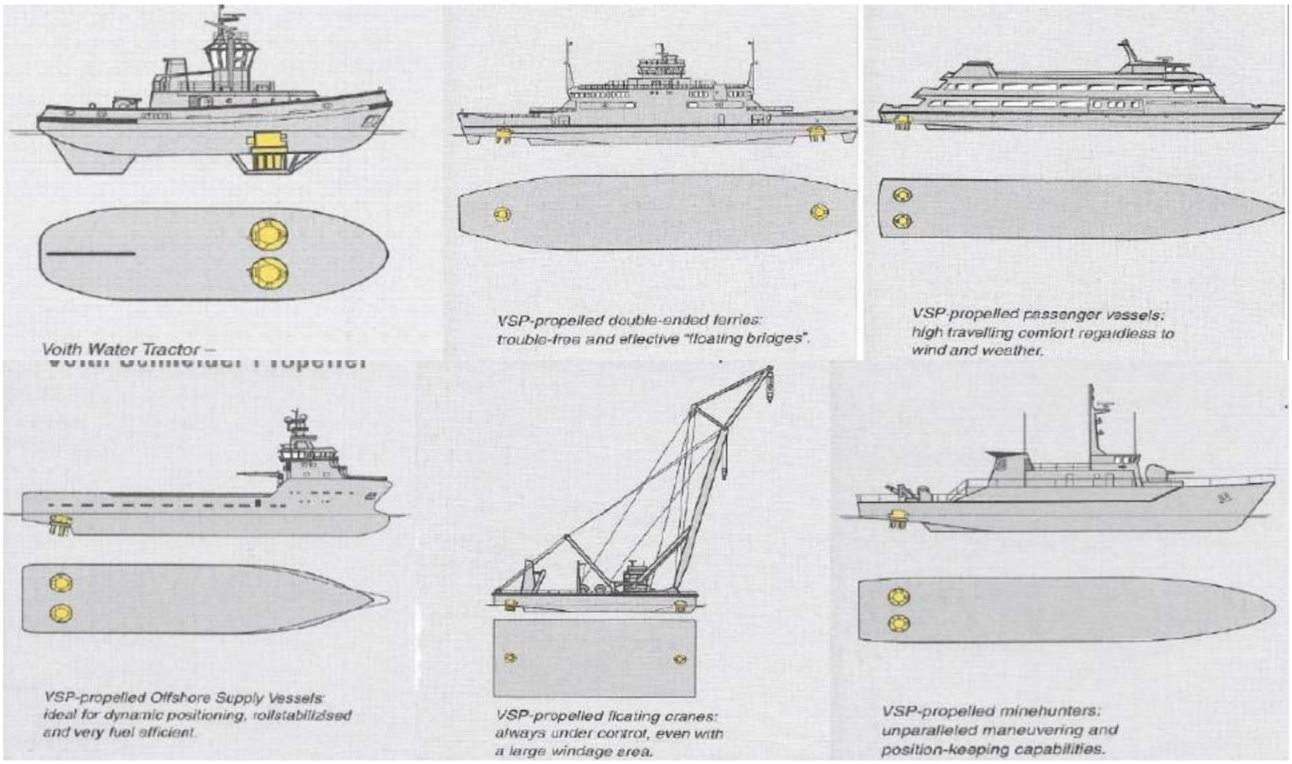


Figure 4-23 Application and Arrangement of VPS on Various Types of Ships

4.7.6.3.1.3 Precision of Positioning of Voith Schneider and Z-Drive

Results of the test of similar offshore supply vessels which were equipped with pod propulsion system and VSP revealed that the VSP has far more positioning precision than Z-drive propulsion system.

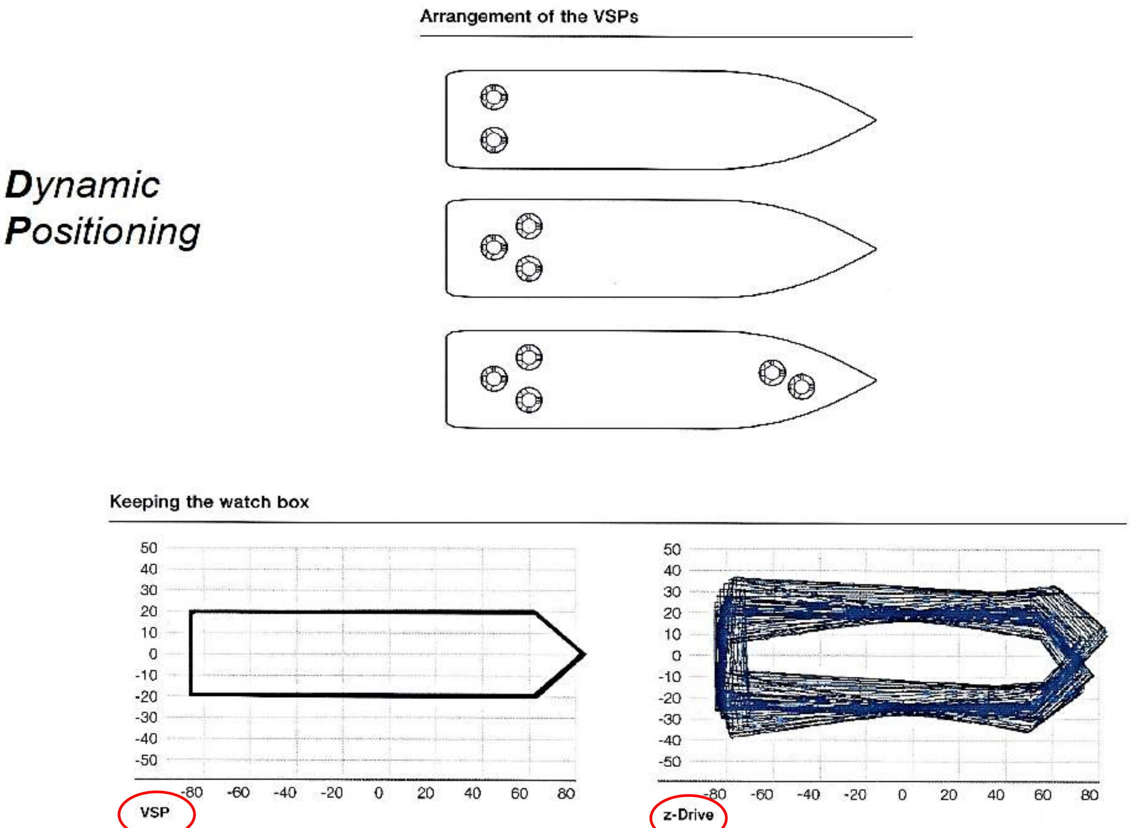


Figure 4-24 Comparison of Precision of Keeping in Location of VSP & Z-Drive

Having considered that construction vessel needs to be positioned precisely alongside the wind turbine, therefore, accurate positioning system need to be employed onboard these kinds of vessels. According to the revealed results of actual test, this propulsion system is suitable for the wind industry. However, the application, size and other factor may impact the decision.

4.8 Fuel Systems and New IMO Regulation

The energy source for the propulsion of vessels has undergone significant transformations over the last centuries. It started with utilizing sails (renewable energy) through the use of coal to heavy fuel oil (HFO) and marine Gasoil (MGO), now the dominant fuel for this sector (Mofor , Nuttall and Newell 2016). Marine fuel currently contributes approximately 3% to global man-made CO_2 emissions (DNV.GL 2019).

Apart from technological advancement, regulation play colossal role in selection of fuel for ship industry as well offshore[36] industry. The International Convention for the Prevention of Pollution from Ships (MARPOL[37]) has stipulated, among other measures, low sulfur emission control areas (ECA)[38] in the marine environment. Some of the emission control areas are North Sea, Baltic Sea, US Coasts and harbors which based on MARPOL the maximum sulfur content in fuels should be limited to maximum 0.1%. With the Greenhouse Gas Strategy towards 2050, the IMO[39] has set the goal to reduce carbon intensity by 40% within the next decade up to 2030 and by 50% in total (70% intensity) up to 2050. The greenhouse gas strategy was approved by the IMO in 2018. The reduction rates are related to the baseline of 2008. Short-term, mid-term and long-term measures are distinguished to achieve the goal (DNV.GL 2020).

Furthermore, mandatory technical and operational measures requiring ships to be more efficient in energy use and to reduce emissions were set in this convention. As an illustration, MARPOL regulations make the Energy Efficiency Design Index (EEDI) mandatory for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships. Not only this regulation covers new ships, but also the Energy Efficiency Existing Ship Index (EEXI) will be applicable for all vessels above 400 GT falling under MARPOL Annex VI. More importantly, the industry itself has set targets to reduce carbon dioxide (CO_2) emissions by 50% by 2050. Ship operators, therefore, need to consider cleaner fuel and power options, including the use of renewables, to meet these targets. Furthermore, rising bunker fuel prices, amid a globally volatile market,

[36] Offshore industry means offshore oil and gas sector as well as offshore wind industry.

37 "MARPOL Convention" means the International Convention for the Prevention of Pollution from ships.

[38] North Sea is an Emission Control Area based on MARPOL

[39] The International Maritime Organization (IMO) is the United Nations specialized agency responsible for safe, secure and efficient shipping and the prevention of pollution from ships.

provide another compelling reason to scale up modern shipping solutions based on renewable sources and technologies (Mofor , Nuttall and Newell 2016, 3).

All in all. a number of cost-effective technology options for new and existing ships and operators have been identified to improve energy efficiency of ships or lower their energy intensity. These options can be categorized into four option groups as following:

I. Improving energy efficiency (for example increasing productivity using the same amount of energy, using more efficient engine, reduce hull resistance, optimize bulbous etc.);
II. Using renewable energy (for instance solar and wind);
III. Using fuels with lower carbon content (for example LNG and biofuels) and
IV. using emission reduction technologies (for example through chemical conversion, capture and storage).

Therefore, in order to select the right type of fuel for the designed vessel, first of all we need to review the emission and specification of mostly used fuel as following:

4.8.1 Heavy Ful Oil (HFO)

Overwhelming majority of ships are powered by heavy fuel oil and diesel oil with sulphur. Heavy fuel oil (HFO) is waste coming from the process of refining crude oil. It contains about 2.7 % sulphur and several other toxic and pollutant compositions.

4.8.2 Marine Diesel Oil (MDO)

The term marine diesel oil (MDO) generally describes marine fuels that are composed of various blends of distillates (also called marine gasoil) and heavy fuel oil. Unlike diesel fuels on land that are used for cars and trucks, marine diesel oil is not a pure distillate.

Large ships can run on heavy fuel oil as well as marine diesel oil. Smaller vessels such as barges are not designed to run on heavy fuel oil (marquard-bahls 2015).

4.8.3 Very Low Sulphur Fuel Oil (VLSFO)

Very Low sulphur fuel oil (VLSFO) is a mixture of about 40% HFO with fuels with lower sulphur content which consumption of this fuel result is sulphur emission of maximum 0.5 %.

4.8.4 Hydrogen Fuel Cell

Hydrogen fuel cells as a power source for shipping also hold great potential but the sustainability of the energy source used to produce the hydrogen, as well as lack of cost-effective and reliable low-pressure storage options for the fuel remain as critical issues to be addressed.

4.8.5 LNG Fuel

Of all relevant fossil fuels, LNG produces the lowest CO_2 emission (DNV.GL 2019). Figure 4-25 illustrates the CO_2 footprint of various fuels. LNG is sulphur-free so there are no SO_X emissions. LNG-powered vessels have been in operation since 2000. As of 1 December 2018, 137 LNG-fuelled ships were in operation and 136 newbuilding orders were confirmed (DNV.GL Maritime 2019). Compared to HFO, LNG greatly reduces emissions to air. In terms of NO_X emissions, the four-stroke and two-stroke low-pressure engines reduce these emissions by 85% compared to HFO. While the high-pressure two-stroke engines still reduce NO_X by 40% without exhaust gas treatment, particle emissions are reduced by 95% and more. Because LNG does not contain sulphur, these emissions are eliminated completely. All emissions to the atmosphere relevant for human health and the so-called black carbon effect on global warming are reduced significantly by burning natural gas instead of HFO or MGO. As explained below, the effect on CO_2 emissions is also positive (DNV.GL Maritime 2019).

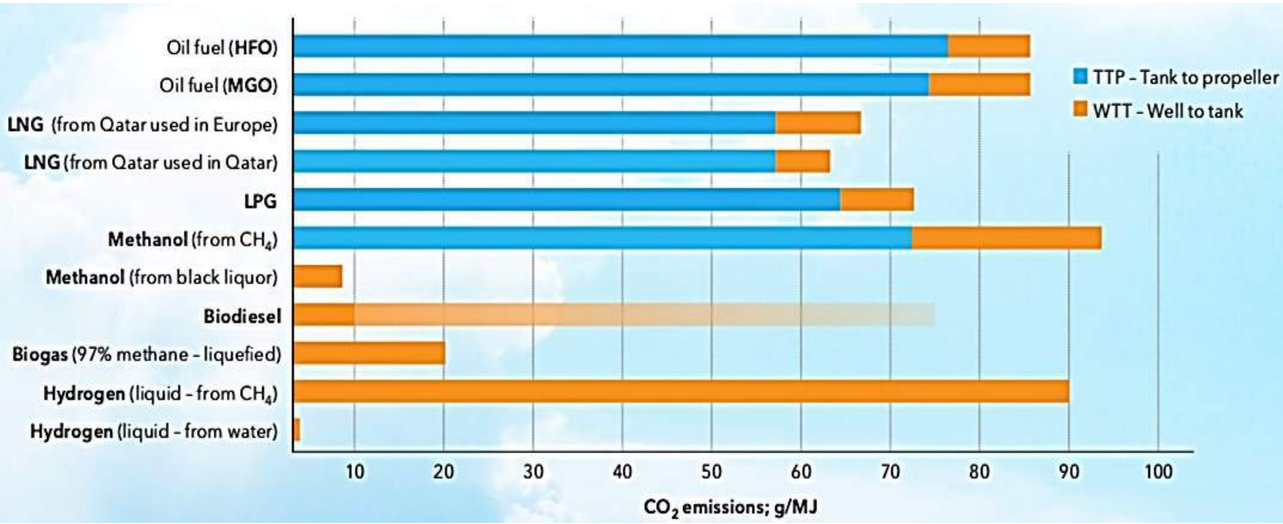


Figure 4-25 CO2 Emission of Various Fuel Types

Reduction of environmental footprint resulting from using LNG are listed in the Table 4-2.

Table 4-2 Environmental Impact of LNG

Emission Component	Emission Reduction with LNG	Comments
SO_X	100%	Complies with ECA and global sulfur cap
NO_X Low-Pressure Engine	85%	Complies ECA 2016 Tier III regulations
NO_X High-Pressure Engine	40%	Need EGR/SCR to comply with ECA 2016 Tier III regulations
CO_2	25-30%	Benefit for the EEDI requirement, no other regulations
Particulate Matter (PM)	95-100%	No regulations (yet)

4.8.6 Environmental and Calorific Comparison of LNG with Diesel Oil

Every type of fuels has its own pros and cons. Among the proposed alternative fuels for shipping, DNV-GL has identified LNG, LPG, methanol, biofuel and hydrogen as the most promising solutions. Therefore, in this research the author is comparing the LNG with diesel oil in order to see what the advantage and disadvantage of each type of fuels are. However, it should be noted that both are considered as fossil fuels which means that they are exhaustible source of energy.

In addition to above, the comparison has been made in terms of calorific value as well as the emissions.

Table 4-3 shows the advantage and disadvantage of LNG against diesel oil.

Table 4-3 Advantages and Disadvantages of Diesel Oil and LNG

Advantages	Disadvantages
Appr. 20% -25% less CO_2 emission than diesel oil (equal heat production)	The density of liquified natural gas is lower than diesel oil. So, the LNG tank volume has to be increased compared to diesel oil tanks
Negligible CO emission.	The LNG tank technology is much more complex than diesel tank technology
No soot and no micro particles emission	Approximately 10 % of the overall energy content of natural gas has to be used to for liquefying the natural gas.[40]
Appr. 80% less nitrogen oxide (NO_X) than diesel oil	The LNG volume with the same heat content is 1,45 more than the Diesel oil volume
No sulphur oxide (SOX) emission.	

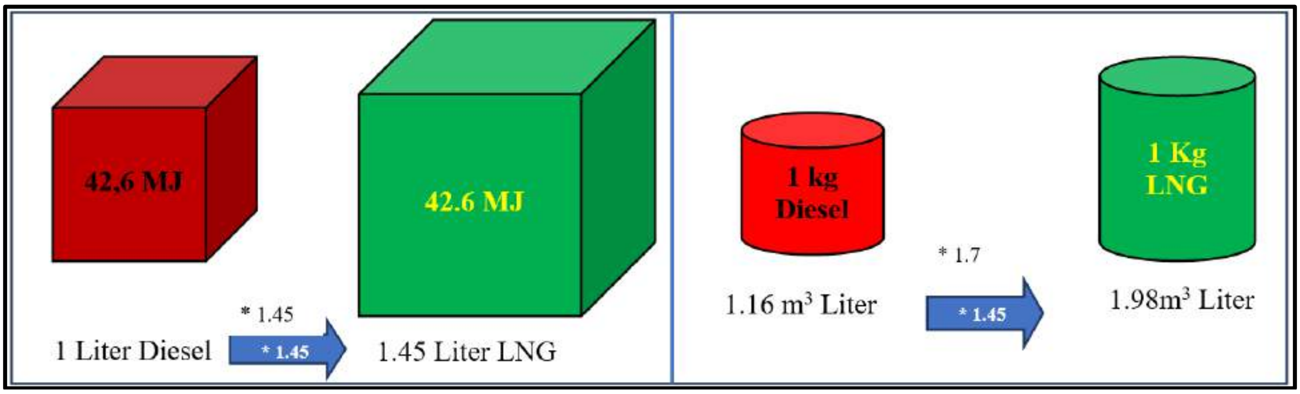


Figure 4-26 Volume and Calorific Value of Diesel Oil VS LNG

[40] In order to bunker more natural gas, it should be liquified. The volume of LNG is $\frac{1}{600}$ $natural\ gas$

Table 4-4 shows the carbon content as well as price of various fuels. The figures shows that the emission of LNG is approximately 25% less than diesel fuel. But it should be noted that LNG engines need pilot fuel for combustion.

Table 4-4 Carbon Content of Various Fuels

Sr.	Type of Fuel	Reference	Carbon Content	CF ($t\text{-}CO_2/t\text{-}Fuel$)
1	Diesel / Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.206000
2	Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.151040
3	Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.85	3.114400
4	Liquefied Natural Gas(LNG)		0.75	2.750000

4.8.7 Fuel Price Comparison

Fuel pricing depends on a number of factors, including market conditions, which are difficult or impossible to predict. The price ranges illustrated in Figure 4-27 reveal a qualitative trend based on price history. The calculations for the diagram use the gas price on the European spot market as a basis for LNG price predictions. The diagram demonstrates that only LNG and, to some extent, LPG can currently compete with HFO in terms of market price. Methanol and biofuels may eventually be able to compete with MGO to some extent. Hydrogen is not price competitive.

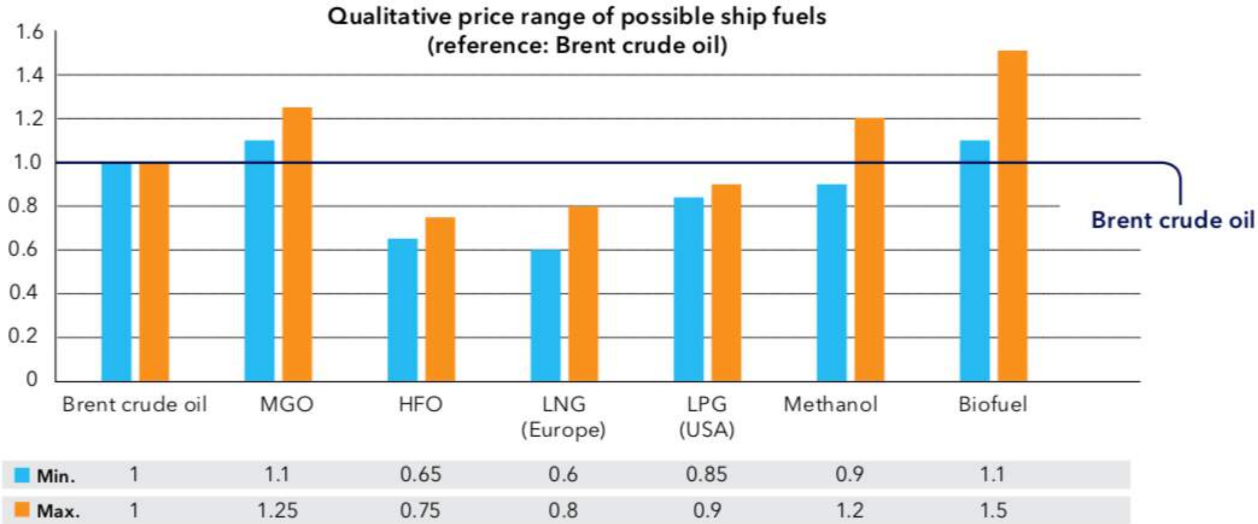


Figure 4-27 Price of Different Fuel Types

Table 4-5 shows the calorific values and prices of three common fuels namely heavy fuel oil (HFO), marine diesel oil (MDO) and Liquified Natural Gas (LNG). According to this table, LNG has the highest heating value and lowest price compared to other three mentioned fuels.

Table 4-5 Calorific Value and Price of Fuels (Carmen Hsieh & Felby)

Properties	Heavy Fuel Oil (HFO)	Marine Diesel Oil (MDO)	Liquified Natural Gas (LNG)
Heating value (MJ/kg)	39	43	48
Sulphur (% m/m)	<3.5	2	0
Price (USD/Mt)	290	482	270

4.8.8 Fuel Availability

Apart from its price, a future fuel must be available to the market in sufficient quantity (DNV.GL 2019, 12). Figure 4-28 gives an indication based on a comparison of the energy content of the worldwide production of specific alternative fuels with the energy need of the shipping industry. The energy consumption of the global fleet serves as the 100% baseline. This comparison shows that for all alternative fuels, with the exception of LNG, a rapid rise in demand would require massive investments in production capacity. In theory, a switchover of the entire global fleet to LNG would be possible today since the current LNG production is higher than the shipping industry's energy requirement, and the share of LNG in the total gas market is only 10%.

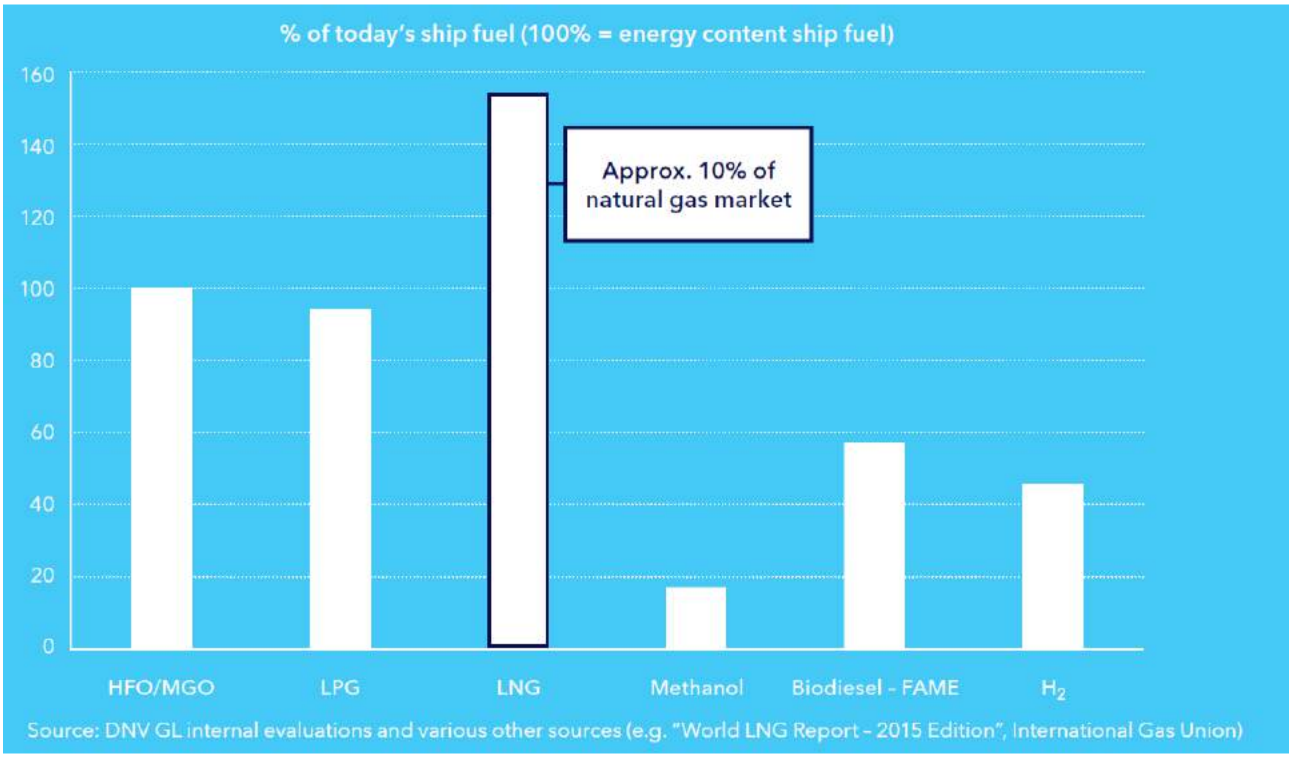


Figure 4-28 Production of Possible Ship Fuels Per Year (Relative Energy Content)

4.8.9 Renewable Source of Energy as a Ship Fuel

Renewable power applications in ships of all sizes include options for primary, hybrid and/or auxiliary propulsion, as well as on-board and shore-side energy use. The role and extent of renewable energy technology adoption by the shipping sector will vary greatly depending on the scale, function and operational location of the particular vessel. Apparently, the greatest potential lies in using a combination of renewable energy solutions that maximizes the availability and complementarity of energy resources in hybrid modes. In this sense, achieving the full potential of renewables in a ship will require an integrated system engineering approach that also addresses the barriers to their deployment. Potential renewable energy sources for shipping applications includes:

1) Wind assisted propulsion systems such as soft sails, fixed wings, rotors, kites and conventional wind turbines
2) Solar photovoltaics,
3) Biofuels,
4) Wave energy and
5) The use of super capacitors charged with renewables.

4.8.9.1 Flettner Rotors

Flettner Rotors harness the Magnus Effect, created when wind passes over an already revolving cylinder, for propulsion. It was first proven in the 1920s on a number of ships, including the 3000 DWT Barbara. Figure 4-29 shows the Enercon E-Ship 1 with deadweight of 12800 which began trials of four Flettner rotors powered initially by the exhaust gas from the main conventional turbine motor. There are now modern concept designs adopting Flettner style rotors. (Mofor , Nuttall and Newell 2016, 21). According to the recorded fuel consumption, Enercon E ship 1 with motor powered only and with sail-rotor operation, up to 22.9% fuel consumption have been saved on the voyage between Emden and Portugal (Schmidt 2013).

Figure 4-29 Enercon E-Ship 1 is Equipped with 4 Rotors[41]

[41] 4 x Rotor diameter 4 meter and height of 25m

4.8.9.2 Solar Photovoltaics and Hybrid Systems

Solar PV applications use electricity generated by photovoltaic (PV) cells. All advances in this fast-evolving technology are available for maritime transport use. The primary limitations are the lack of sufficient deployment area for the PV panels and the energy storage required. Recent advances in energy storage technology offer higher potential and better prospects for solar PV-powered propulsion systems for ships in the short term, but full ship propulsion using solar PV requires further technical development and is likely to be confined to relatively small ships (Royal Academy of Engineering, 2013). Figure 4-30 shows the IMOFlexMAX vessels. Stena Bulk unveils solar and rotor sail tanker design. Their aim is to reduce greenhouse gas (GHG) emissions by at least 25% on current designs with using a solar and rotor. The basic concept of the IMOFlexMAX is to dramatically reduce local SOx, NOx and particle emissions, as well as greenhouse gas emissions. With the combined fuel and energy efficiencies, Stena Bulk expects to reduce greenhouse gases by at least 25% with a potential to reach up to 45% compared to modern product tankers run by low-sulphur fuel oil.

Figure 4-30 Stena Bulk IMOFlexMAX vessels

4.8.10 Performance and Costs of Renewable Energy

One of the reasons that development of renewable energy solutions for shipping has been hampered is that the market is over-supplied by fossil fuel-powered shipping in recent years and the related depressed investment market (Mofor , Nuttall and Newell 2016). In the case of rotor technology, the amount of fuel savings decreases as the ship size increases. Savings of up to 60% for small ships have already been achieved while savings of up to 19% on Very Large Crude Carriers (VLCC) are being modelled. For example, Enercon reported in 2013 that their prototype rotor sail ship, the E-Ship 1, had achieved 25% savings after 170 000 sea miles (Mofor , Nuttall and Newell 2016)·

4.8.11 Role of Batteries In Shipping and Offshore Industry

It should be noted that using of full electrical propulsion system is not a new technology. Utilization of Battery have several advantages too, since they enable the vessel engine to run at more favourable loads. This reduces fuel consumption and therefore emissions to air. Further benefits include an improved response time in safety-critical operations, an extended engine lifetime, less maintenance and less noise and vibrations (DNV.GL, Mollestad and Valøen 2015).

Electric propulsion of ships is not a new invention. The first electric powered boat we know about was a 24-foot boat in St. Petersburg in 1839 that could carry 14 passengers at a speed of three knots (DNV.GL, Mollestad and Valøen 2015). Nowadays, a number of vessels with different applications are equipped with state-of-the-art battery and electrical system. For example, the first large-size all-electric battery-powered car ferry, Norled's Ampere, came into operation in January 2015. This 120-car and 350-passenger ferry is equipped with a 1MWh battery system. Quick charging takes place during the 10-minute period between each trip and at night-time (DNV.GL, Mollestad and Valøen 2015).

4.8.12 Various Topologies for Installation of Batteries Onboard a Vessel

Depending on the vessel consumption and batteries size, vessel can be categorized in three different types as following:

I. Full-electric ships (ES)
II. Plug-in hybrid ships (PHES)
III. Hybrid ships (HES)

However, the topology of using battery and feeding the consumer play vital role. The below scenarios are the possible topologies for using batteries onboard a vessel.

4.8.12.1 Mechanical Propulsion with Battery Hybrid Electrical Power Plant

Figure 4-31 shows a battery integrated into the electrical system of a vessel with traditional mechanical propulsion. In this case, the battery will be effective for smoothing the connected electrical load and helping to handle large load steps. When the large load steps are reduced, the number of auxiliary engines may also be reduced. In cases where the load can regenerate power, such as in cranes, the battery can be used to harvest this energy.

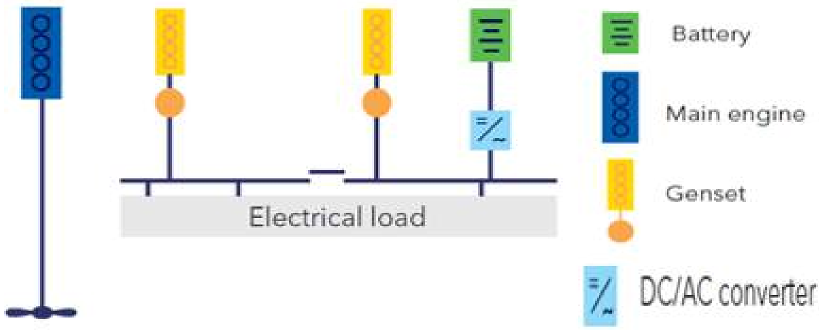


Figure 4-31 Mechanical Propulsion with Battery Hybrid Electrical Power Plant

4.8.12.2 Hybrid Battery Propulsion

Figure 4-23 Figure 4-32illustrates batteries integrated into a power system for electrical propulsion. In this case, the battery will provide power to the large propulsion motors. The vessel may run on just batteries, just generator sets or in parallel operation using both batteries and generators. In addition to being a source of energy for propulsion, the batteries will smooth the load variations on the generator sets. The introduction of such a battery hybrid system will reduce the noise and vibration levels on the ship. The topology can also facilitate the use of zero emission operation when entering a harbour.

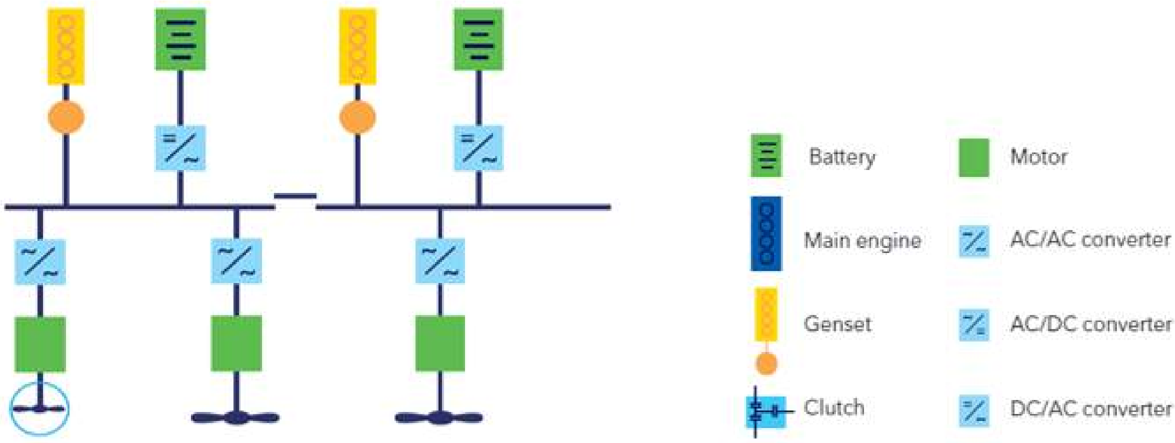


Figure 4-32Hybrid Battery

4.8.12.3 Hybrid Battery Propulsion, with Distributed Batteries

One challenge involved in the electrical propulsion concept is its efficiency. As seen in the previous figure, the system has several power converters and each of them typically represents a 2% power loss. Figure 4-33 shows if the batteries are distributed into the propulsion converters, the losses are reduced. Another benefit with the distributed battery concept is that each propulsion unit is independent of a common source of energy. This might be a smart solution for vessels that require a highly reliable propulsion thrust, such as redundant dynamic positioning vessels (DP2 and DP3).

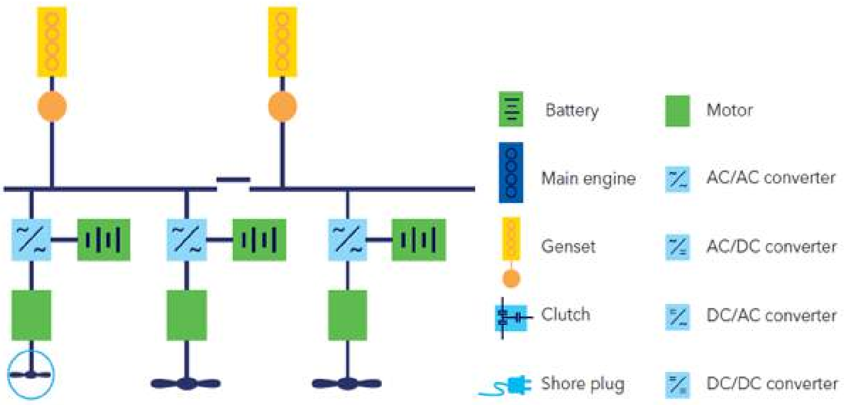


Figure 4-33 Hybrid Battery Propulsion, with Distributed Batteries

4.8.12.4 Hybrid Battery, Electrical, Mechanical Propulsion and DC Distribution

Figure 4-34 shows a power system with an electrical/mechanical hybrid solution, a battery hybrid with plug-in possibilities and a DC distribution. With a DC-distributed system, the speed of the prime movers for the generators can be adjusted to the load-dependent optimum fuel level. Hence the fuel consumption is reduced, and the environmental footprint is minimized. The electrical/mechanical hybrid solution allows electricity to be generated by the main engine (Power Take Out (PTO)) or propulsion power to be produced by generator sets and batteries (Power Take In (PTI)). A boost mode is possible (additional thrust power) when the main engine and PTI motor are running in parallel.

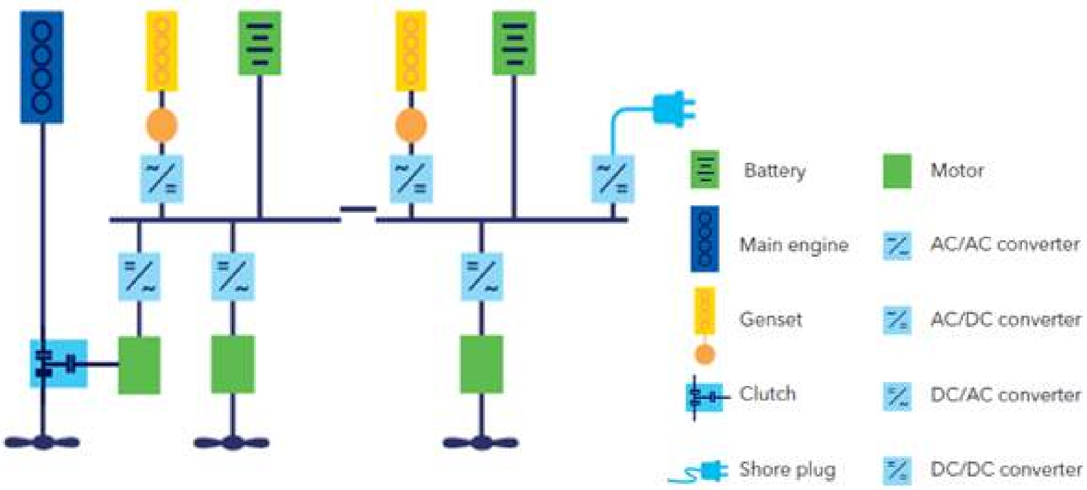


Figure 4-34 Hybrid Battery, Electrical, Mechanical Propulsion & DC Distribution

4.8.12.5 Battery Propulsion

Figure 4-35 shows a power supply system for a purely battery-driven vessel. The batteries are charged through an AC/DC converter (either located on the vessel or on shore). Two independent battery systems deliver power to the thruster.

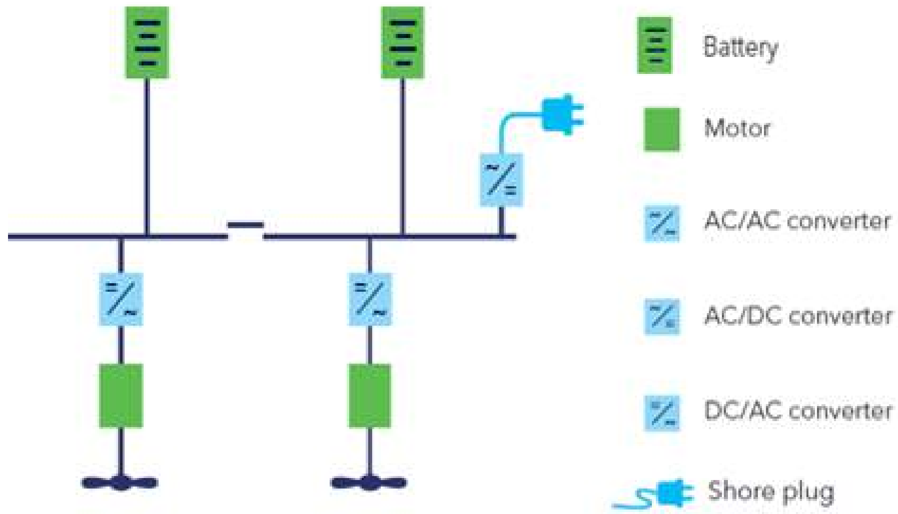


Figure 4-35 Battery Propulsion

4.8.13 Advantage of Storing Electricity Onboard a Vessel

In order to improve grid-power quality and reliability and optimize the matching of supply and demand, organizations have sought ways to safely store energy (DNV.GL, Mollestad and Valøen 2015). Furthermore, utilization of renewable energy onboard a vessel such as solar system, compel the ship owners or shipyards to implement energy storage system onboard. Methods and technologies of storing electric energy varies in different industries, however, the most of available technologies in maritime industry have been listed in Table 4-6.

Having battery onboard a vessel allows the operator the freedom to store unused or excessive energy and then utilize the energy when it would benefit the operation of the ship such as manoeuvring etc. in that high energy profile is needed (DNV.GL 2016). This feature will improve the overall efficiency of the vessels.

Furthermore, the battery onboard a vessel improves the efficiency of the engine and minimize the emission. The battery can help smooth the load of the engine. Some battery systems are designed to provide high power with very high response rates which allows the engine to run steadily and more efficiently. When the vessel is slowing down or is operating at less than its peak efficiency, such as in-field transit-transit between the wind turbines- or when the vessel is entering/leaving the port, the battery can be charged, storing energy for the next task. In other words, utilizing battery power to avoid inefficient regions of engine operation (DNV.GL 2016). More importantly, batteries enable us to provide standby power for redundancy with zero fuel consumption penalties. Thus, not only are battery systems increase system efficiency, but also provide a means to increase system reliability and robustness (DNV.GL 2016).

4.8.14 Comparison of Electric Power Storage Technologies

In addition to the battery as a mean to store the electricity onboard a vessel, there are various methods for storage of electricity in the market. Amongst all of the possible technologies to store the electricity onboard a vessel, so far, the battery is most promising option. Table 4-6 shows 19 methods and technologies to store the energy onboard a vessel.

Under column feasibility status the cell with green colour shows "High feasibility", yellow shows "Medium feasibility" and red shows "Low feasibility".

Table 4-6 Available Energy Storage Technologies for Maritime Propulsion (DNV.GL, Mollestad and Valøen 2015)

Sr.	Energy Storage Technologies	Abbreviations	Feasibility Status
			Maritime Propulsion
1	Valve regulated lead acid	VRLA	
2	Thermal storage (Hot)	Heat	
3	Pumped Hydro P-Hydro	P-Hydro	
4	Litium – ion – High power [42]	LIB-p	
5	Ni batt. (NiCd, NiZn, NiHM)	Ni-batt	
6	Thermal storage (cold)	Ice	
7	Compressed-Air ES, cavern	CAES-c	
8	Sodium Sulphur	NaS	
9	Flywheel	FlyWi	
10	Litium – ion – High energy[43]	LIB-e	
11	Advanced Lead Acid	LA-adv	
12	Hybrid LA and IDL-CAP	Hybrid	
13	Vanadium Redox Battery	VRFB	
14	Zink Bromide	ZnBr	
15	Sodium Nickel Chloride	NaNiCl	
16	Double Layer (super) Capacitors	DL-CAP	
17	Adv. Vanadium Red. Flow. Battery	A-VRFB	
18	Zinc-Air Battery	ZnAir	
19	Compressed-Air ES, small	CAES-s	

[42] High-power applications often need storage to discharge all their energy within an hour, or often a much shorter time.

[43] High-energy applications require storage devices to discharge their energy at rated power for longer than one hour.

According to the finding of DNV.GL best technology for storage of energy to be used for maritime propulsion which is available in the market are Lithium-ion battery, Hybrid LA and IDL-CAP and Double Layer (super) Capacitors. One of the advantages of the lithium-ion batteries is compared to traditional batteries with water-based electrolytes such as lead acid and nickel cadmium batteries, it can store between two and eight times more energy per weight unit (DNV.GL 2016).

From recycling perspective, it can be argued that Facilities for recycling of lithium-ion batteries are existing and the value of the recycled materials more or less pays for the cost of the recycling.

In conclusion, the preferred electricity storage technology will be lithium-ion batteries onboard a vessel.

4.8.15 Battery Space and Location

DNV GL Class rules require that the battery space has to meet a general fire integrity level of A-0 and A-60 towards any muster stations or evacuation routes. If the battery power shall be used for propulsion under normal operation, dynamic positioning, or other relevant operations, it shall also meet a fire integrity level of A-60 towards any machinery space of category A as defined in SOLAS Reg. II-2/3. The battery space can also not be located in the forward collision bulkhead (DNV.GL 2016).

4.9 Conclusion

- Large two-stroke cross head engines are most efficient combustion engines in the universe.
- The most important influential factor for the ship propulsion is the hull resistance which is affected by ship's dimensions, hull shape, displacement, weight and draft of the vessel.
- According to application of Decom Tools ships, this ship needs to have precise manoeuvring capability since it needs to approach to the foundation precisely and move on the predefined route for cable extraction operation. Amongst all the available propulsion system Voith Schneider has the highest degree of accuracy in term of manoeuvring. Furthermore, the vessel is floating ship which can have all six degrees of freedom. The less movement increase the productivity and stability of the vessel. Given the fact that VSP is reducing the vessel rolling, therefore, the vessel rolling will be minimized due this propulsion system which will contribute to more productive vessel. Therefore, VSP is the best option for this vessel.
- Among all of the existing fuel system, LNG is the best option, because of the emission resulted from using this fuel (less CO_2 emission, less NOx emission, less SOx emission etc), availability, price, the calorific value, availability of technology for construction and maintenance etc.
- Among all the renewable source of energy, the Flettner rotor and solar power system can improve the efficiency of the ship. Flettner rotor efficiency depends on wind speed and relative direction. Having considered that the vessel is working in high-wind profile area, the contribution of Flettner rotor can be significant.
- Also having solar system can have many advantages. It is to some extend free of maintenance system. Furthermore, normally the installation and decommissioning would take place in the summer when the average irradiation of sun is high. Therefore, the solar system automatically will capture the exhaustible energy from sun.
- Having hybrid system onboard a vessel has a number of significant impacts as following:

  I. Utilize energy from shore power.
  II. Run engines at optimum loads.
  III. Avoid transient engine loads.
  IV. Use power redundancy.
  V. Reduce local emissions.

VI. Reduce noise and vibrations.

VII. Facilitate energy harvesting and energy recovery.

5 Basis of Design of Decom Tools Vessel

5.1 Introduction of Multi-Function & Multi-Purpose Green Decom Tools Vessel

According to the revealed data of installed wind farms, for the installation of offshore wind turbines, normally the wind turbine components transported offshore by the installation vessel, especially jack up DP2 vessel. Then the installation was taken place with the same vessel. This configuration is called pendulum configuration. Normally 3 to 8[44] sets of wind turbines were loaded on the vessel in the port. The number of transported sets of wind turbine depend on the following factors:

I. Deck area of the vessel,
II. Vessel deck load capacity,
III. Wind turbine size and,
IV. Cargo loading arrangement,
V. Weight of components and so forth.

A comprehensive study has been conducted in chapter three and the finding shows that pendulum configuration is the most inefficient type of logistic configuration in terms of incurred cost to the project as well as environmental impact which was measured by CO_2 emission. To boost the efficiency of offshore operations namely decreasing the cost of decommissioning project as well as mitigating the emission resulted from offshore operations, study on various aspects of feeder configuration has been carried out. It shows that feeder configuration with a combination of heavy lift vessel and a cargo vessel will boost the efficiency of the offshore operations. However, it should be noted that loading capacity of cargo vessel is the major factor in the productivity of the feeder configuration. The more loading capacity of cargo vessel- the more capacity to load the wind turbines set on the cargo vessel- results in more productive[45] operation. To accomplish this productivity, in this research a multi-purpose and multi-function green vessel has been designed. The vessel has unique and special functions which so far none of the available vessels in the market have these functions which means the vessel does not have competitor. To design this vessel, specifications of more than 50 numbers of various types of vessels in the market has been reviewed. Authors and designers of the vessel which have broad range of practical experience of ship's navigation and stability as well as various offshore operations mightily strived and closely collaborated more than one year to design this vessel based on the current and future market of wind industry as well as oil and gas industry. It should be noted no cargo vessel specifically based on offshore wind turbine's size

[44] For example, in installation of Hornsea 1 wind park, the vessel by the name of Bold Tern were used and 4 set of wind turbines were loaded on each voyage.

[45] Productive here means cost-effective, less environmental impact as well as less offshore duration.

and geometry has been designed so far[46]. Enercon ship by the name of E-Ship 1 is designed just for the transportation of onshore wind turbines.

5.1.1 What is the Definition of Multi-Function Vessel?

In this project, multi-function vessel means that the vessel does not have just one function. However, the primary function and mission of this vessel is transportation of wind turbines components from port to the offshore field or vice versa, but it has other functions as following:

- Extraction of monopile from seabed.
- Cut the monopile into small pieces for easier offloading at port and further transportation and processing.
- Extraction of in-field and export cable.
- Cut the cables into small pieces.
- Cut the blades into small pieces for easier offloading, transportation, and further process.
- Transportation of other materials such as nacelle and towers from offshore to port or decommissioning yard.

5.1.2 What is the Definition of Multi-Purpose Vessel?

Primarily and basically the vessel has been designed according to objectives and deliverable of Decom Tools project which is about decommissioning of offshore wind parks in the North Sea Region. However, the vessel has a great potential for the installation of newly developed extra-large wind turbines. It means not only does the vessel fulfil the requirement of Decom Tools project but also it can be used in installation of offshore wind parks. Furthermore, the vessel can be used for the installation and decommissioning of offshore oil and gas infrastructure namely transportation and installation/decommissioning various oil and gas modules, pipe transportation, fibre optic cable retrieval and so forth. Therefore, the vessel has multiple purposes which can cover the demands of installation and decommissioning of wind industry as well as oil and gas industry.

5.1.3 Basis of Design of Decom Tools Vessel

Noticing the findings of previous chapter, utilization of feeder configuration with combination of a heavy lift vessel along with a cargo vessel for transportation of materials to shore will result in remarkable saving in terms of cost and environmental impact. In the market, there are various

[46] January 20, 2021

types of heavy lift vessel and jack up vessel. The omission to design and construct a cargo vessel or a heavy load carrier vessel is noticeable in this industry. Therefore, the authors strived to design a vessel in order to cover the demand of market of wind industry for various generations of wind turbines.

The Decom Tools vessel must have some specifications in order to fulfil the objectives of Decom Tools project. Generally, by decreasing the number of vessels voyage or by increasing the number of transported wind turbines set per voyage, cost of transportation as well as CO_2 emission can be reduced. Moreover, the vessel for transportation of the wind turbine components should be designed based on various generations of wind turbines, considering geometry of components, size and weight of wind turbines.

In order to design such vessel, the following steps which are listed below has been taken. These steps form the basis for the discussion in this section:

- Identify the challenges of the wind industry in installation and decommissioning of wind parks.
- Outline the specifications and the functions of the novel vessel in order to come up with innovative design.
- Studying the best propulsion system for decommissioning operation considering the functions and missions of vessel.
- Studying the alternative fuel system for powering the vessel.
- Studying various technology for green shipping.
- Increase the capability of vessel in order to minimize dependability to other vessels for decommissioning.
- Decrease the duration of construction vessel which can be either jack up or heavy lift vessel for decommissioning.
- Try to avoid using cable laying vessel for cable retrieval.
- Optimize the vessel design in order to transport the maximum set of wind turbines components.
- Use the potential capacity of the floating vessels.
- Use the time that vessel is in the field or under voyage and do the simultaneous operations (SimOps) as much as possible.

5.2 Criteria for Designing of Decom Tools Vessel

Comprehensive studies were conducted to increase the capability of the vessel in order to increase the efficiency of the vessel. The vessel shall have some features in order to be efficient as following:

- Multi-function in order to be able to conduct the most of decommissioning operations.
- Suitable for almost all generations of wind turbine.
- Applicable for most of wind farm's location.
- Low fuel consumption by using hybrid system.
- Low CO_2 emissions by using green technology.
- Engineering of right propulsion system.
- Low charter rate.
- Optimized hall design in order to transport materials as much as possible.
- User friendly technology in order to be operated with low-wage crew (riggers).

5.3 Hull of Decom Tools Vessel

To fulfil above criteria, the Decom Tools vessel should have some technical specifications. This specification includes the machineries that the vessel should be equipped with, the geometry and hull of the vessel. Structural strength is not engineered in this document which is beyond the scope of this research. Before explaining about the vessel's deck design and the installed equipment on the Decom Tools Vessel, we would like to illustrate the overall hull of the Decom Tools vessel. See Figure 5-1 to Figure 5-7.

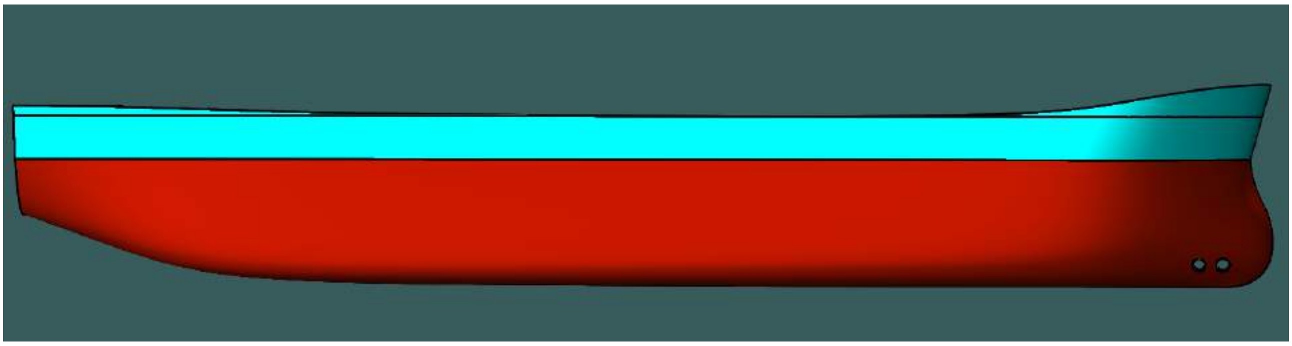


Figure 5-1 Side View of Hull of Decom Tools Vessel

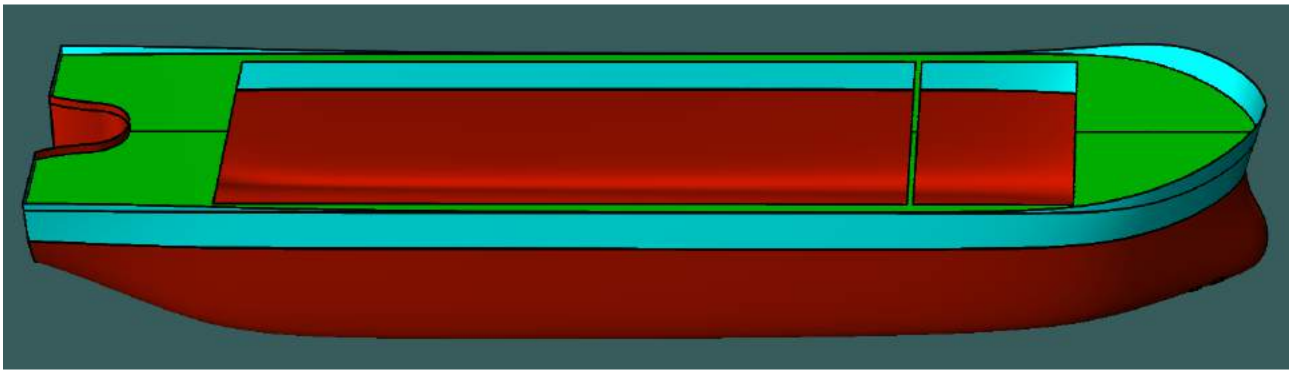


Figure 5-2 Multiview of Decom Tools Vessel

Figure 5-3 Plan of Decom Tools Vessel

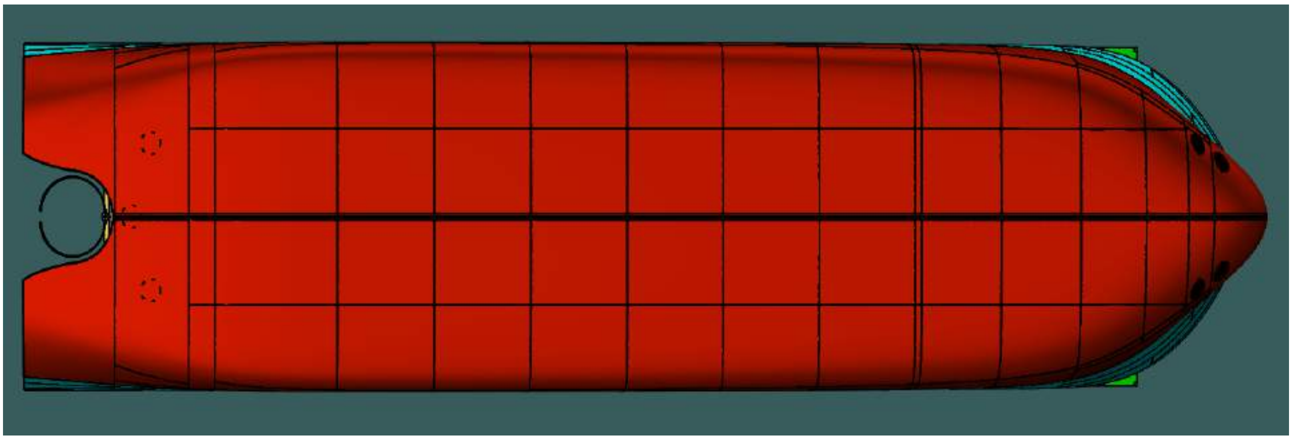


Figure 5-4 Bottom View of Decom Tools Vessel

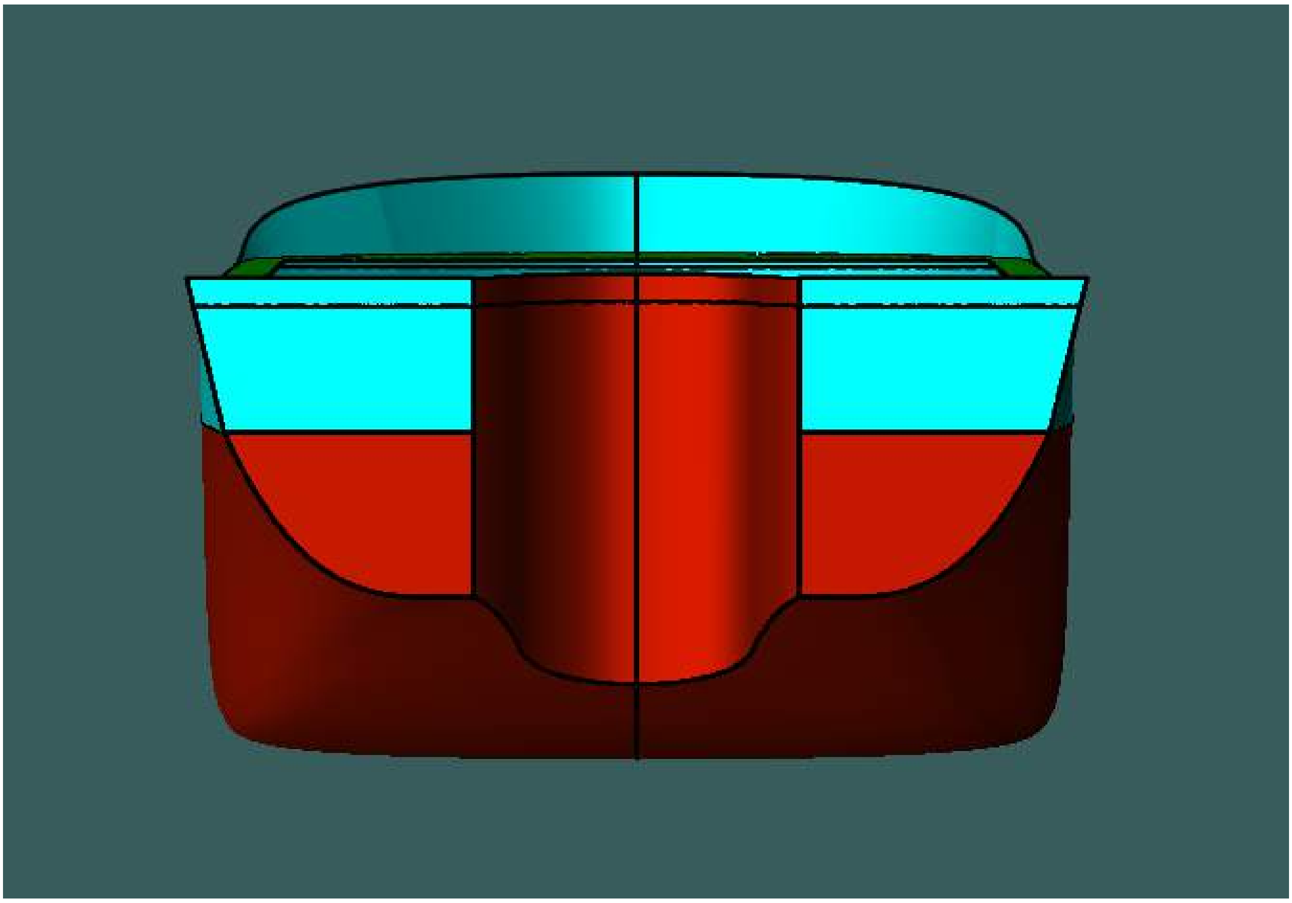


Figure 5-5 Aft (Stern) View of Decom Tools Vessel

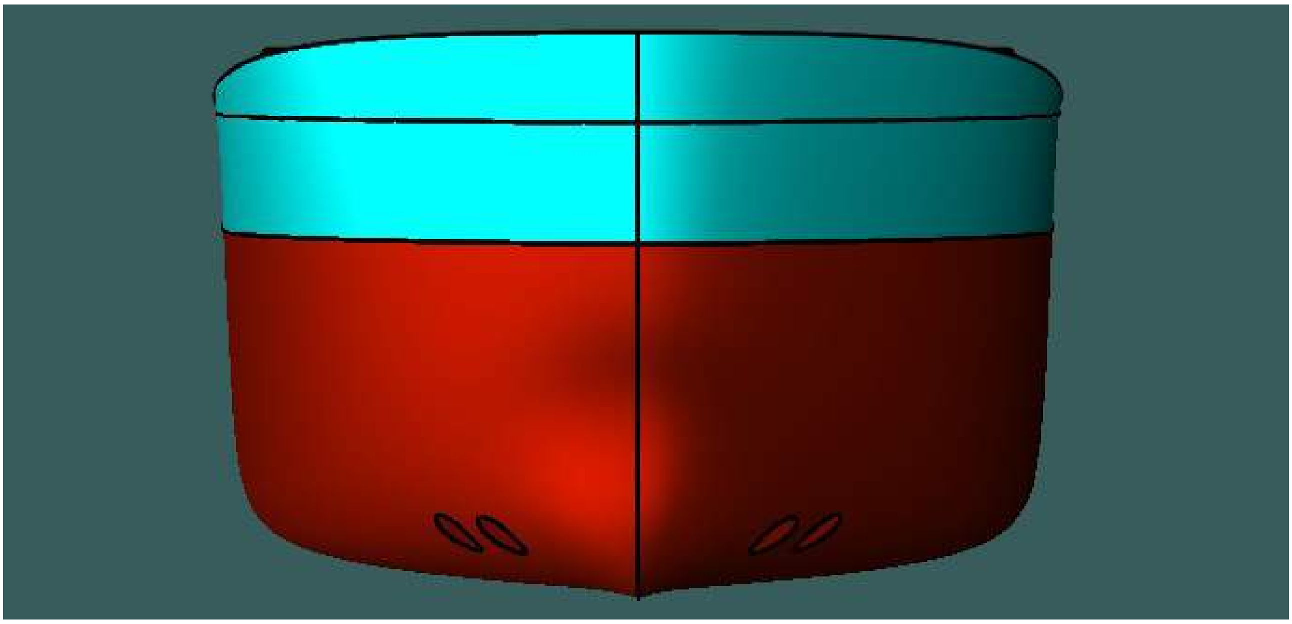


Figure 5-6 Bow (Forward) View of Decom Tools Vessel

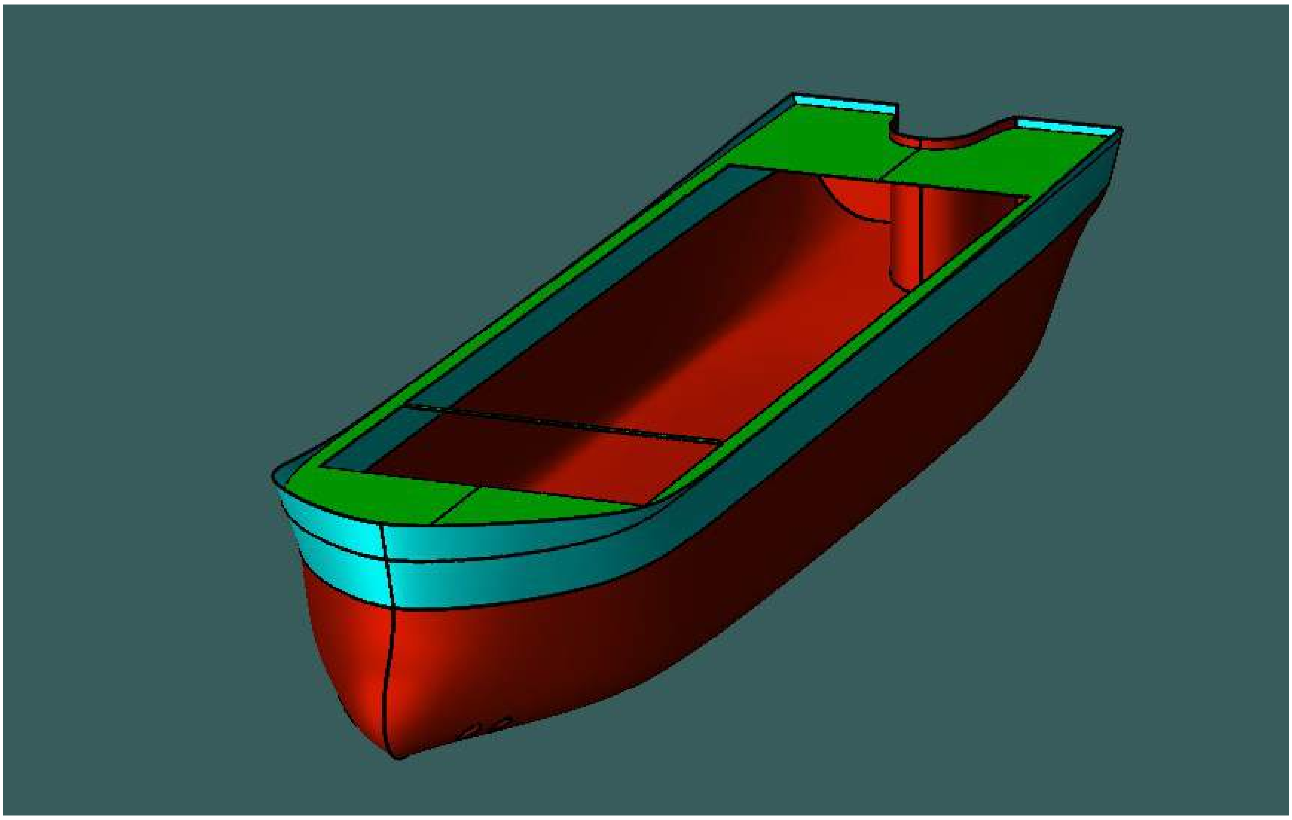


Figure 5-7 Birds-eye View of Decom Tools Vessel

5.4 Decom Tools Decks Design

Prior to showing how the loading of wind turbines components undertake onboard the Decom Tools vessel, the dimension of the vessel and design of the decks must be explained.

Decom Tools vessel is a ship which has three vertical loading surfaces which is designed to load and transport heavy cargos, in particular the latest generations of wind turbine.

The decks of Decom Tools vessel are as following from top to down:

- Top of hatch covers,
- Bulkhead deck (Weather Deck)
- Tween deck and,
- Top tank.

Each of above-mentioned deck has different permissible surface load (PSL can be estimated by calculating the exerted force by components footprint on the area of the deck). For instance, the tower of 12 MW wind turbine will be loaded in two segments and each segment has different weight and footprint area. The weight of heaviest segment is 586 tons, and the bottom area is 23.6 m^2. If the tower's seafastening is a circle shape, and its inner diameter is 0.75 m less than tower diameter, and its outer diameter is bigger than towers diameters by 75 cm, the PSL in this configuration should not be less than 25 tons per square meter ($25\frac{t}{m^2}$ $is\ desired$). In our case, the PSL of the top tank must be 25 tons per square meter or more. Similarly, the hatch cover should not be less than 16 tons per square meter, and the tween deck should not be less than 5 tons per square meter. Figure 5-8 shows the dimension of the vessel, the hatches and holds.

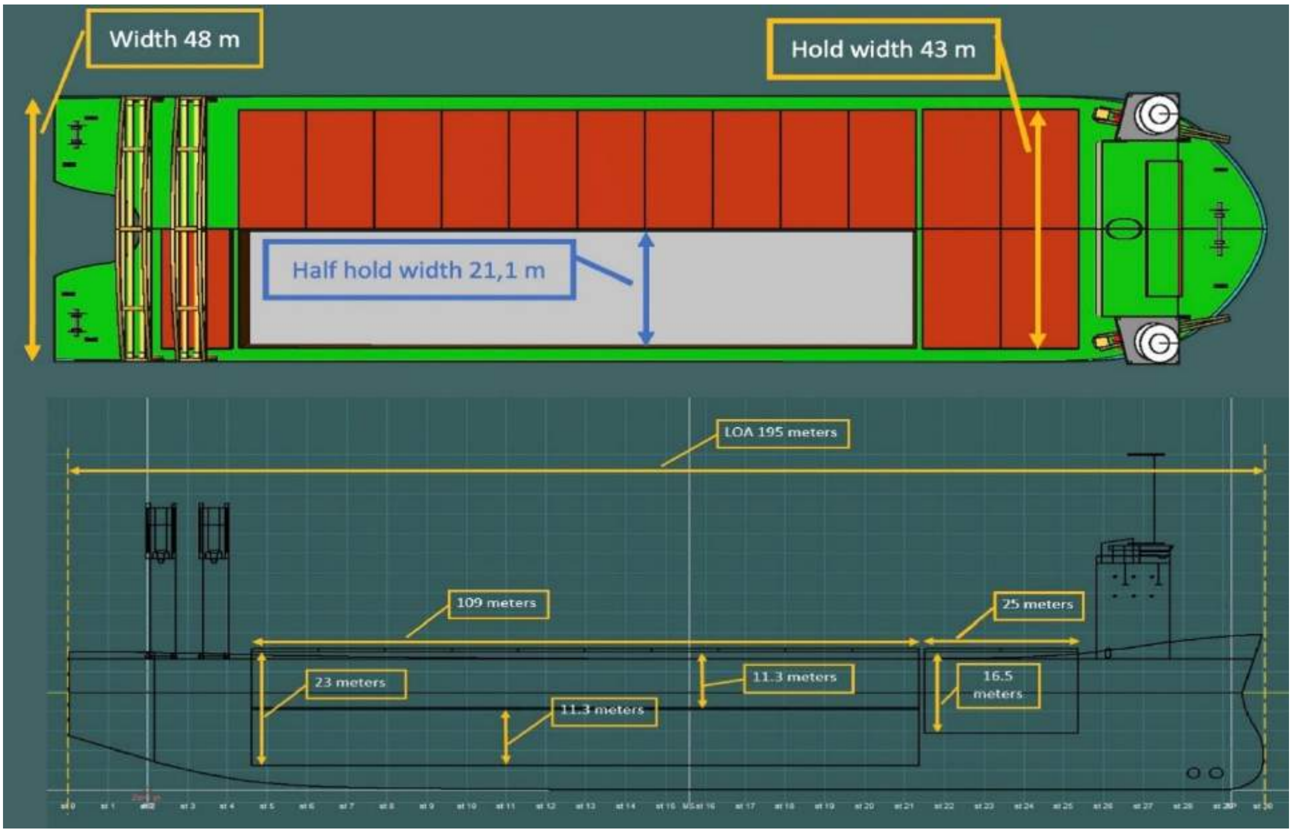


Figure 5-8 Dimension of Decom Tools Vessel

5.5 Bulkheads Deck (Weather Deck)

Figure 5-9 shows that bulkhead deck is totally flat with dimension of 193.363m x 48m which results in deck area of 2978 m^2. This area is occupied by other facilities and equipment such as cranes rails, accommodation, mooring winches, stowage place for hatch covers, cable hydraulic clamp and so forth.

Figure 5-9 Plan of Bulkhead Deck

5.6 Top of Tank Deck

Figure 5-10 shows all the decks of the Decom Tools vessel. As it stated earlier, the Decom Tools vessel has bulkhead deck, forecastle deck, top tank deck, tween deck and top of hatch cover.

The Decom Tools vessel consists of two holds which are divided into 4 sections longitudinally and transversely as shown below.

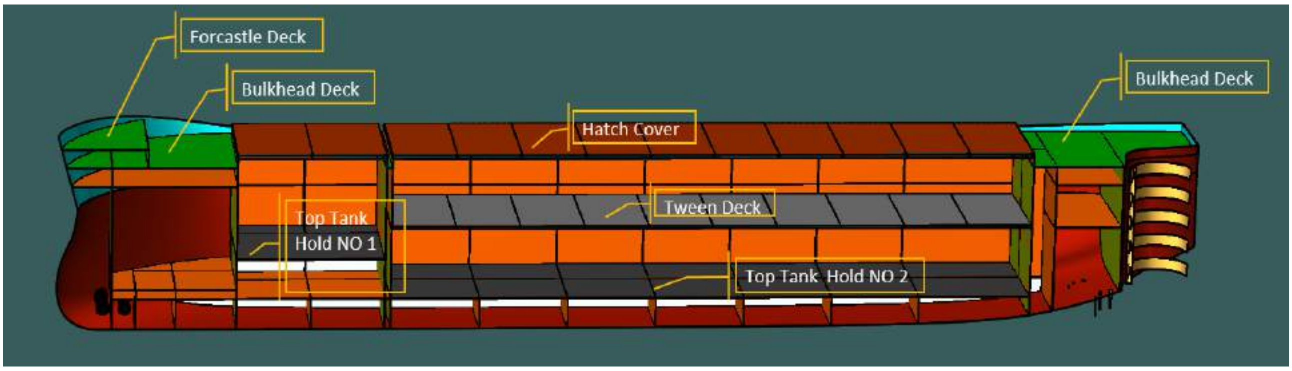


Figure 5-10 Decom Tools Vessels Decks

Figure 5-11 to Figure 5-13 shows the holds of Decom Tools vessel. There is one longitudinal hold which is laid over the length of the vessel and is comprised of two sections. In addition, the transverse hold laid over the breadth of the vessel. The transverse hold in the vessel is the first hold and the second hold is the longitudinal hold.

Figure 5-11 Decom Tools Vessel Holds

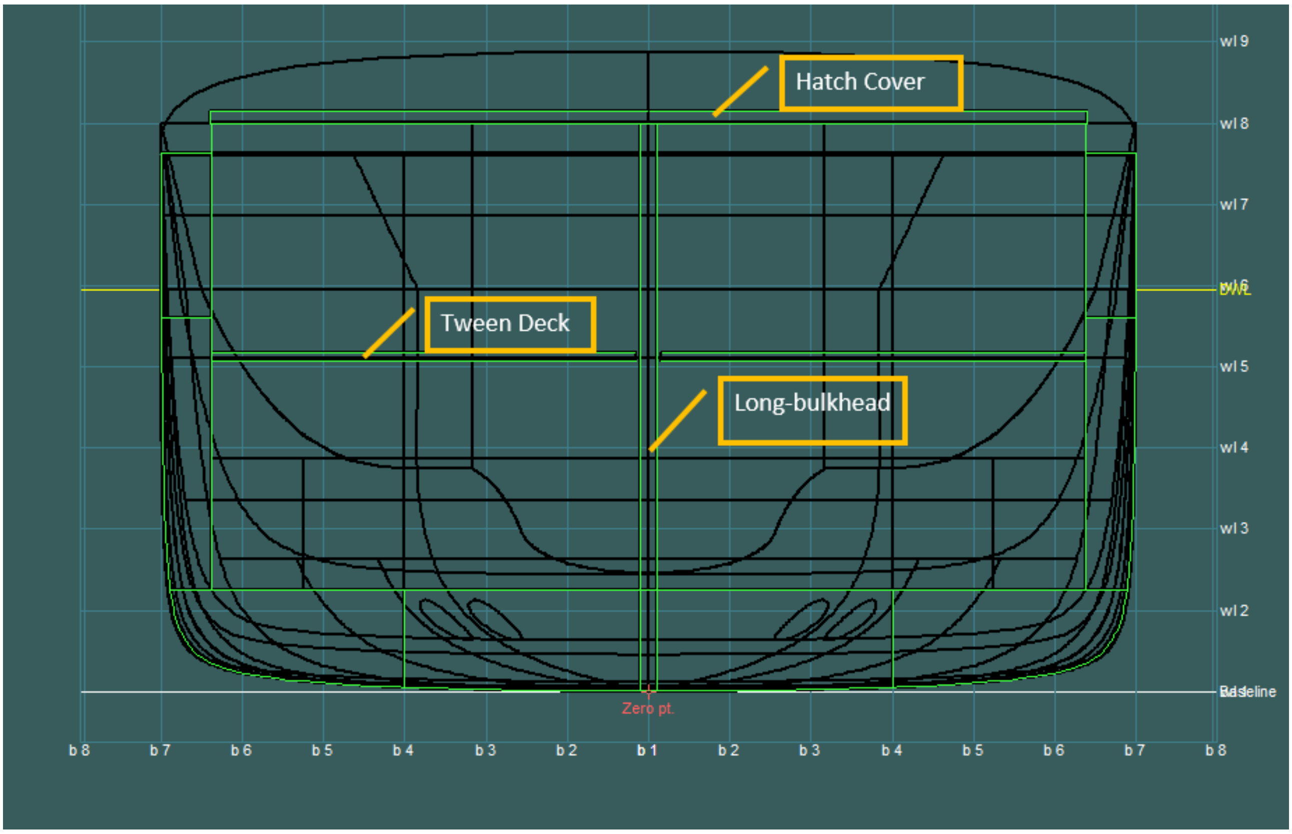


Figure 5-12 Aft View of Decom Tools Vessel's Deck

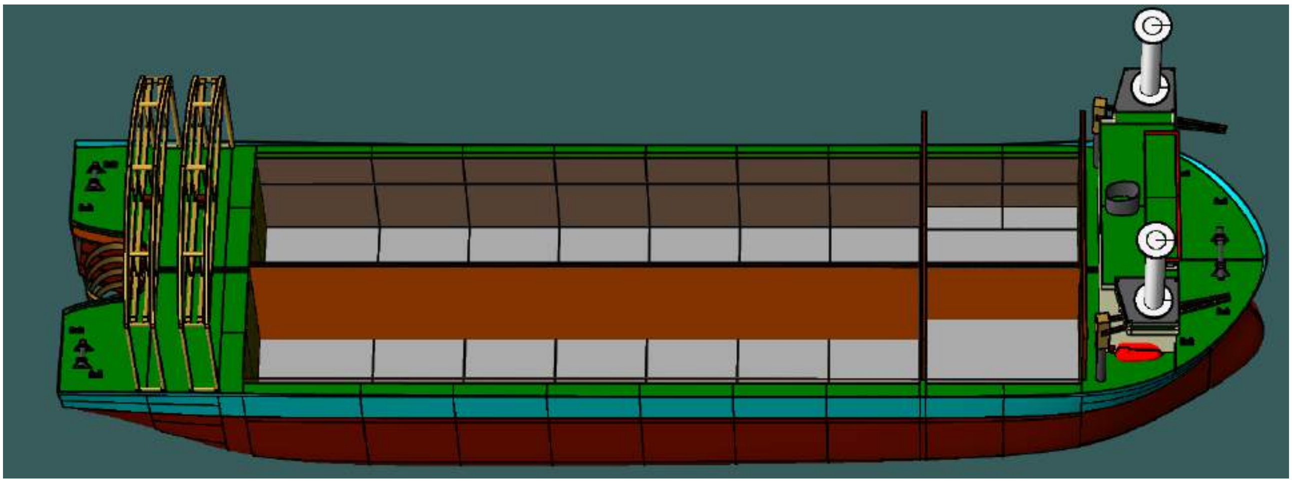


Figure 5-13 Decom Tools Vessel Holds

5.7 Tween Deck

Tween deck is only existed inside the hold number 2 at height of 16.3 m from keel. There are ten panels on each side, each panel has length of 10.87 m and width of 21 m. Panels can be stowed on weather deck (Bulkhead deck) or on the onshore warehouse. It is not necessary to insert tween decks panel in every cargo loading arrangement. In the next chapter it is explained that tween deck is just needed when segregation load out needs to be carried out. Therefore, in most cases, the panels of this deck need to be stored in the onshore warehouse.

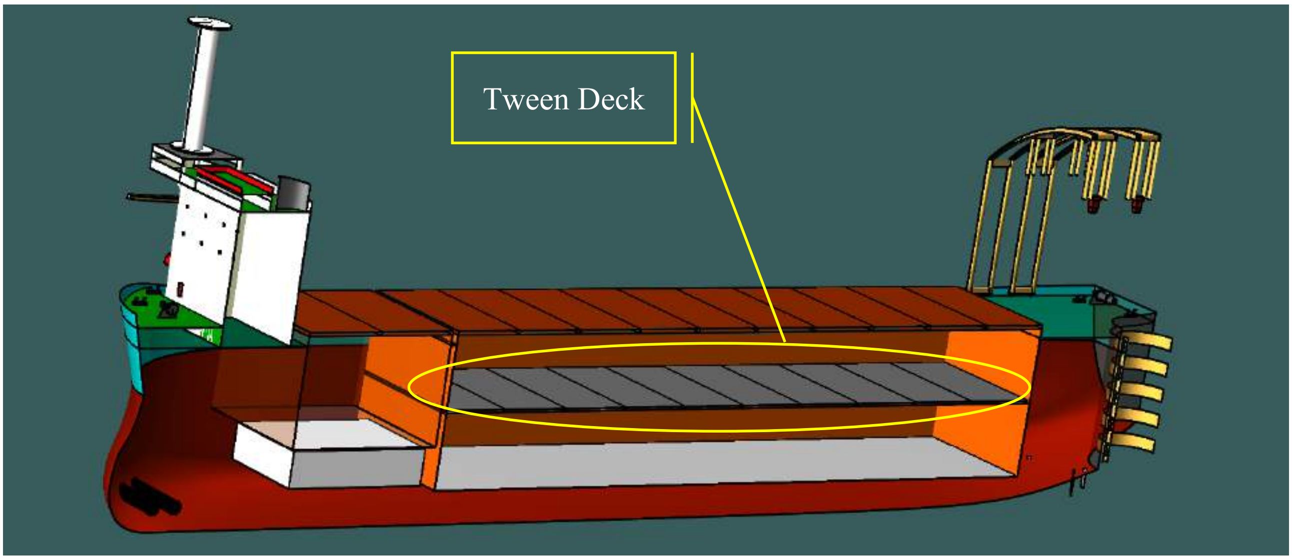


Figure 5-14 Cross Section of Decom Tools Vessel to show the Tween Deck

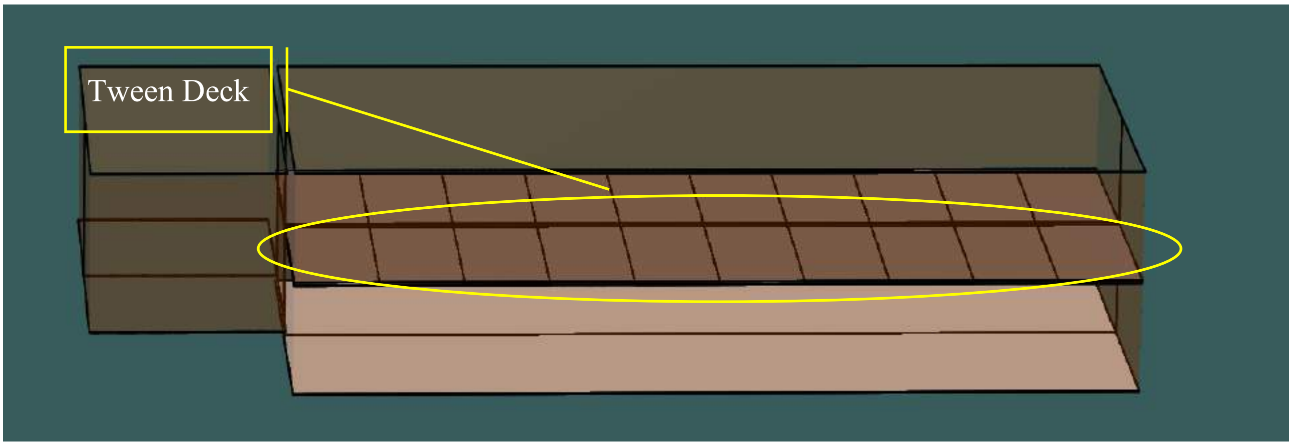


Figure 5-15 Holds and Tween Deck of Decom Tools Vessel

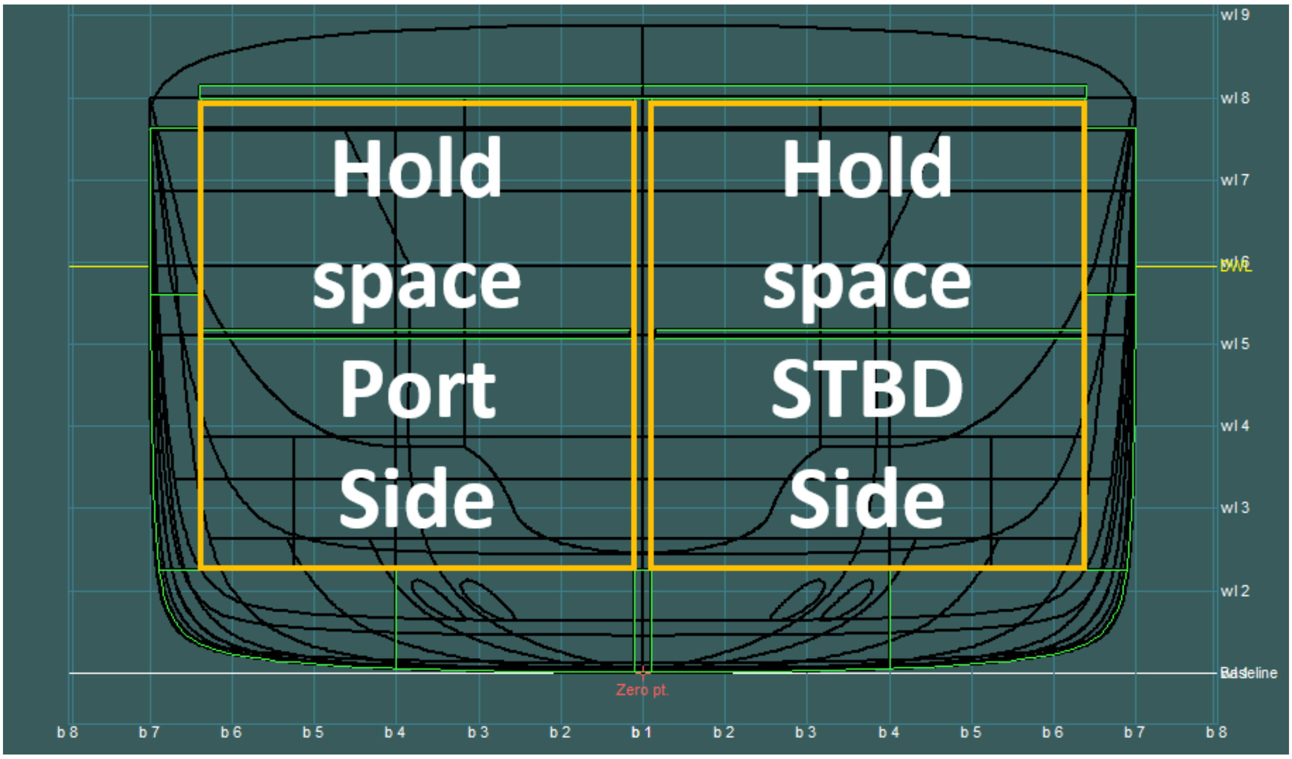


Figure 5-16 Aft View of Decom Tools Vessels Hold

Figure 5-16 shows the holds and tween deck from aft of the vessel. It also shows the side tanks and double bottom tanks in green colour. The holds are totally flat bottom and rectangular in order to provide more room for cargo loading.

Furthermore, the exact dimensions of the holds and decks are mentioned in the Table 5-1.

Table 5-1 Details of Dimensions of Decom Tools Vessel Holds and Deck

Deck	Side	Length (m)	Width (m)	Height (m)	Area (m^2)	Volume (m^3)	PSL ($\frac{Tones}{m^2}$)
Hatch Cover Hold No 1	STBD	25	21.5	0.6	537.5		> 16
Hatch Cover Hold No 1	PS	25	21.5	0.6	537.5		> 16
Hatch Cover Hold No 2	STBD	109	21.5	0.6	2343.5		> 16
Hatch Cover Hold No 2	PS	109	21.5	0.6	2343.5		> 16
Tween deck Hold No 2	STBD	108.7	21	0.4	2282.7		> 5
Tween deck Hold No 2	PS	108.7	21	0.4	2282.7		> 5
Top Tank Hold No 1	STBD	25	21.1		527.5		> 25
Top Tank Hold No 1	PS	25	21.1		527.5		> 25
Top Tank Hold No 2	STBD	109	21.1		2299.9		> 25
Top Tank Hold No 2	PS	109	21.1		2299.9		> 25
Hold No 1	STBD	25	21.1	16.5	527.5	8703.75	
Hold No 1	PS	25	21.1	16.5	527.5	8703.75	
Hold No 2	STBD	109	21.1	23	2299.9	52897.7	
Hold No 2	PS	109	21.1	23	2299.9	52897.7	
Overall loading Area on Hatch covers					5762		
Overall loading Area on Tween deck					4565.4		
Overall loading Area on top tanks					5654.8		

In the next chapter the sequences and the different cargo loading arrangement onboard the Decom Tools vessel are shown and explained in detail. Therefore, the reason of such design will be clear in the next chapter.

5.8 Bulkheads and Sections of Decom Tools Vessel

There is one longitudinal bulkhead which divides the breadth of the ship into 2 sections namely port and starboard side. In addition, there exists five transverse bulkheads which divides the vessel into 6 longitudinal compartments. Therefore, longitudinal and transverse bulkheads structured the ship into 12 compartments (or sections) in total. Figure 5-17 shows the longitudinal and transverse bulkhead of Decom Tools Vessel as well as collision bulkhead (in the forward of the ship).

Figure 5-18 shows all 12 sections of the Decom Tools vessel both from side and top view (Plan).

Figure 5-19 shows the dimension of holds, hatch cover and overall length of vessel. As it shown the tween deck exactly divide the hold number 2 into two equal heights.

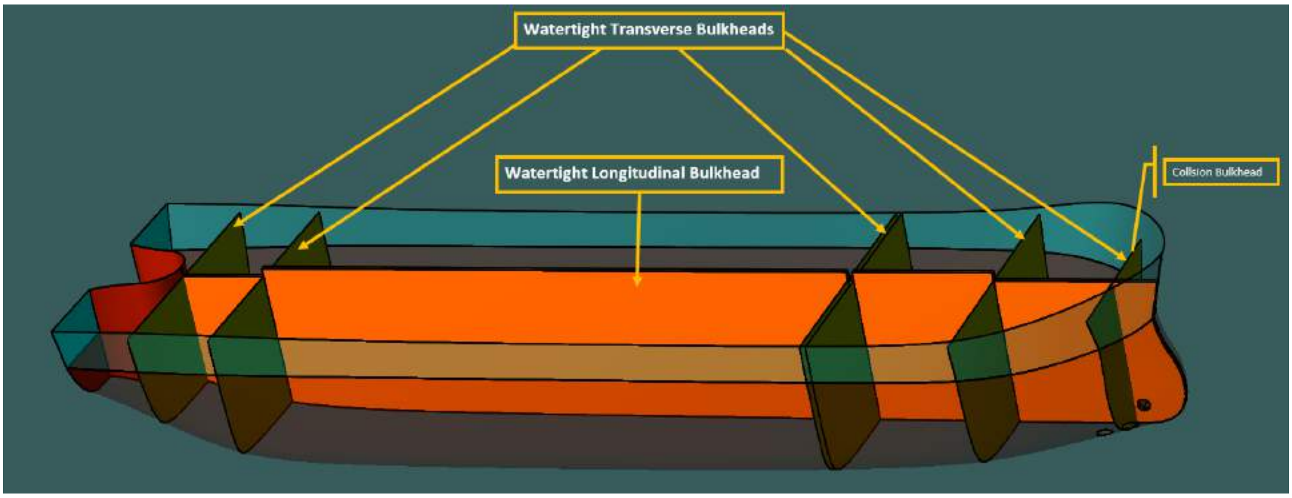


Figure 5-17 Longitudinal and Transverse Bulkhead of Decom Tools Vessel

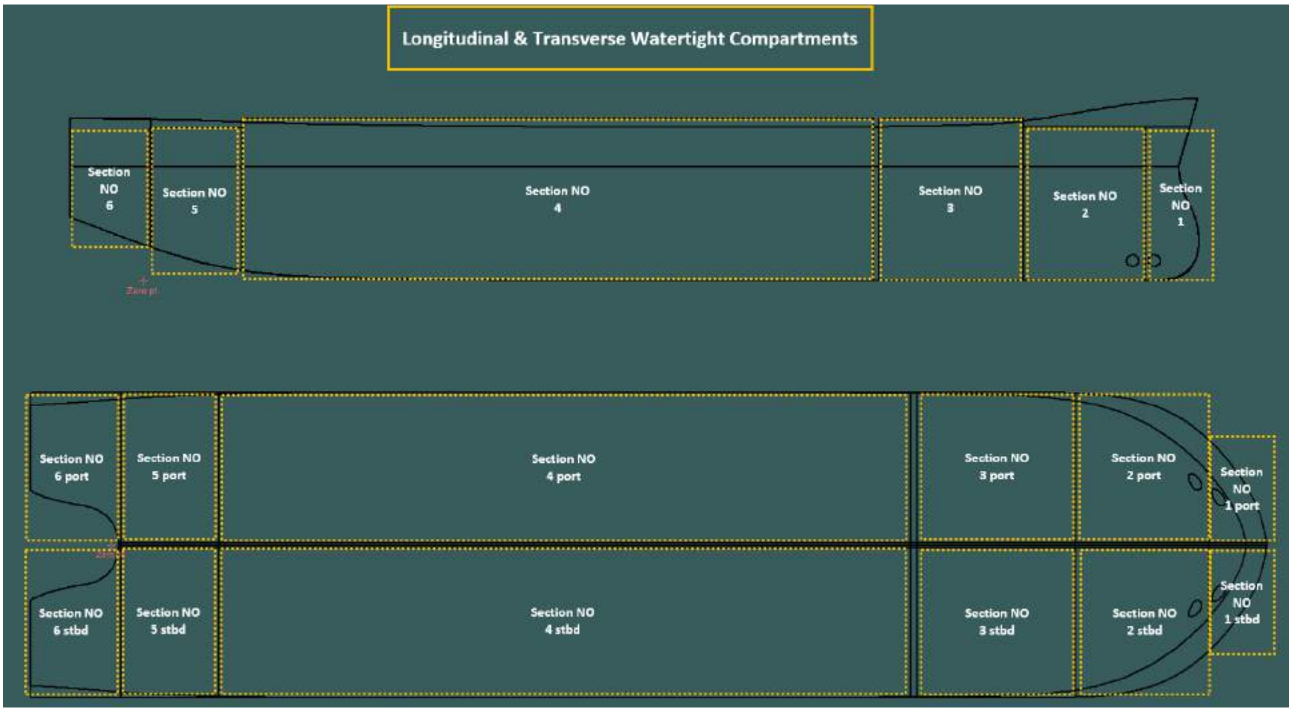


Figure 5-18 Longitudinal and Transverse Watertight Compartment

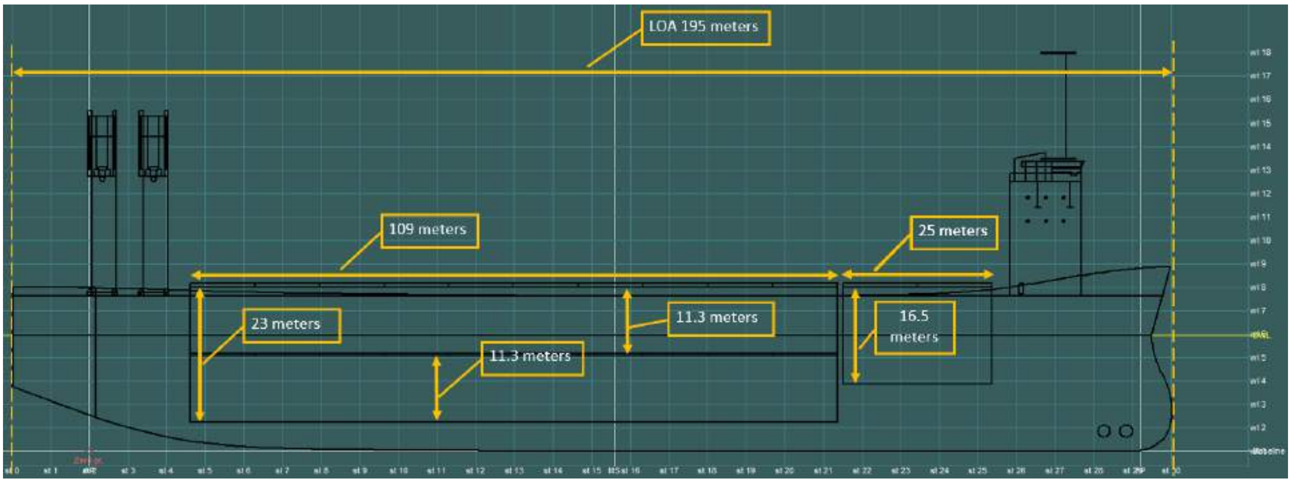


Figure 5-19 Dimension of Decks and Holds

5.9 Tanks of Decom Tools Vessel

Every vessel has different types of tanks for different purposes. Decom Tools vessel the same as other vessel has large number of tanks which they serve various applications. This vessel consists of 98 tanks. Number of tanks and types of them are as following:

I. 46 number of double bottom ballast tanks including fore and aft peak tanks.
II. 22 number of Side tanks.
III. 18 number of topside tanks.
IV. 2 number of heeling tanks.
V. 2 number of freshwater tanks.
VI. 2 number of Lube oil tanks.
VII. 4 number of DO tanks.
VIII. 2 number of LNG tanks.

As it mentioned above, tanks serve different purposes and lays in various location of the ship. the following figures show the location and types of Decom Tools Tanks.

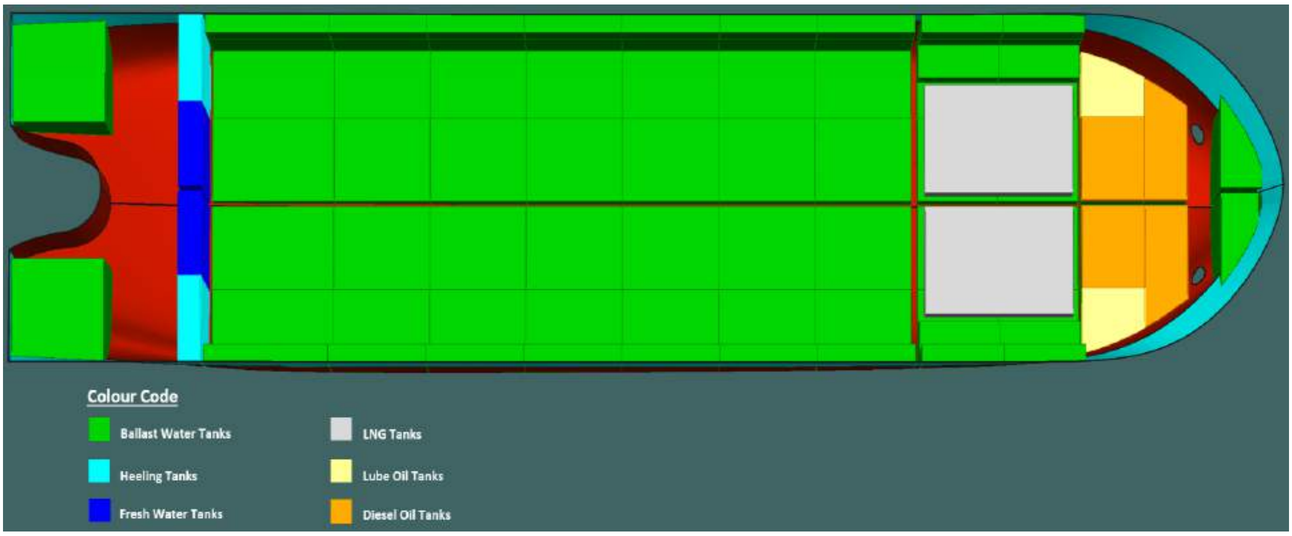


Figure 5-20 Plan of Tanks of Decom Tools Vessel

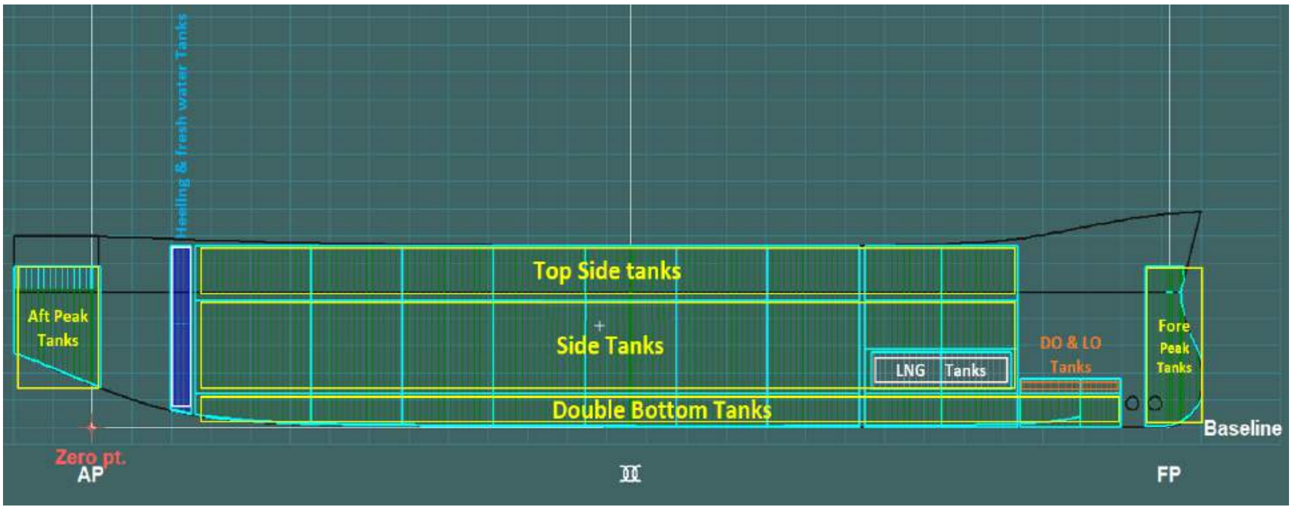


Figure 5-21 Side View of Decom Tools Vessel's Tanks

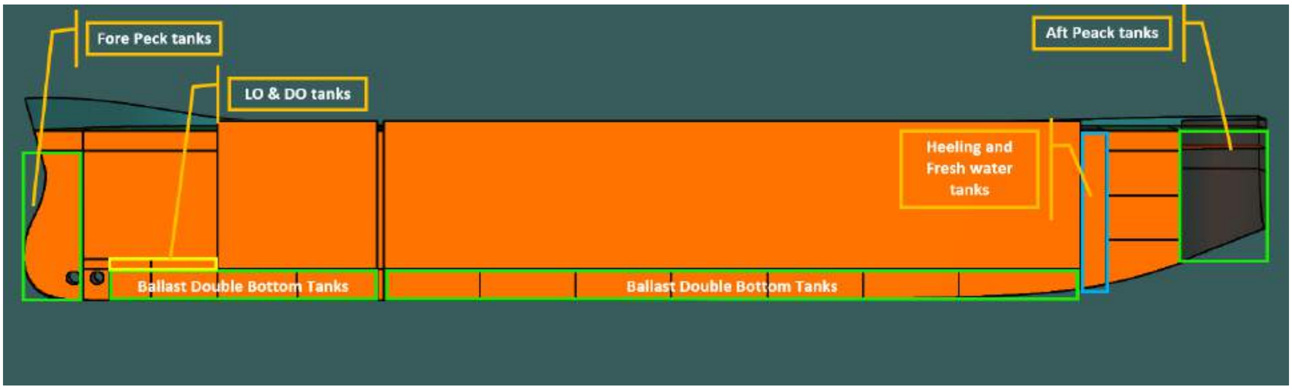


Figure 5-22 Side View of Decom Tools Vessel's Tanks

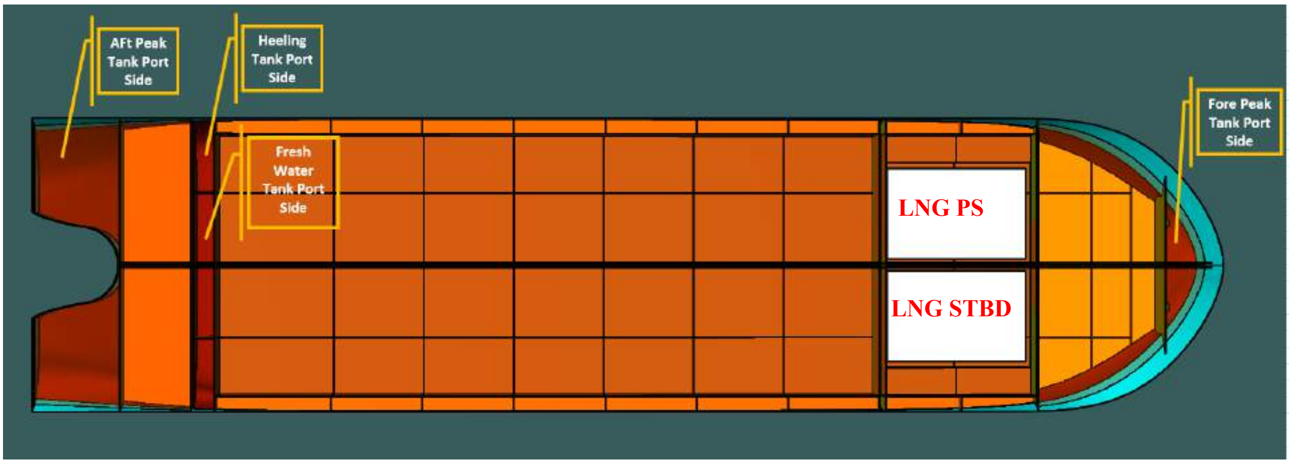


Figure 5-23 Top View of Decom Tools Vessel's Tanks

5.10 Topside, Side and Double Bottom Tanks

The double bottom tanks, top side tanks and side tanks are ballast tanks. In overall, the double bottom tanks have volume of 27 930.404 m^3.

The side tanks have volume of 9 110.264 m^3. In addition, topside tanks have volume of 5 128.556 m^3. Figure 5-24 show topside tanks, side tanks and double bottom tanks.

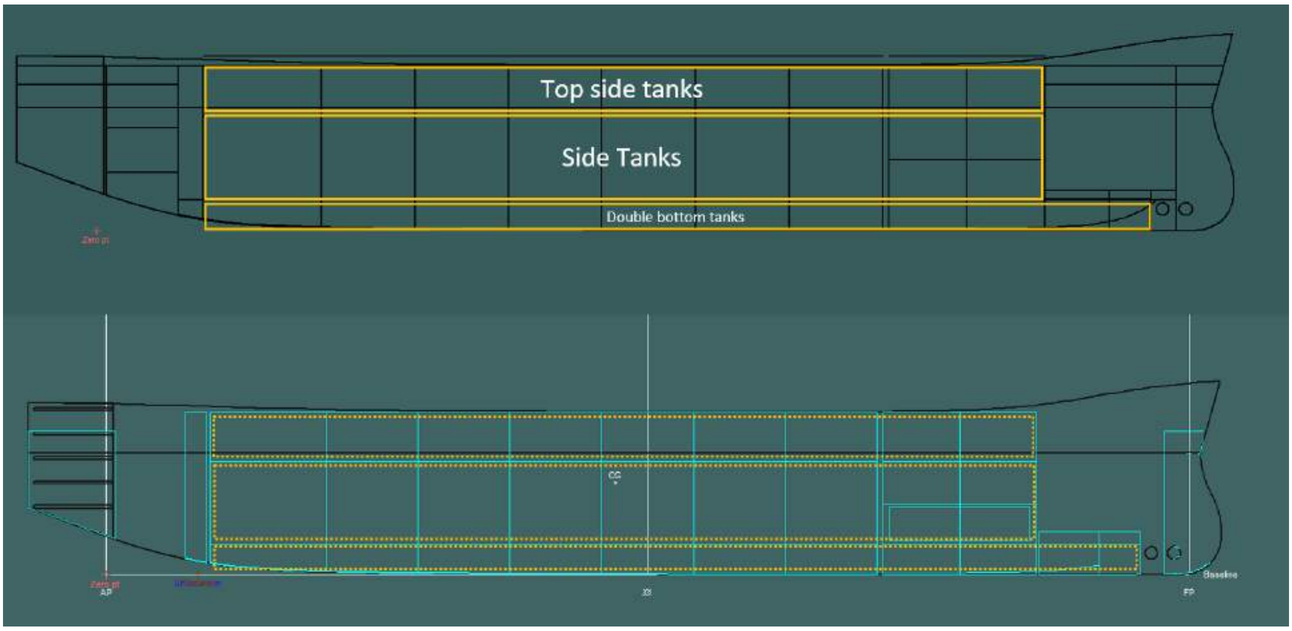


Figure 5-24 Side, Topside and Double Bottom Tanks of Decom Tools Vessel

Figure 5-25 shows the bow view of the vessel. In this view the location of topside tanks, side tanks and double bottom tanks are shown clearly.

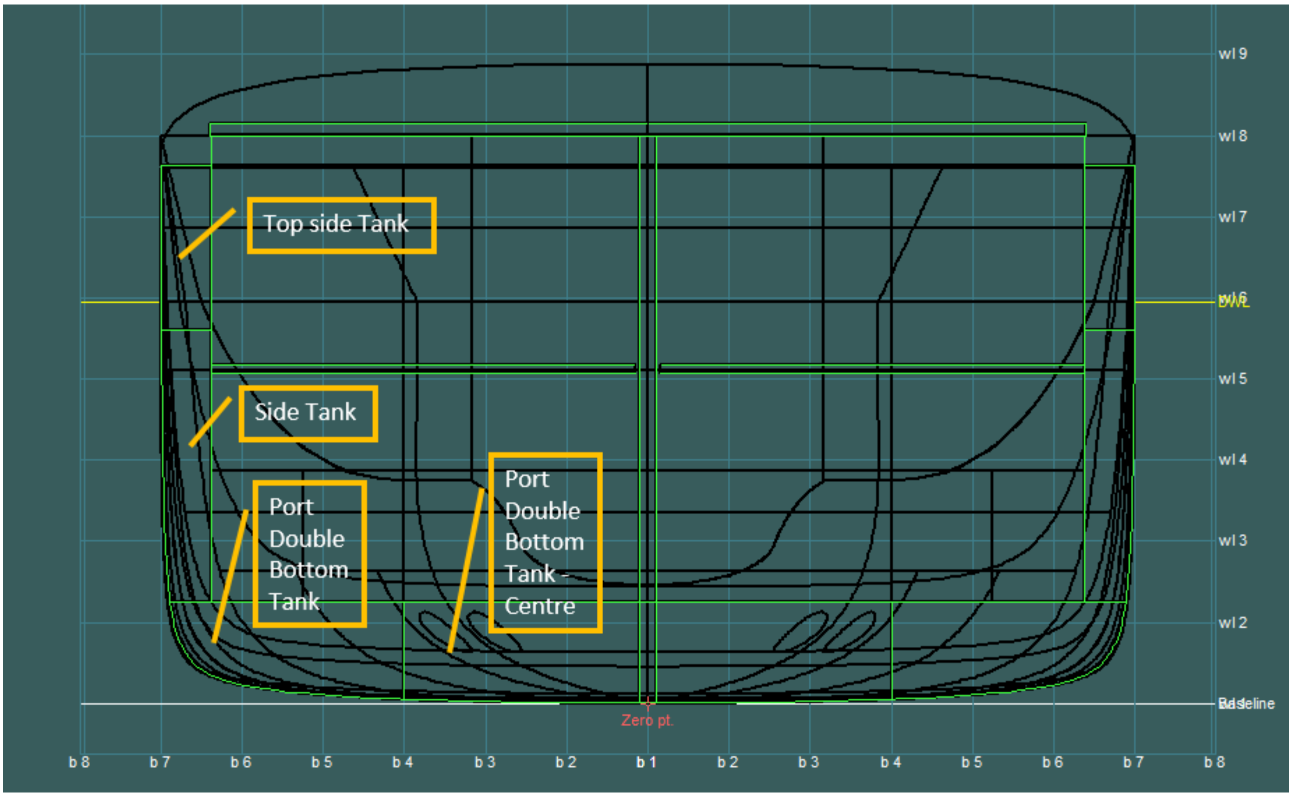


Figure 5-25 Bow View of Double Bottom Tanks, Side Tanks and Topside Tanks

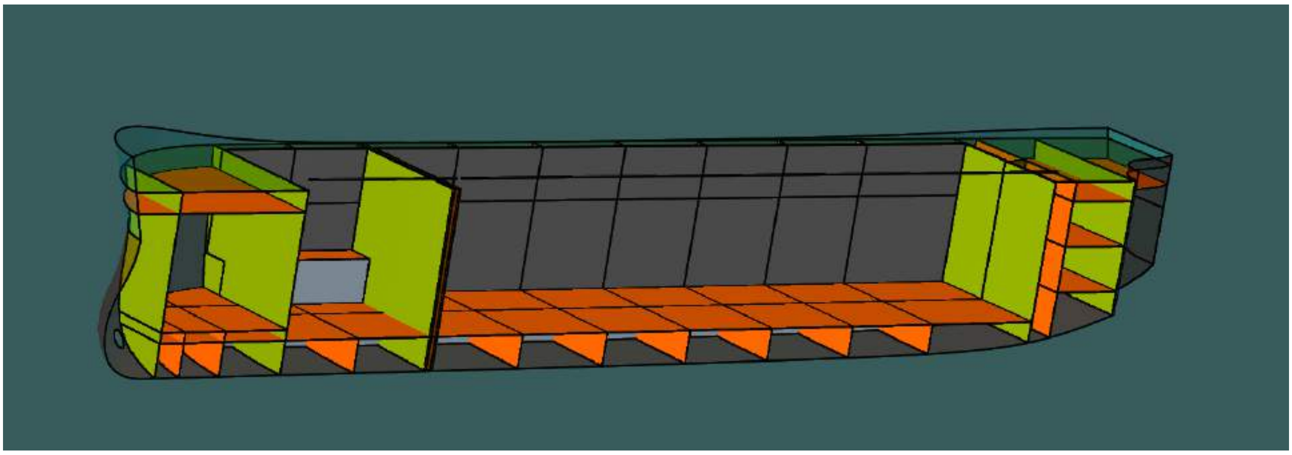


Figure 5-26 Cross Section of Double Bottom, (top)side Tanks

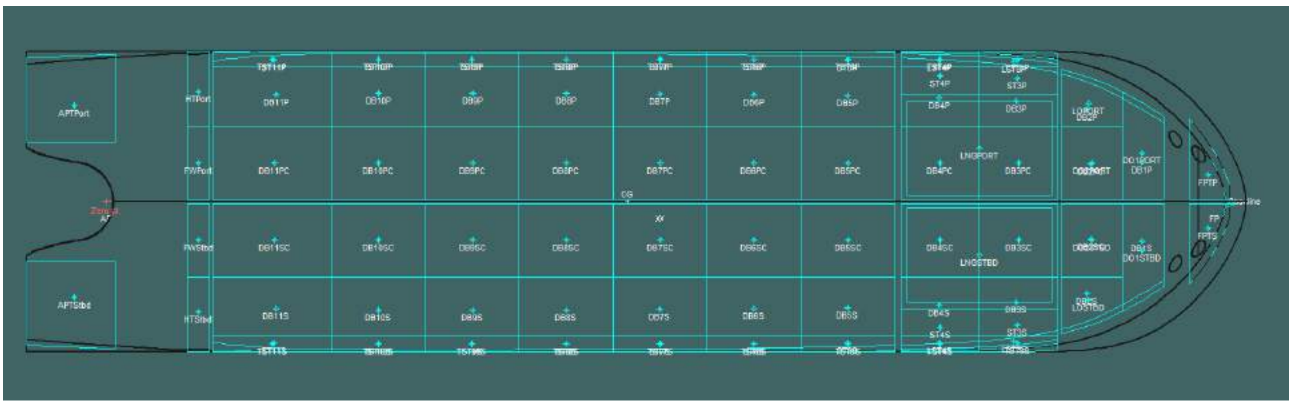


Figure 5-27 plan of Double Bottom (DB) Tanks of Decom Tools Vessel

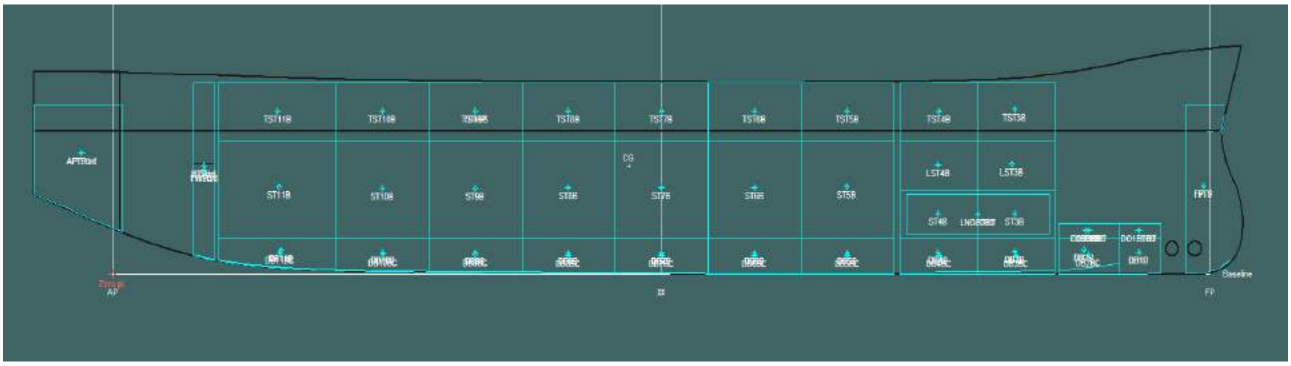


Figure 5-28 Cross Section of Top(side) Tanks

5.11 Engine Room and Battery Room

The Decom Tools vessel is equipped with two engine rooms and two battery room. Three number of batteries are located in the AFT battery room and four of them are located in the forward battery rooms. The reasons of this number of batteries in this vessel are explained in the section of Batteries and Batteries Sizing.

The dimension of engine room is as following:

I. **FWD Engine Room:**
- Length: 21m
- Beam AFT: 47m
- Beam FWD: 30m
- Height: 17 m

II. **AFT Engine Room:**
- Length: 11.5m
- Beam AFT: 47 m
- Beam FWD: 47.5m
- Height: 22.5 m

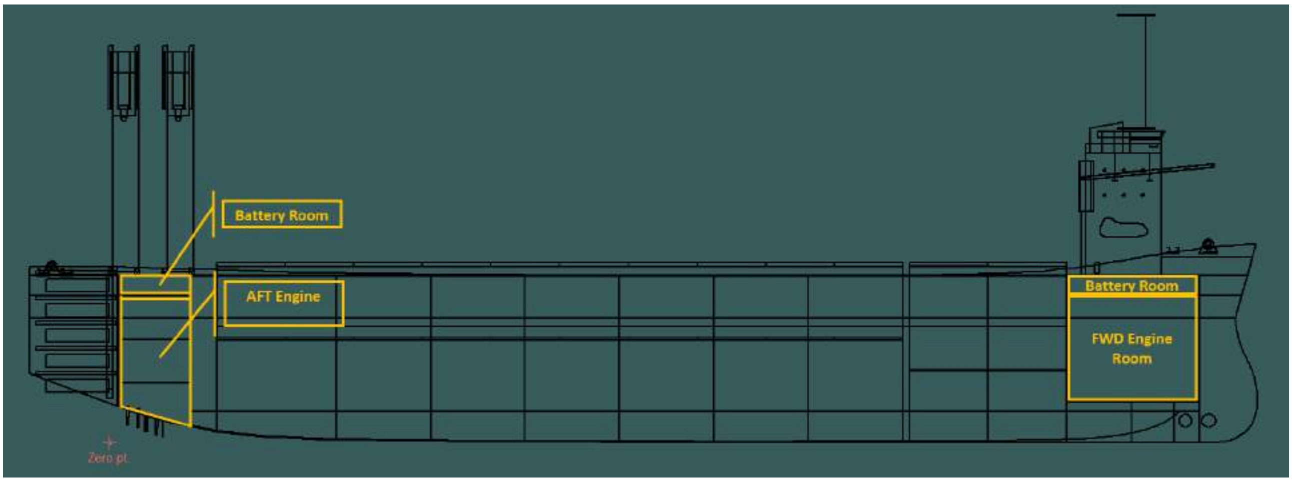


Figure 5-29 Location and Dimension of Engine Rooms

5.12 LNG, Diesel Oil and Lube Oil Tanks

The Decom Tools vessel has 4 number of marine gas oil (DO) tanks with overall capacity storage of 831.726 m^3.

Furthermore, the Decom Tools vessel has 2 LNG tanks with overall capacity storage of 3719.1m^3. Having considered that the main fuel system is LNG, therefore, the LNG tanks are approximately 4.5 times bigger than Diesel oil tanks.

Based on the previous chapter, this volume of LNG is equivalent to 2200 m^3 marine gasoil.

According to the IGF code section §5.3.3, the distance of LNG tanks from side of the vessel shall not be less than $\frac{B}{5}$, where B here is the beam of the vessel. However, in another clause, it is stated that for ships other than passenger ships and multihulls, a tank location closer than $\frac{B}{5}$ from the ship side may be accepted. Furthermore, the minimum distance from bottom line should be $\frac{B}{5}$ or 2 m whichever is less.

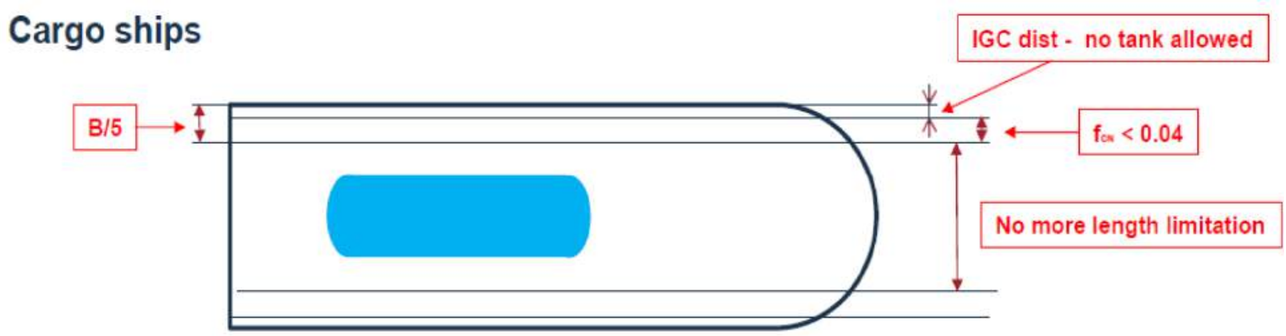


Figure 5-30 Location of LNG tank based on IGF code (Kokarakis 2015)

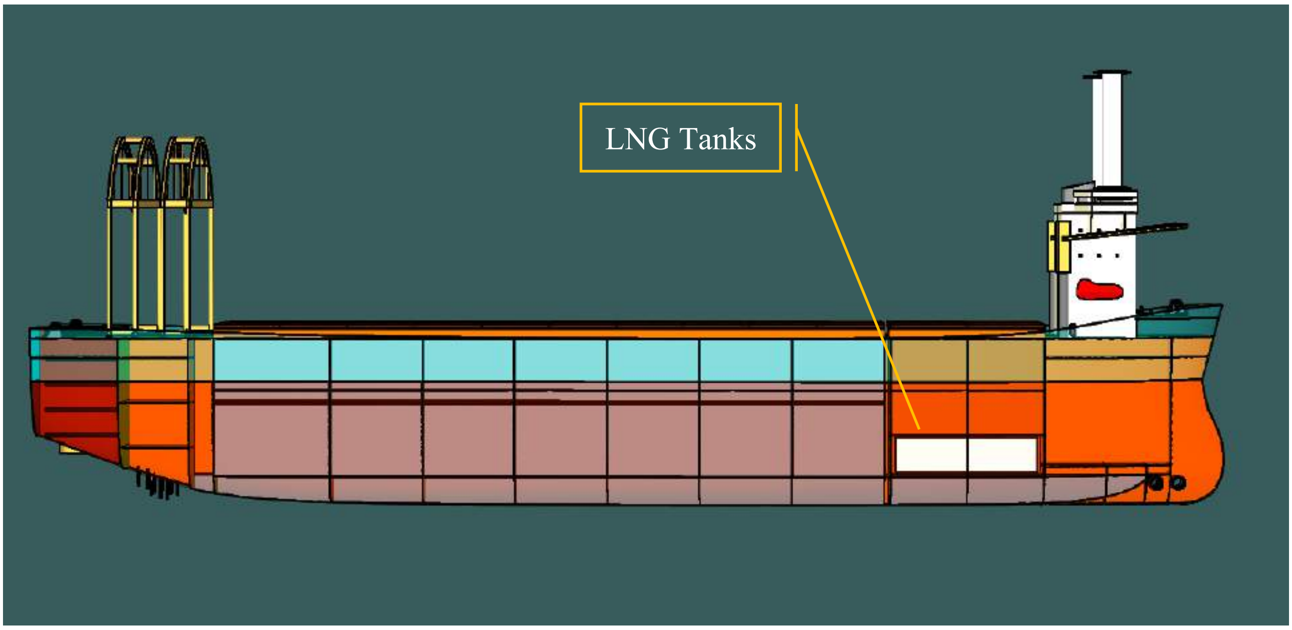


Figure 5-31 Location of LNG tanks of Decom Tools Vessel

In the Decom Tools vessel, the distance of LNG tanks from side is considered 8 meter while the $\frac{B}{5}$ $is\ 9.6m$. Moreover, the distance of LNG tanks from bottom line is 5.5 meters. Furthermore, the membrane LNG tanks are considered for the Decom Tools vessel (The membrane tank currently is the most expensive types of LNG tanks). The reason of less distance and devising membrane tanks is to bunker more LNG within the available space.

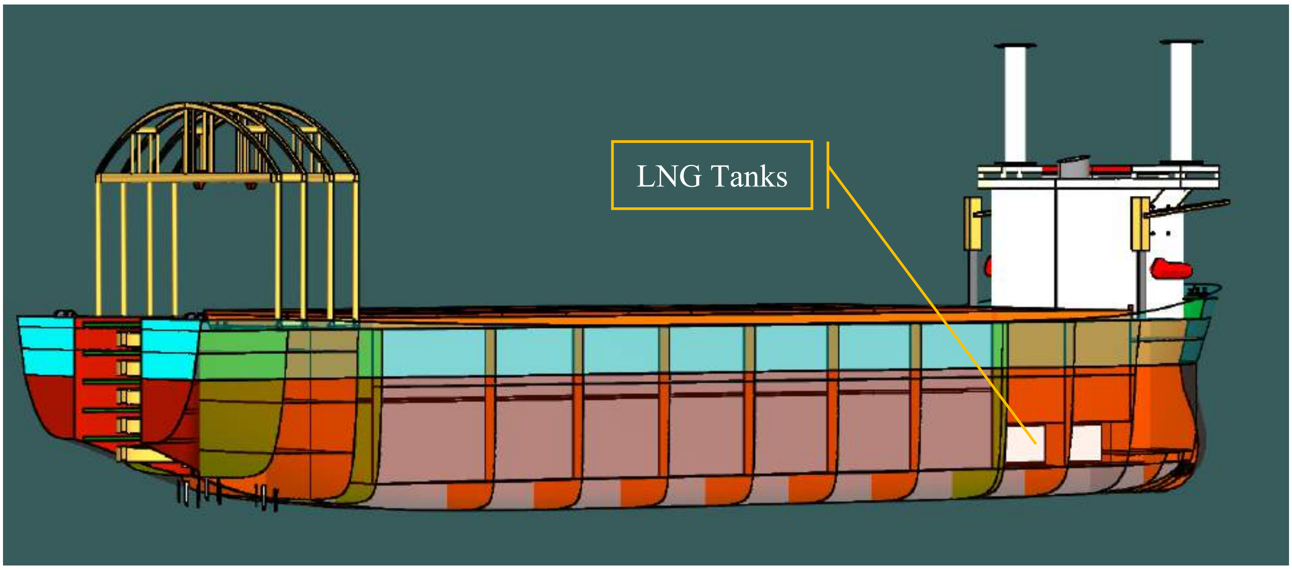


Figure 5-32 LNG tanks of Decom Tools Vessel (Perspective View)

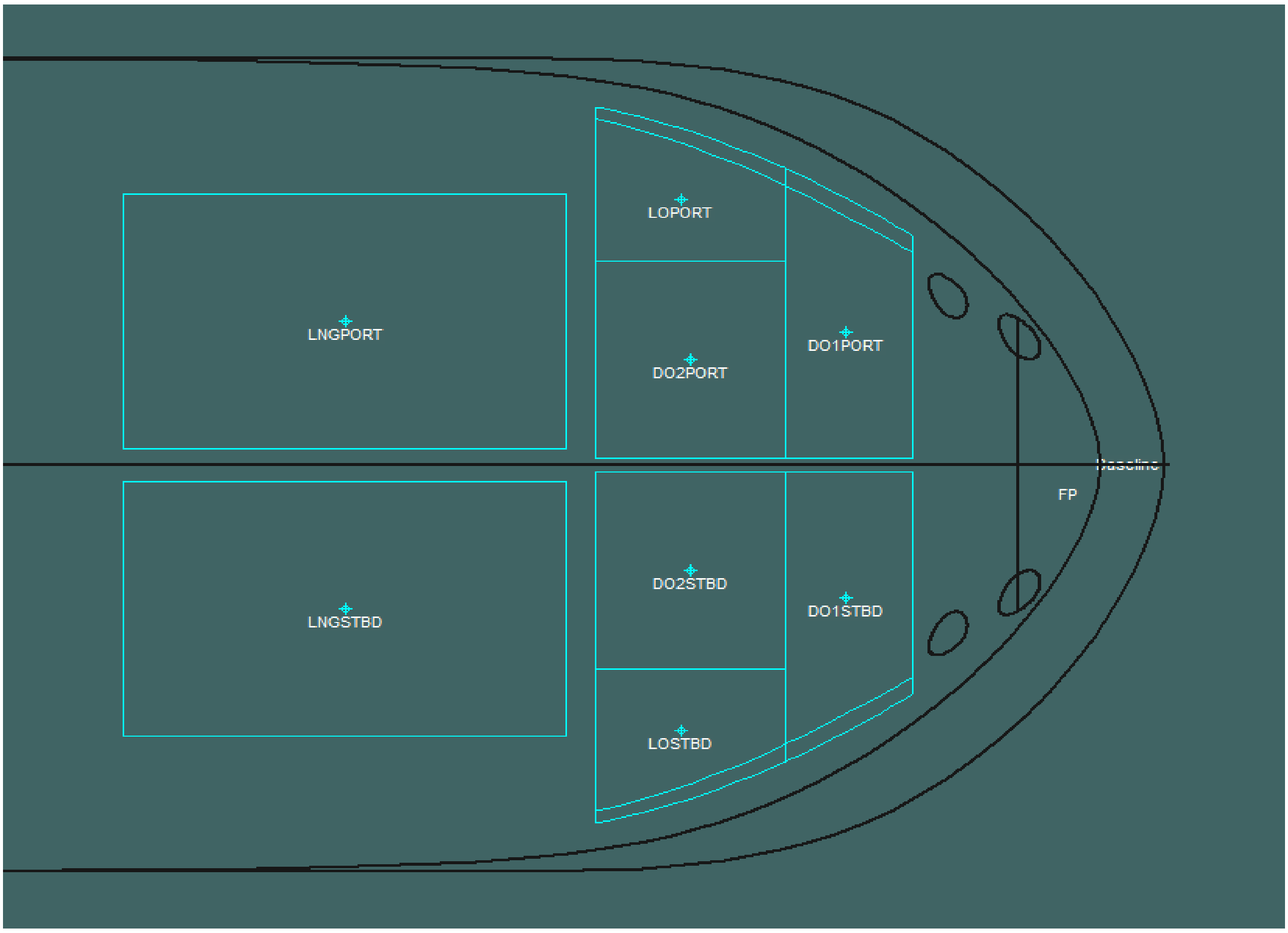


Figure 5-33 Plan of LNG and Diesel Oil Tanks

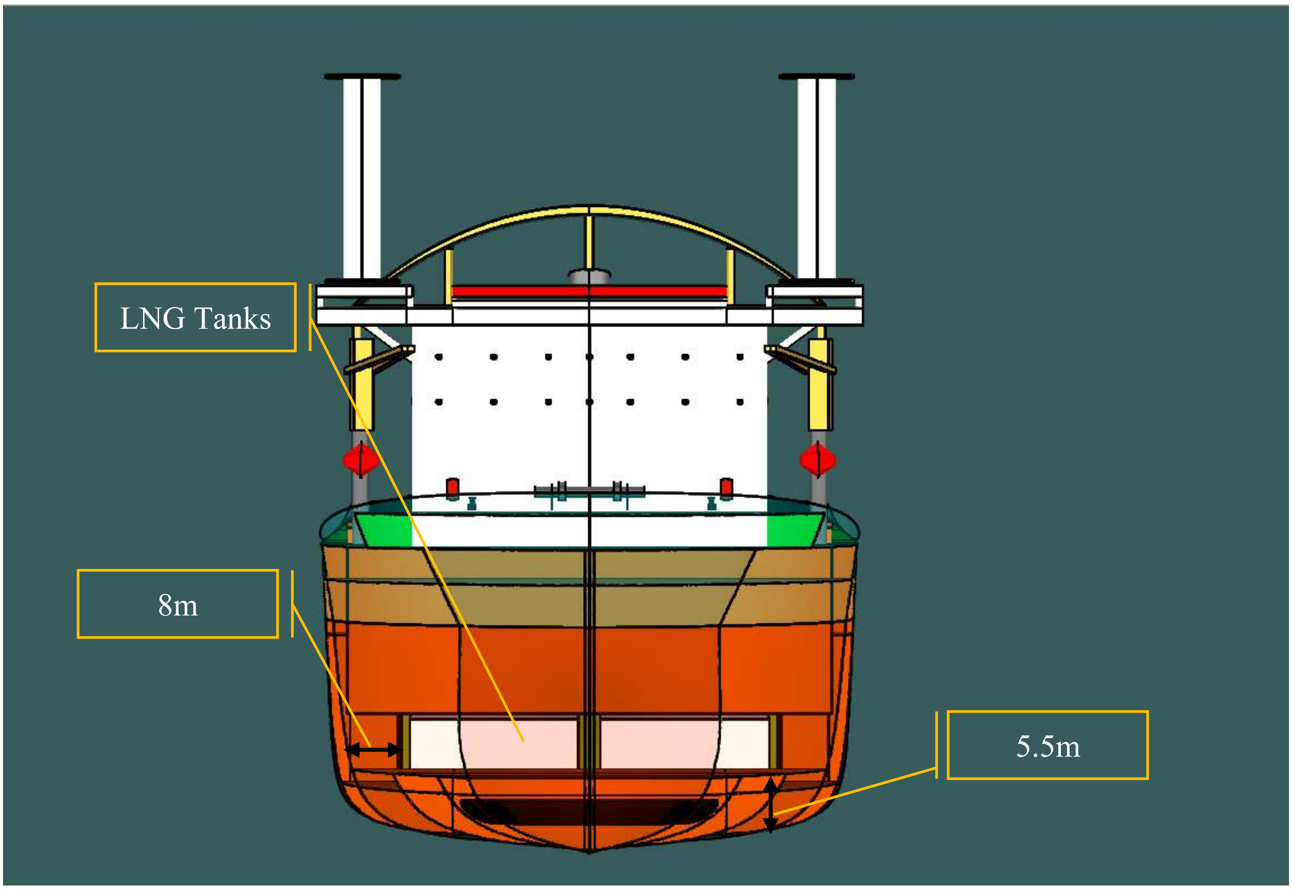


Figure 5-34 Location of LNG tanks of Decom Tools Vessel

5.13 Fresh Water and Heeling Tanks

The Decom Tools vessel is equipped with 2 numbers of freshwater tanks with overall capacity of 1931.782 m^3. In addition, two heeling tanks with overall capacity of 1829.15 m^3 have been designed for this vessel.

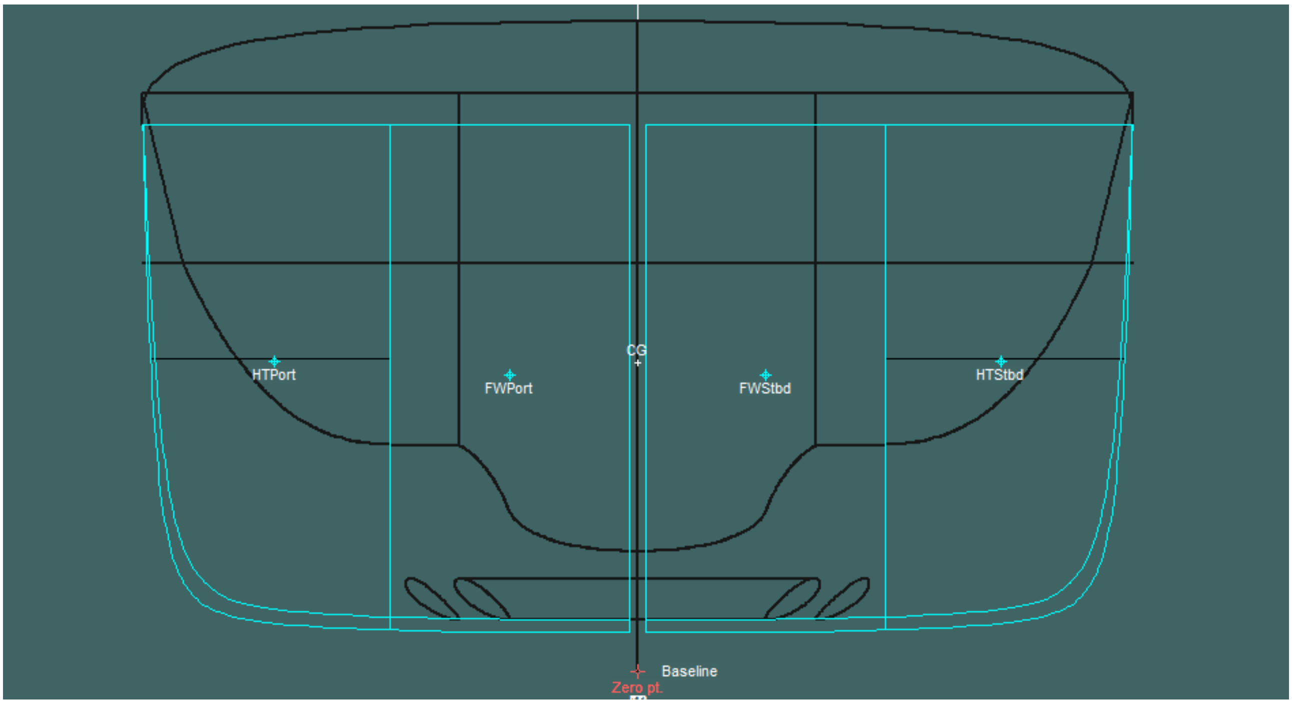


Figure 5-35 Back View of Fresh Water and Heeling Tank

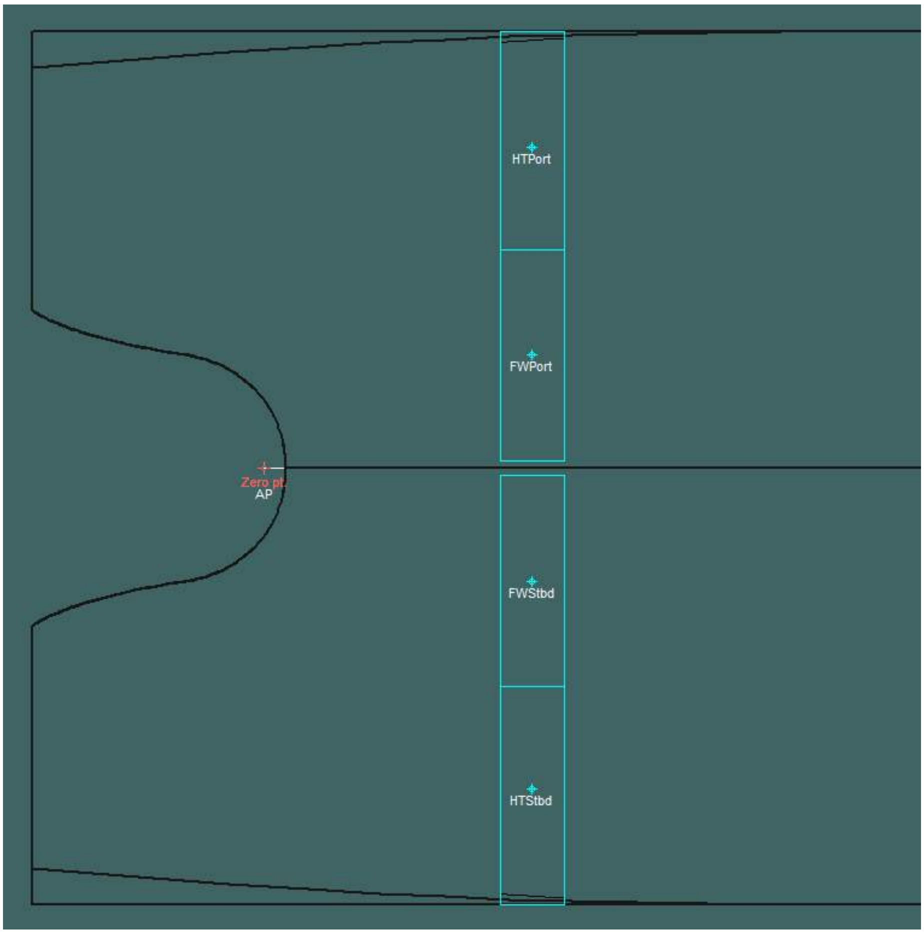


Figure 5-36 Plan of Fresh Water and Heeling Tanks

5.14 List of Tanks and Volumes

Table 5-2 shows the list of tanks onboard the Decom Tools vessel along with their storage capacity.

Table 5-2 Tanks List and Tanks Storage Capacity

List of Tanks	Quantity of Tanks	Storage Capacity (Ton)	Storage Capacity Volume (m^3)
For Peak Tanks	2	2154.263	2101.72
Aft Peak Tanks	2	4813.71	4696.302
Double Bottom Tanks	42	28628.668	27930.404
Side Tanks	22	9338.022	9110.264
Top Side Tanks	18	5256.768	5128.556
Heeling Tanks	2	1874.88	1829.15
Freshwater Tanks	2	1931.782	1931.782
Lube Oil Tanks	2	253.248	275.27
Diesel Oil Tanks	4	698.65	831.726
LNG Tanks	2	1747.976	3719.1
Total	**98**	**56697.967**	**57554.274**

5.15 Accommodation of Decom Tools Vessel

As it stated before, one of the reasons that charter rate of installation or construction vessel are high is that for installation operation, different specialists with different experiences need to be mobilized in order to do the installation operation. But for transportation of cargos, there is no need to mobilize almost most of the installation team. Lack of complex equipment on the cargo vessel leads to mobilization of less specialist to run and maintain the vessel and the machineries which lead to lower charter rate of the vessel. Less number of crew means less wage, less supervisor, less demand of victual and so on. Normally the construction vessel has accommodation capacity of between 80-300[47] personnel. However, larger vessel has bigger living quarter. In this design, we consider the accommodation for maximum 90 persons. During the transportation operation, approximately 25 number of crew needs to be mobilized based on our estimation. However, for pile extraction as well as cable extraction the number of crew can be increased to 50 persons. Some extra cabins for clients as well as third parties and contractors are included which compel us to enlarge the size of the accommodation. The dimensions of accommodation of Decom Tools Vessel are as following:

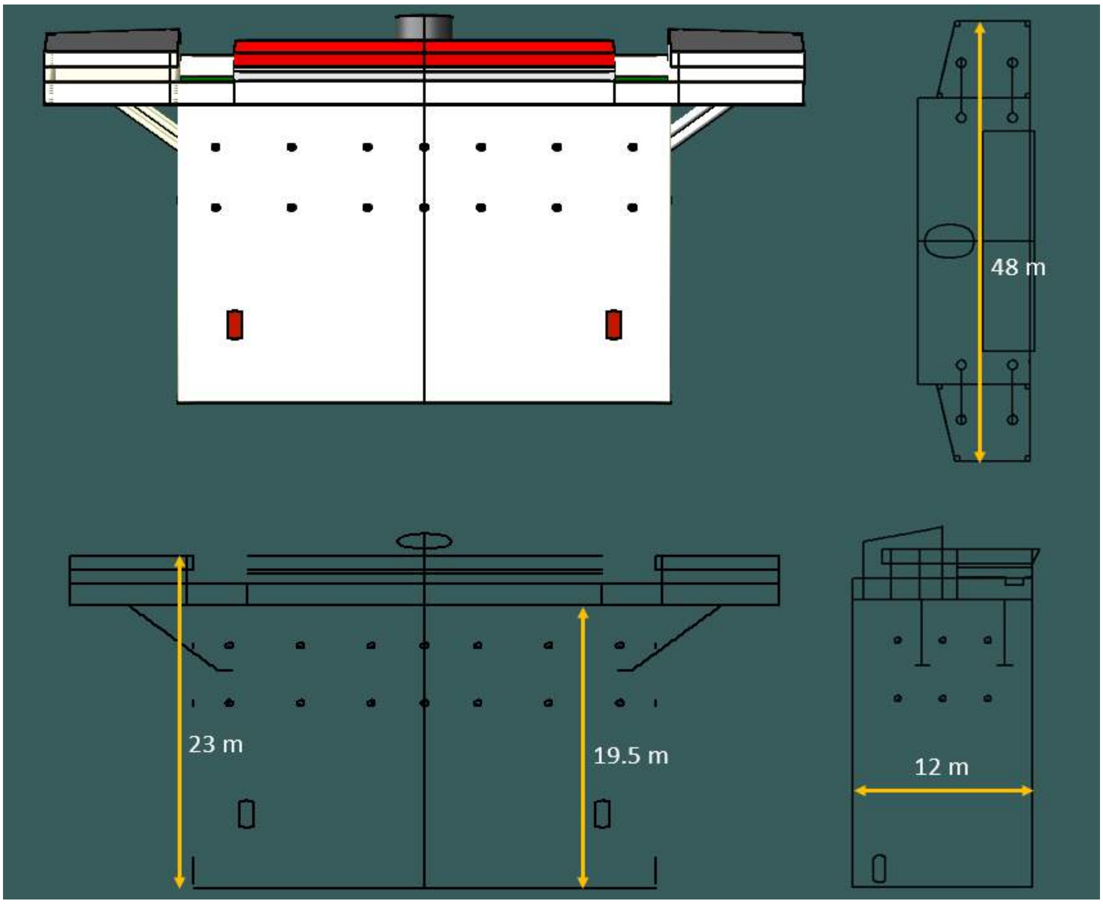


Figure 5-37 Dimension of Accommodation

[47] Pioneering spirit vessel has accommodation for 571 persons. Oceanic 500 has accommodation for 400 persons. Thialf vessel has living quarter for 736 persons (https://hmc.heerema.com/fleet/thialf/).

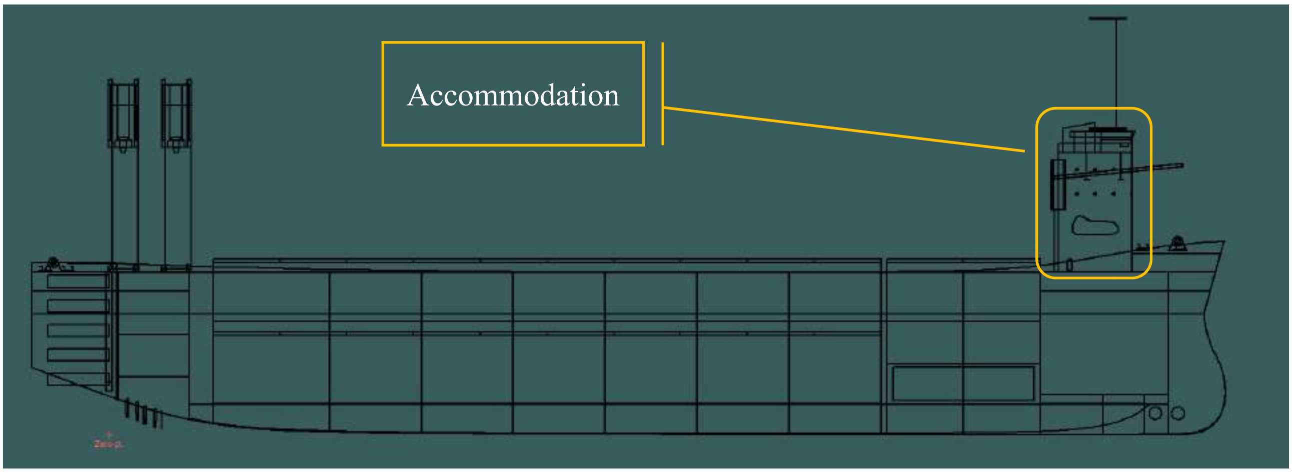


Figure 5-38 Side View of the Decom Tools Vessel (Showing Sections)

5.16 Major Machineries of Decom Tools Vessel

Decom Tools vessel is equipped with some basic equipment in order to meet the objectives of Decom Tools project and generally to be suitable for decommissioning projects. However, some of the used tools have never been used in any vessel so far. But the operations principal of the tools is so ordinary and common which means in most of operations normal crew can run the vessel. It is proofed in this document that it is possible to decommission the offshore wind parks with some basic machineries. The question of which tools are necessary for decommissioning operation and how to design the equipment and utilize them makes this vessel unique and special for decommissioning operations. The section which is called Decom Tools operation manual are explained in the next chapter.

5.17 List of Major Equipment

Engineering of this vessel necessitate to design some of the major equipment on various locations. However, in every corner of this vessel, some equipment is devised to be installed. The list of main equipment as well as main sections of the vessel are as following:

1. Accommodation.
2. Holds and hatch covers.
3. Hatch lifting tools.
4. Mooring winches.
5. Storm anchors and position anchor winch.
6. Gantry cranes.
7. Life-Saving Appliances (LSA) including Lifeboats; lift raft and etc.
8. Flettner Rotors.
9. Solar system.

10. Batteries and battery rooms.
11. Hydraulic Grippers.
12. Pile/Transition piece cutting tool.
13. Automatic and manual marine growth removal system.
14. Cable rollers.
15. Cable extraction winches.
16. Cable hydraulic gripper.
17. Cable shear cutter.
18. Cable cutting Cabin.
19. Automatic and adjustable seafastening for blades.
20. Blade cutting tools.
21. Propulsion system.
22. Engines and generators.
23. Engine rooms.
24. Propulsion system.
25. Propulsion rooms.
26. Water desalination system.
27. Different types of tanks.

In the following sections, the various equipment and assets of this vessel are shown one by one. However, the detail design of some of the equipment and tools will be attached as appendices to this document such as Flettner rotors, solar system, Blade seafastening and cutting tools, hydraulic grippes etc.

5.17.1 Cranes of Decom Tools Vessel

Four cranes are engineered for the Decom Tools vessel, and all are located on the bulkhead deck or weather deck. Two of them are gantry cranes and others are provision cranes. Each type of cranes serves different applications.

5.17.1.1 Gantry Cranes

The gantry cranes are designed to be employed for the following applications:

I. Lifting and loading the components and cargos from the deck into the holds.
II. Lifting and placing the hatch covers.
III. Pile extraction.
IV. Transition Piece removal and so on.

The pile extraction function of Decom Tools vessel compels us to increase the lifting capacity of gantry cranes. In this design, each gantry crane has Safe Working Load (SWL) of 750 tones which in tandem configuration (using both cranes simultaneously), they can lift 1500 tones. 1500 tons lifting capacity is enough to maintain the weight of monopile.

Based on the manufacture recommendation, the gantry crane with this specification required a hoist with electromotor of 1100 kW for lifting of 750 tones. But it should be considered, in many cases the loads are so light and need to be transferred by the gantry crane, for example during lifting the blade. The blade of 12 MW turbine has weight of 55 tones which need to be lifted and lowered into the holds by using both gantry cranes. In order to minimize the consumption of gantry crane, two electro motors for hoists have been devised. The small electro motor is designed for lifting object with weight of 50 tones. In addition, the large size electromotor can be used to lift items with 750 tones.

The application of gantry crane for the pile extraction operation is explained in the next chapter. Not only in the pile extraction operation, but in cable extraction, cargo loading, marine growth removal and other operations these cranes can be used.

There are many types of the cranes in the market. The reasons why we select the gantry cranes are as following:

- There is no need to construct huge structure for this type of cranes on the vessel deck since the crane is mobile and move longitudinally. The crane has access/move from aft of the vessel to the accommodation and the winches provide access from port to starboard side.
- This type of cranes can be operated by normal crew (riggers, barge foreman or deck foreman) and no need to be operated by certified crane operator[48]. The day rate of heavy lift crane operator is between 500-800$ per day which in this case, no need to mobilize such crane operators.
- This type of crane is not so much influenced by the rough sea state and bad weather condition which means that can be operated in most of weather conditions.
- The lifting capacity in all condition is fixed since the boom angle does not change. So, it does not have load lifting chart for different boom angle which make the operation so easier.
- The motion of vessel does not impede the function of this type of the crane.
- There is no need to reinforce the vessel structure since the load are distributed to the beam of the ship.

[48] Crane operator with stage 2 or stage 3 certificate

The idea of design of the gantry crane structure is taken from the American vessel by the name of VB 10000[49] which is shown in the Figure 5-39. Each gantry crane on VB-10000 can support a single Claw, and each Claw is capable of lifting 1.800 metric tons from locations as deep as 110 m underwater. The total lifting capacity of a single Claw is 2.700 metric tons, but the claw itself weighs 910 mt (Wikipedia 2021).

Figure 5-39 VB 10000 (Greeves n.d.)

Figure 5-44 shows the structure of gantry cranes of Decom Tools vessel. This structure is drawn very roughly without conduction of any structural analysis and simulation. Therefore, the geometry of members of the structure are not engineered. Also, the size of structure members is not sized and designed. The aim of showing such structure is to stress that the width between the vertical member of the gantry crane (gantry legs) is 47 m and the conventional gantry cranes have lower width. So, the structure of common gantry crane which is shown in the Figure 5-40 may not fit this purpose. However, similar equipment needs to be installed on this gantry crane too. Figure 5-41 shows the electro motors of the gantry cranes. As it stated before, each gantry crane has two electro motors.

Figure 5-42 shows the height of winches of gantry crane with respect to the top of the hatch covers. As it shows the heigh in this design is considered 24.4 meters.

[49] Deployed for the first time in October 2010, this new system, designated the VB 10,000, is the largest lift vessel ever built in the United States.

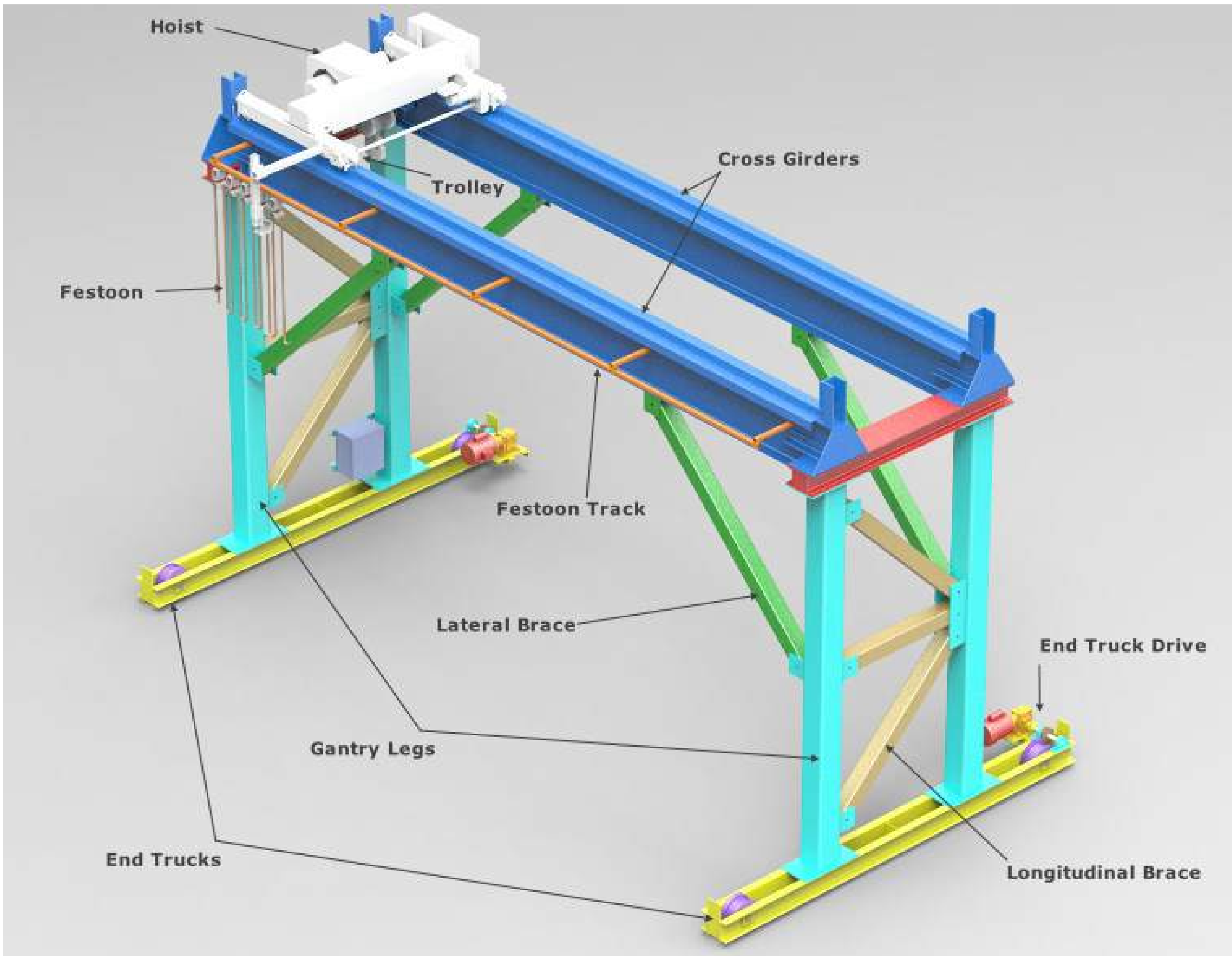


Figure 5-40 Elements of a Gantry Crane (NAICRANES n.d.)

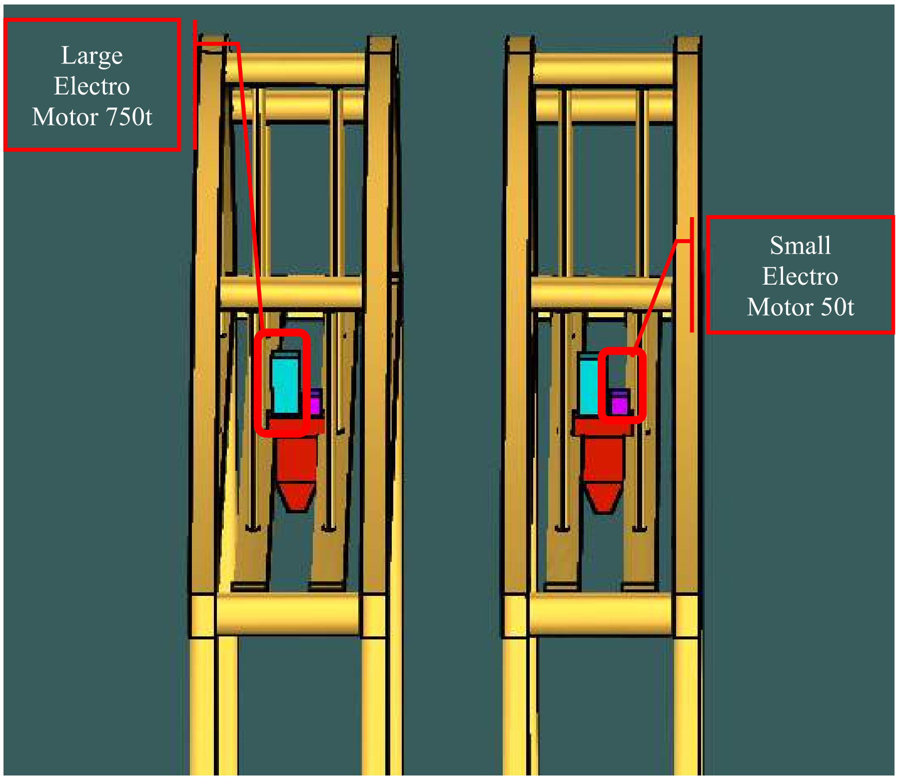


Figure 5-41 Electro Motors of Gantry Cranes

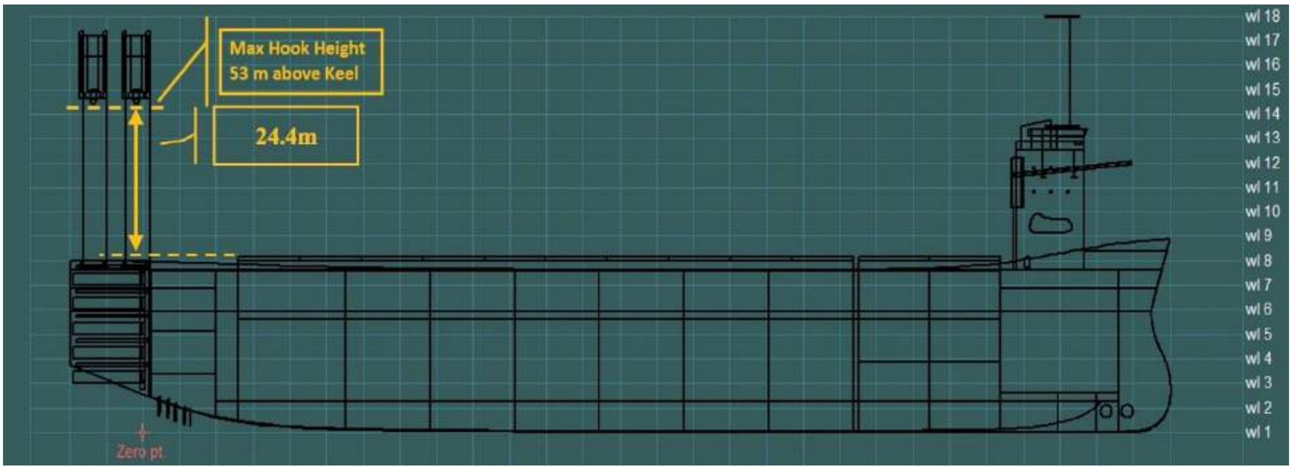


Figure 5-42 Height of Gantry Crane

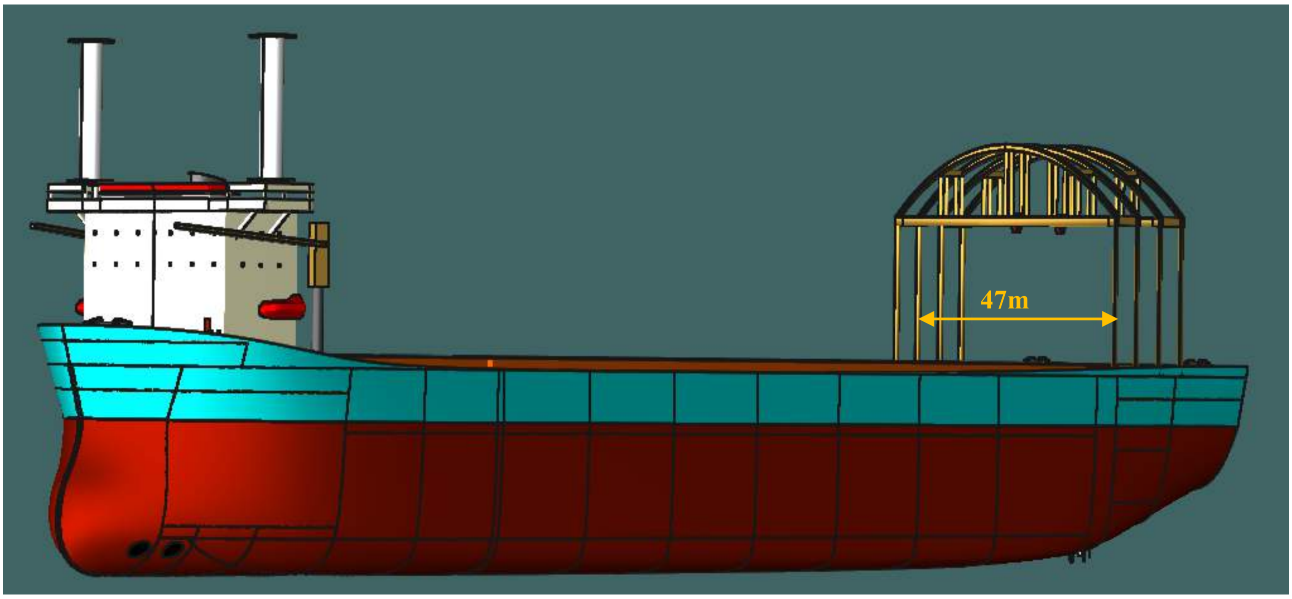


Figure 5-43 Dimension of Gantry Cranes

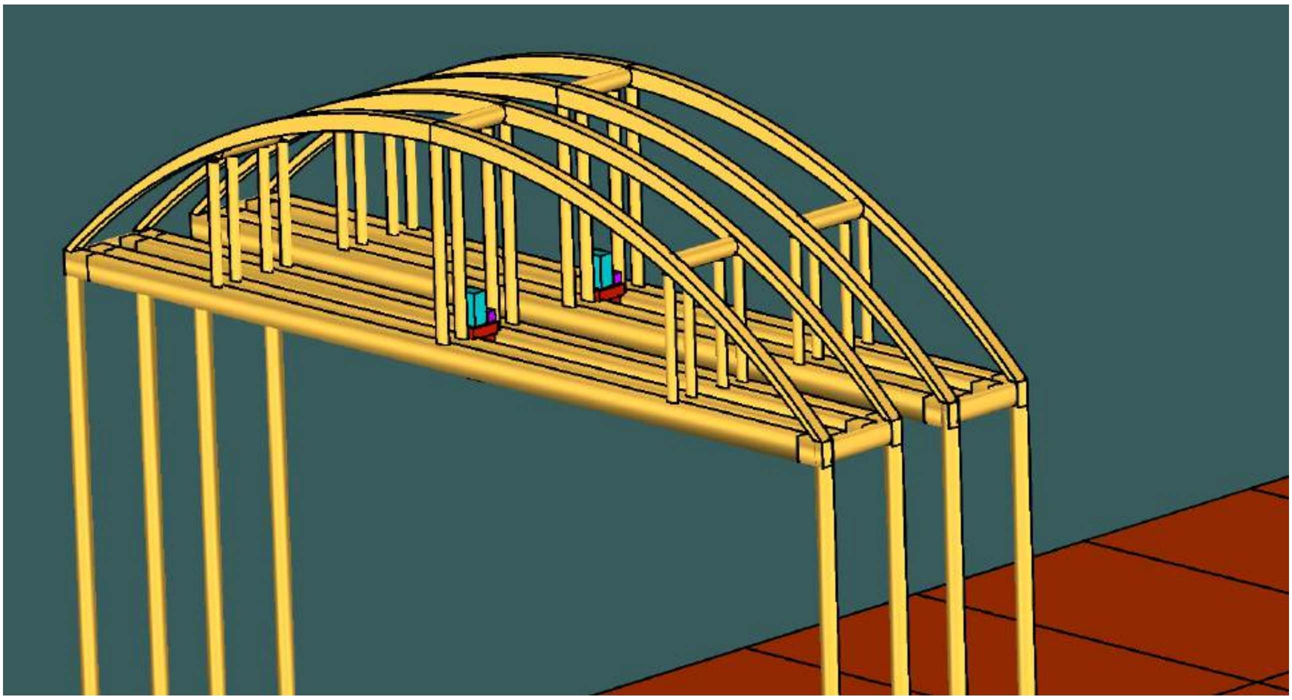


Figure 5-44 Structure of Gantry Cranes

5.17.1.2 Provision Pedestal Cranes

Furthermore, two provision pedestal cranes are designed at port and starboard side of the vessel with safe working load (SWL) of 30 tones. Based on similar ships in the market, the electromotors for this crane consume 44 kW approximately.

These cranes have following applications:

- Transferring crew from/to the vessel.
- Lifting cargos from other vessel or port such as provision, spare parts of the vessel.
- For the maintenance and cleaning of the accommodation, monkey island equipment and so on.
- For the maintenance of the hull.
- For the maintenance of gantry cranes winches.
- For conveying mooring lines.
- Lowering tools to the seabed like beacon etc. and other possible operations.

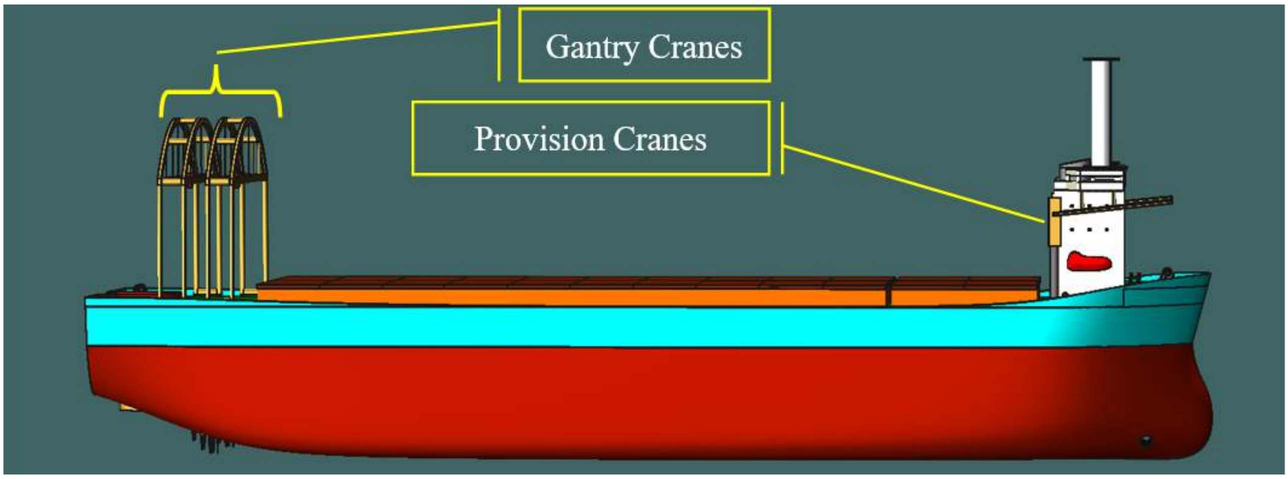


Figure 5-45 Cranes of the Decom Tools Vessel

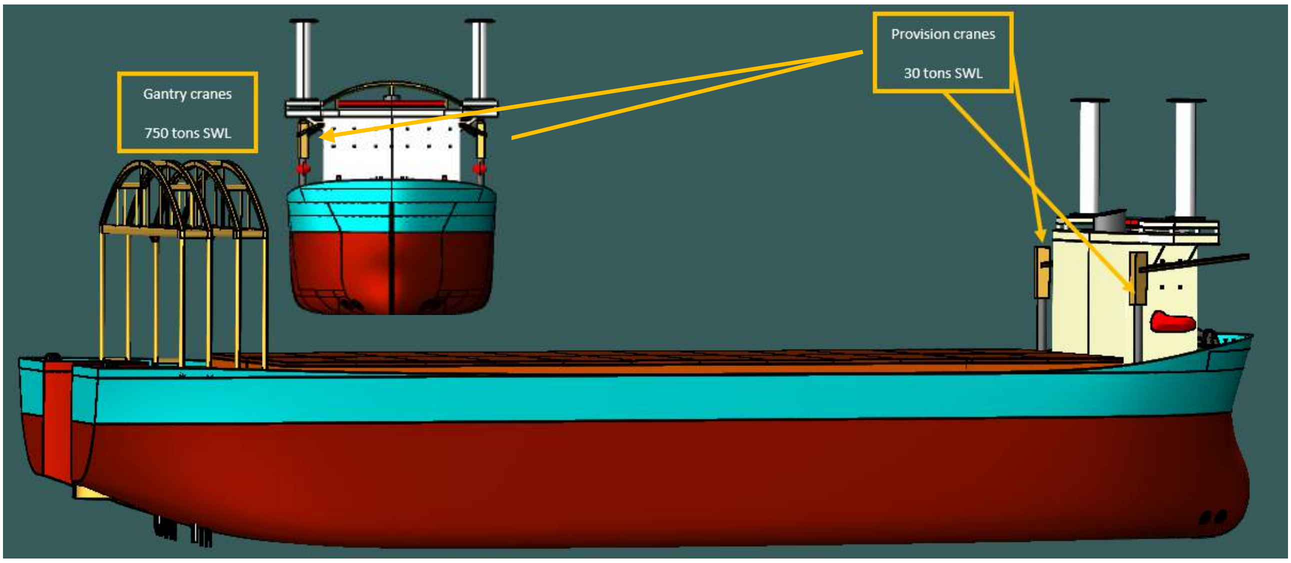


Figure 5-46 Gantry and Provision Pedestal Cranes

These provision cranes should have overlap. In this case the length of boom of provision crane is 33 meters. Figure 5-47 shows the length of provision cranes when the booms tip is located in the centreline of the ship.

To transfer the crew with provision crane, they should be certified for man riding operation. Furthermore, for sending the equipment into the sea, they should be certified for subsea operations.

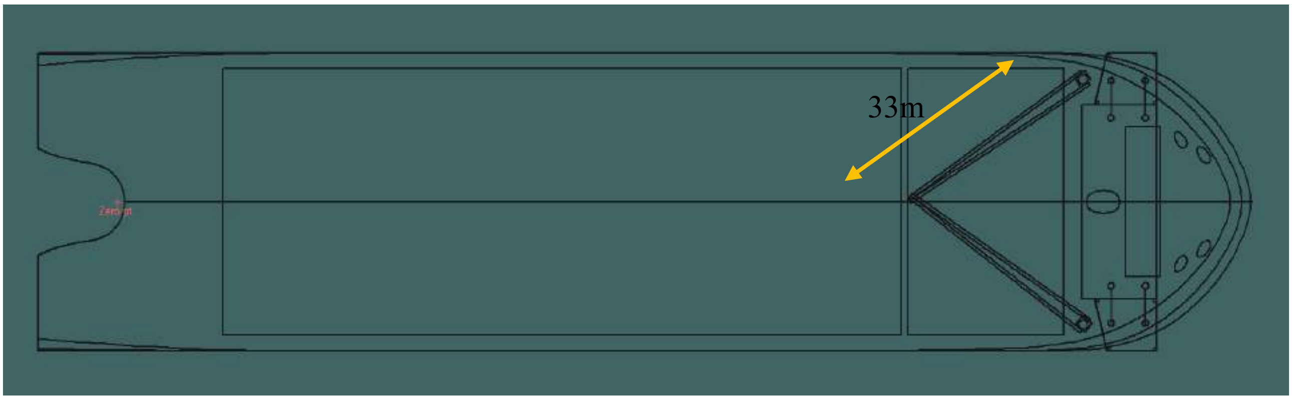


Figure 5-47 Boom Length of Provision Cranes

5.17.2 Flettner Rotors of Decom Tools Vessel

Flettner rotor is a wind assisted propulsion system that harness the power of wind and convert it to additional forward thrust. In the rotor technology, the amount of fuel savings decreases as the ship size increases. Savings of 60% for small ships have already been achieved while savings of up to 19% on Very Large Crude Carriers (VLCC) are being modelled (Mofor , Nuttall and Newell 2016). Enercon E-Ship 1 is the only wind turbine component carrier in the market which is equipped with Flettner rotors.

Figure 5-48 Enercon E-Ship 1 (equipped with 4 number of Flettner rotors)

Two Flettner rotors are designed in the Decom Tools vessel in order to enhance the performance of the vessel which contribute to reduction of the fuel consumption and CO_2 emission.

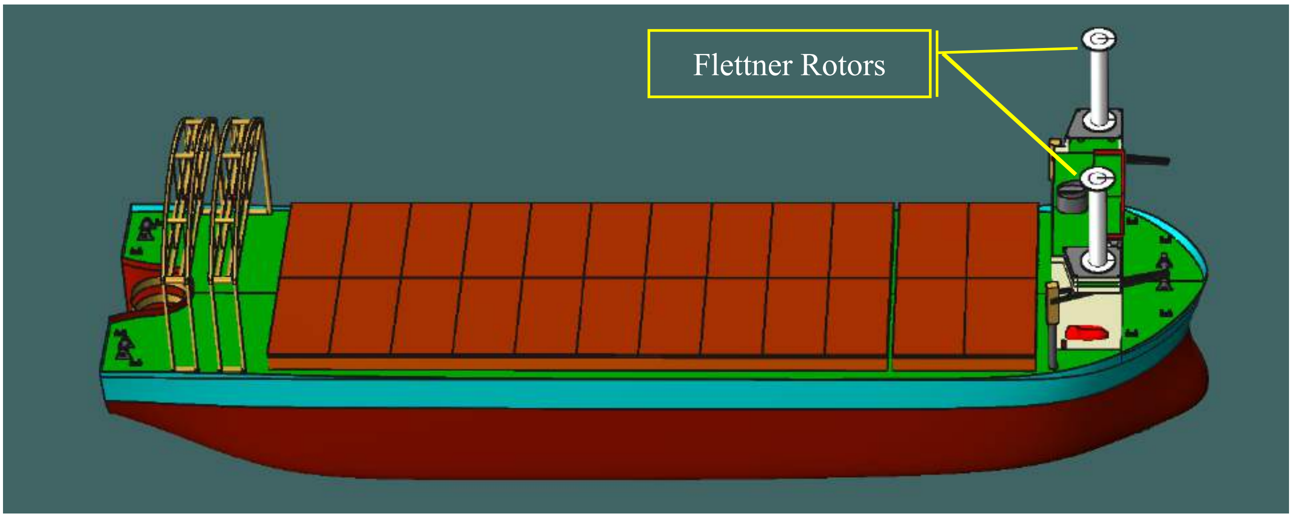


Figure 5-49 Bird's-eye View of Decom Tools Vessel and Flettner Rotor

There are three reasons to place the Flettner rotor on top of the accommodation as following:

- To increase the deck space. Placing them on the deck occupy space which there is demand for all the deck area for cargo loading.
- To prevent clashes and accident during cargo loading.
- The wind speed in higher altitude is more than on the bulkhead deck, so more energy can be captured on the higher altitude which means more efficiency[50].

The rotors are located on top of accommodation on the following location (x, y, z):

- Starboard side rotor: (163, 20, 50)
- Port Rotor: (163, -20, 50)

There might be one problem with installation of Flettner rotor at the accommodation. In this case the air draft of the vessel will be increased which can cause a problem when the vessel wants to sail under bridge. To cope with this problem, the tiltable Flettner rotors have been designed for this ship.

Figure 5-50, Figure 5-51 and Figure 5-52 shows how the tiltable Flettner rotor look like on this vessel. By implementing the tiltable Flettner rotor, the air draft of the vessel can be reduced 12 meters.

[50] https://www.intechopen.com/books/wind-farm-technical-regulations-potential-estimation-and-siting-assessment/methodologies-used-in-the-extrapolation-of-wind-speed-data-at-different-heights-and-its-impact-in-th

In this vessel we are going to use MV "Fehn Pollux" data as a reference vessel. Therefore, it is essential to briefly illustrate the major technical specifications of the implemented Eco Flettner rotors on board the above-mentioned vessel. The Eco-Flettner rotor has an aspect ratio about six, which afford a high aerodynamic lift force with a lower drag force, consequently enhancing propulsion performance particularly in upwind conditions.

The specifications of Flettner rotors are as following:

Table 5-3 Specification of Flettnre Rotor

Description	Values	Units
Cylinder Diameter	3	m
Cylinder Height	18	m
End Plate Diameter	6	m
End Plate Height	0.1	m
Aspect ratio	6	
Projected Area	53.4	m^2
Surface Area	171.5	m^3
Max Rotor RPM (RPM MAX =280)	270	

However, Norsepower claimed that two 35m tall rotor sails are estimated to reduce fuel consumption, fuel costs, and emissions by as much as 25% (Norsepower 2021). Having considered that the full information is not available, we did not consider this size of rotor in the Decom Tools vessel.

In this document, it is considered that the Flettners of the Decom Tools vessel reduce the fuel consumption by 25%, if the vessel sail with 60% of max speed which is 7.57 knots.

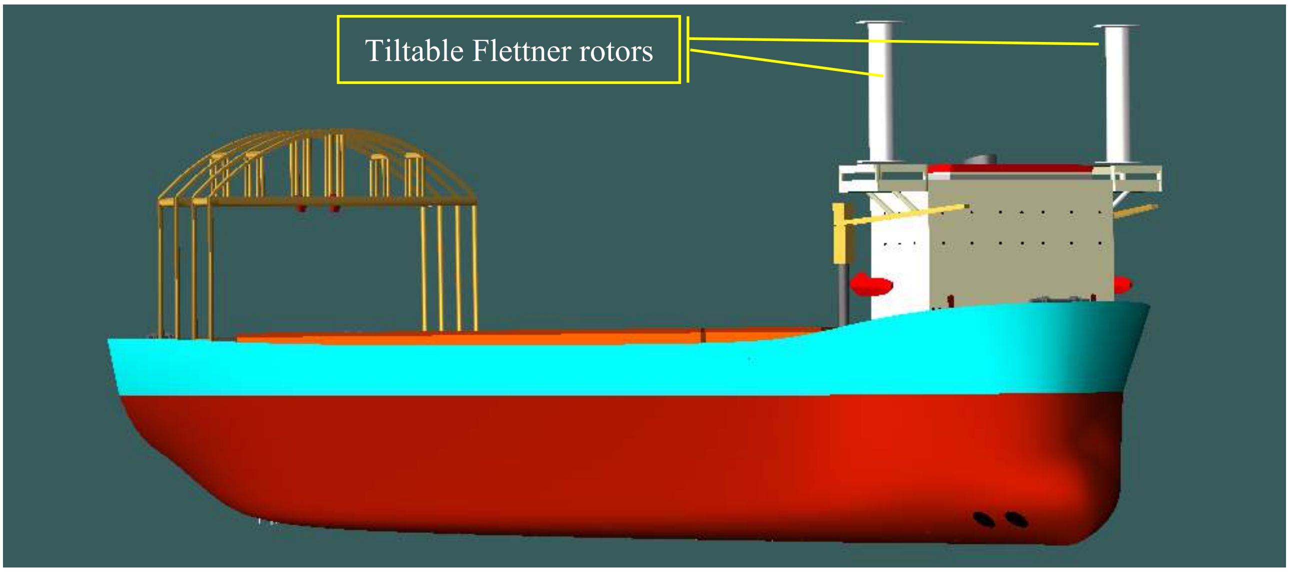


Figure 5-50 Perspective View of Flettner Rotors

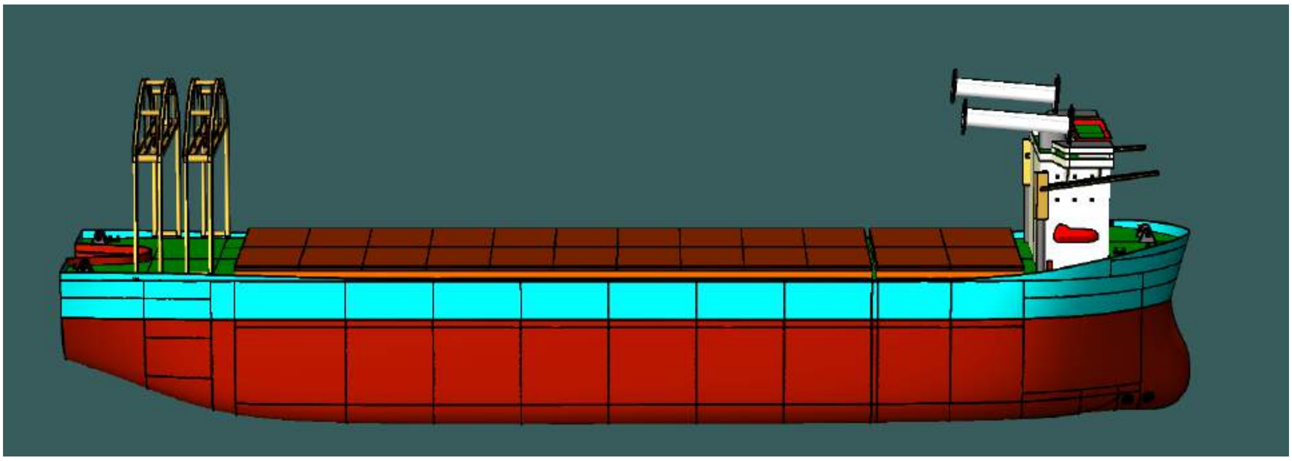


Figure 5-51 Foldable Flettner Rotor

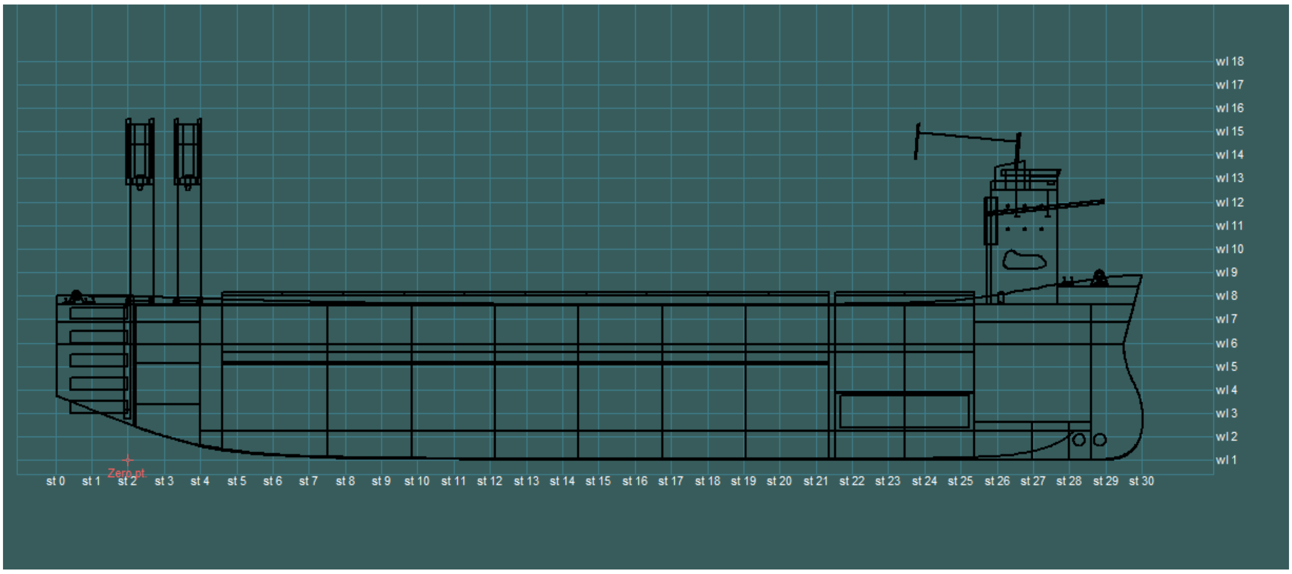


Figure 5-52 Foldable Flettner Rotor

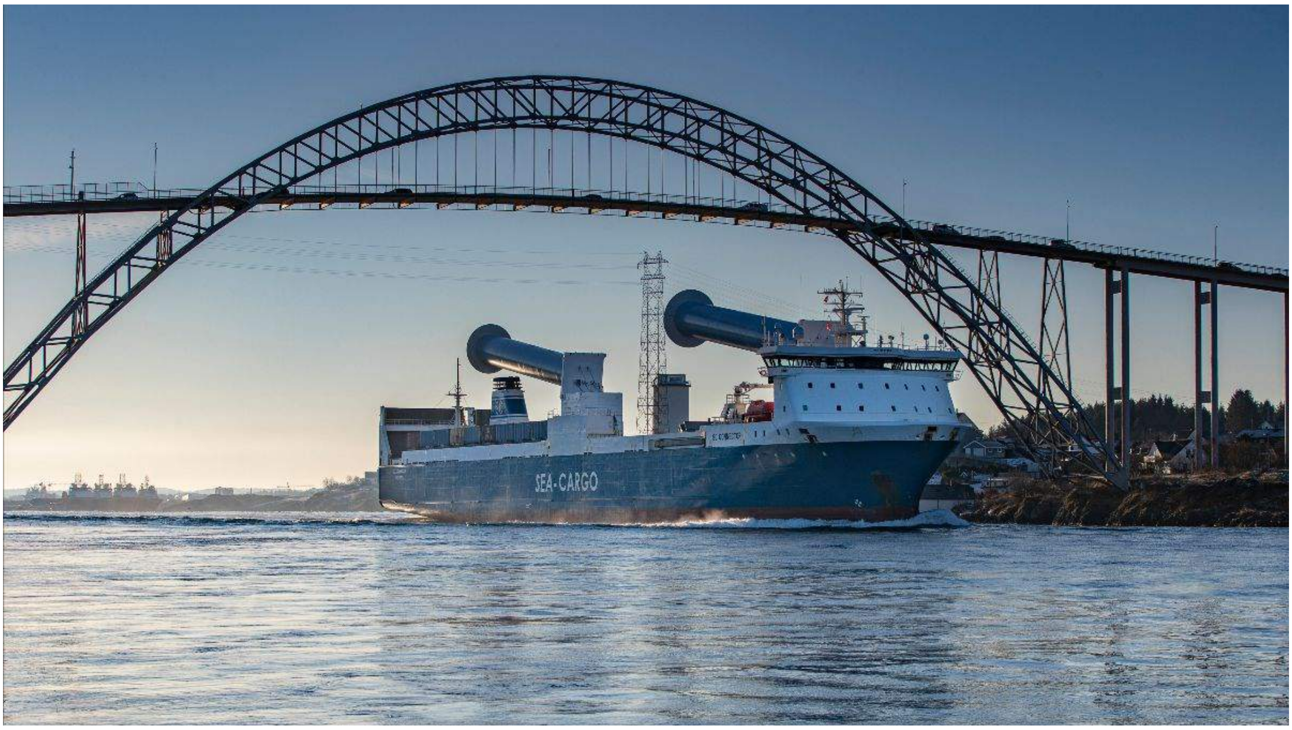


Figure 5-53 Tiltable Flettner Rotor (VPO 2021)

5.17.3 Solar and Hybrid System of Decom Tools Vessel

The conceptual design for implementation of solar system onboard the Decom Tools Vessel has been conducted. The basic study demonstrates that considerable amount of saving can be achieved by using solar system as well as hybrid system. The advantages of using hybrid and solar system are as following:

1. Utilize energy from shore power.
2. Run engines at optimum loads (implementation of batteries onboard of this kind of vessel can lead to remarkable saving of fuel and CO_2 emission. In addition, the engines depreciation will be decreased. As it discussed in previous chapter, sailing between wind turbines cannot exceed with speed more than 1 knot, or when the vessel is leaving the port or entering to the port the vessel shall sail with low speed, sometime less than 1 knot. This means that the engines should not work on full load. Less load on diesel engines means less efficiency and more depreciation and maintenance. When the vessel cannot sail with high speed, the engines can work on optimum load and by using a shaft generator, batteries can be charged in order to save the energy in necessary conditions.
3. Avoid transient engine loads.
4. Use power redundancy.
5. Reduce local emissions.
6. Reduce noise and vibrations.
7. Facilitate energy harvesting and energy recovery

5.17.4 Solar System Design

Two different solar systems are designed for the Decom Tools Vessel as following:

5.17.4.1 Fixed Solar Panel

Solar panels are designed in this vessel as handrail all over the length and width of the vessel (except stern). Also, the solar panel are designed to be installed on the top and forward of the accommodation. Figure 5-54 shows the location where solar panels can be installed.

System A and B shows that the installation of solar panel can take place on the handrails. System C is top of the accommodation (monkey island) which solar panel can be installed. System D which is forward of the accommodation needs extra structure to be installed from top of the accommodation to the bow of the vessel which is shown in the Figure 5-55

Furthermore, the selected panel for the Decom Tools vessel is Trina Solar, Vertex 605WP. Figure 5-56 shows the dimension and mechanical specification of this panel. This panel so far is the most efficient panel in the market which has peak power of 605 watt per panel.

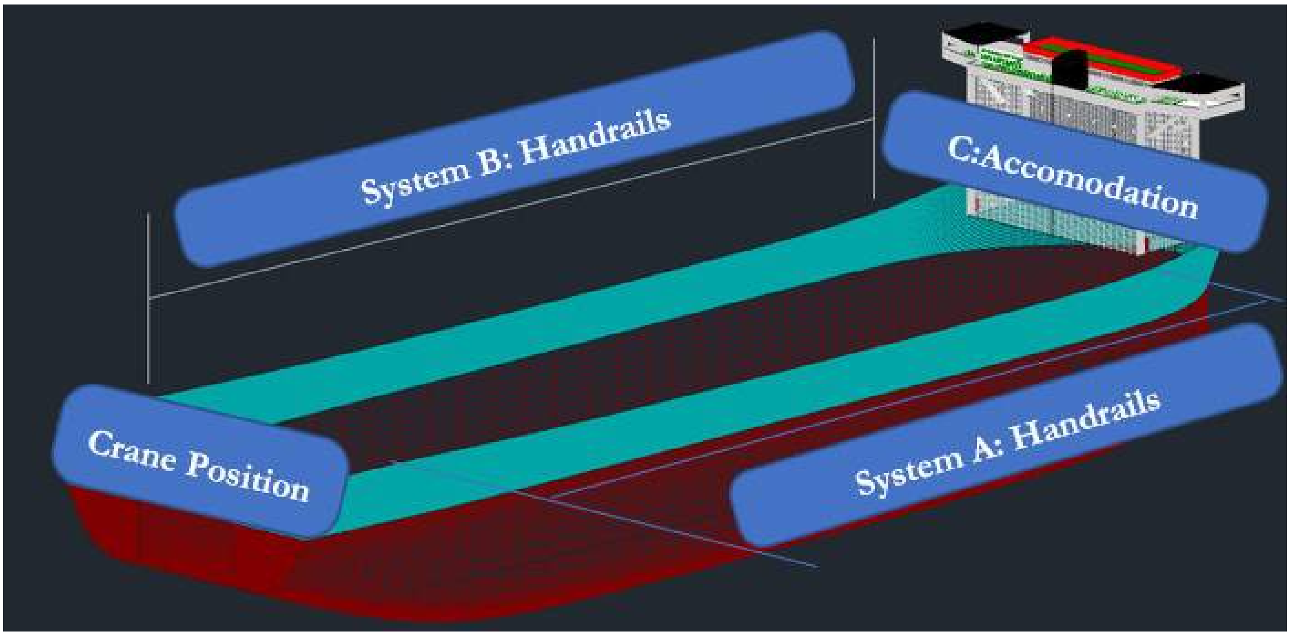


Figure 5-54 Location of Solar Panel on Decom Tools Vessel (System A, B &C)

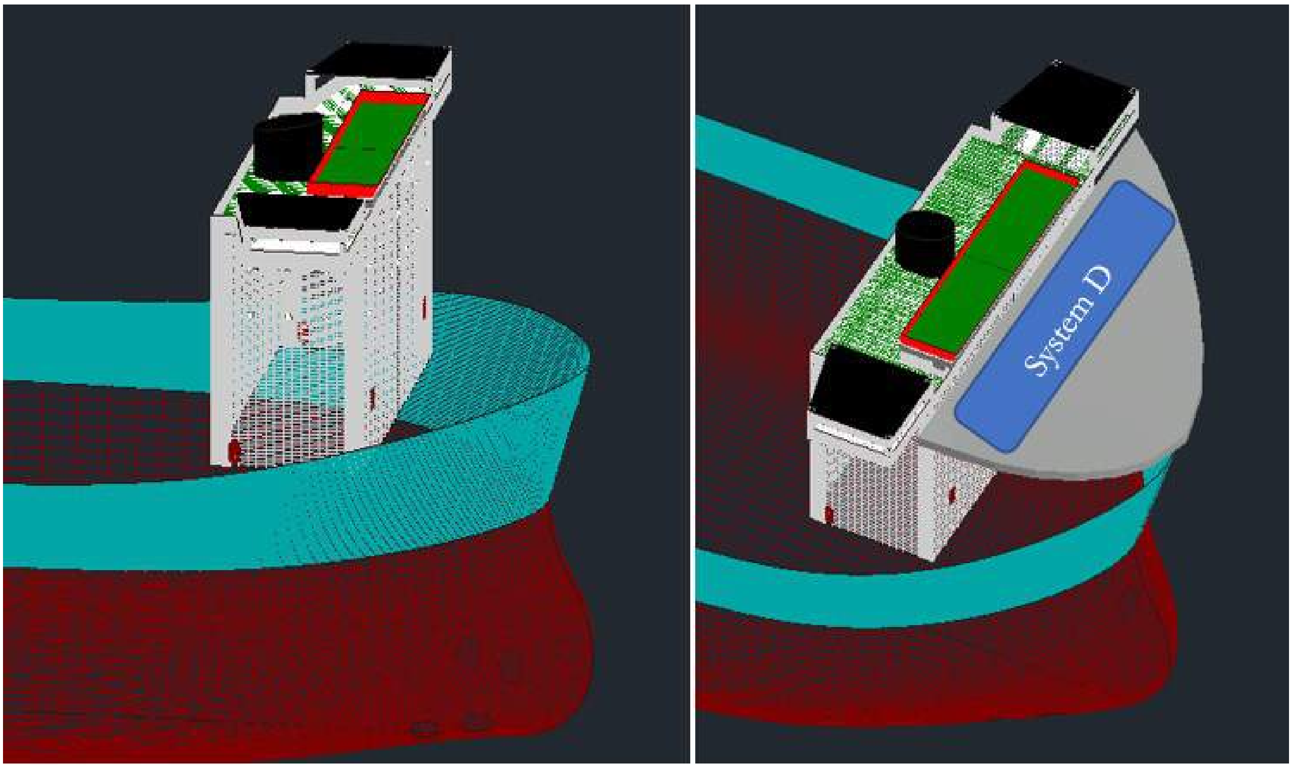
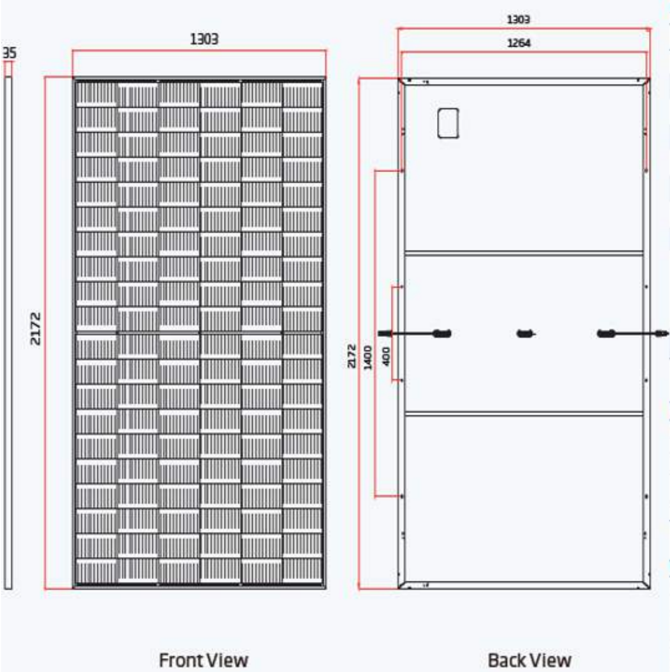


Figure 5-55 Location of Solar Panel on Decom Tools Vessel (System D)

The panel has dimension of = 2172 x 1303 x 35 mm and each of them weigh about 31 kg. According to Figure 5-54, under the A section, which is starboard side of the vessel, starting after 13 m (from the stern of the ship) extending to the accommodation the solar panel can be installed as handrails. These panels are placed with spacing to avoid shadow through tilting of the panels. During the length of 152 m with portrait placement of panels 84 numbers of panel can be installed. This number of panels can generate 50.82 kW_P and weigh about 2.6 tons excluding the structures weight.



MECHANICAL DATA

Solar Cells	Monocrystalline
No. of cells	120 cells
Module Dimensions	2172×1303×35 mm (85.51×51.30×1.38 inches)
Weight	30.9 kg (68.1 lb)
Glass	3.2 mm (0.13 inches), High Transmission, AR Coated Heat Strengthened Glass
Encapsulant material	EVA
Backsheet	White
Frame	35mm(1.38 inches) Anodized Aluminium Alloy
J-Box	IP 68 rated
Cables	Photovoltaic Technology Cable 4.0mm² (0.006 inches²), Portrait: 280/280 mm(11.02/11.02 inches) Landscape: 1400/1400 mm(55.12/55.12 inches)
Connector	MC4 EVO2 / TS4*

*Please refer to regional datasheet for specified connector.

TEMPERATURE RATINGS

NOCT (Nominal Operating Cell Temperature)	43°C (±2°C)
Temperature Coefficient of PMAX	- 0.34%/°C
Temperature Coefficient of Voc	- 0.25%/°C
Temperature Coefficient of Isc	0.04%/°C

MAXIMUMRATINGS

Operational Temperature	-40~+85°C
Maximum System Voltage	1500V DC (IEC)
	1500V DC (UL)
Max Series Fuse Rating	30A

WARRANTY

12 year Product Workmanship Warranty
25 year Power Warranty
2% first year degradation
0.55% Annual Power Attenuation

PACKAGING CONFIGUREATION

Modules per 40' container: 512 pieces

Figure 5-56 Mechanical Specification & Dimension of Trina Vertex Panel (Trina Solar n.d.)

Referring to the Figure 5-54, under section B which is the mirror of section A (portside of the vessel) 84 number of panels can be installed as handrails which produce 50.82 kWP.

Following Figure 5-54 under section C, on top of the accommodation there exist area of 525 m^2. In this available space, 185 number of panels can be installed. This number of panels produce 111.925 kWP. It should be noted normally on the monkey island many equipment such as VSAT, radar, wind measurement instruments, flag and so on are installed. The mentioned equipment may reduce the quantity of the panels that can be installed. In addition, all of the installed equipment can cause shadowing which can reduce the efficiency of the solar panels.

Lastly under section D which is the bow of the vessel as per Figure 5-55, instead of installing the panels as handrails, a better system would be a roof of solar panels, from the top of the accommodation to the forward of the vessel. Surface of this area is about 418 m^2. 146 numbers of panels can be installed. This numbers of panel can produce 88.33 kWP.

5.17.4.2 Portable Solar Panel

The portable solar panel are designed to be installed on top of the hatch cover as well as weather deck of the Decom Tools vessel. When the vessel does not have cargo, this type of panel can be laid on top of the hatch cover by gantry cranes. The foldable and portable solar panels are selected for this part of the vessel. However, panels used in this region could be either the previously used Trina solar panels along with huge structures for portability and foldability. But rollable panels, with less wattage but easier to handle, install and uninstall is selected for this section.

According to Figure 5-54,under section E, the available area is about 6532 m² which this type of panels can be installed there. The required standards area for a single rollable panel is 122 m². According to available space on the top of hatch covers and weather deck, 53 numbers of rollable solar panel can be installed. These amounts of rollable panels produce 572.4 kW_P.

Figure 5-57 Rollable and Portable Solar Panels

Source: (Renova Gen n.d.)

Figure 5-58 Rollable and Portable Solar Panel (Renova Gen n.d.)

In overall, the total solar plant capability is about 874.295 kW_{P}. Therefore, the produced energy can be 2.508 MWh/day.

According to irradiation of sun in the North Sea Region during the different months of the year, the average production is shown in the Figure 5-60. Highest in July, outputting 118.6 MWh and lowest in month of December with outputs of 18.7 MWh. The calculation and simulation can be found in the master thesis of Mr. Adithya Rajeev Nair (Student f Dalarna University).

	MODEL*		
	RAPID ROLL 4 \ 10	RAPID ROLL 7 \ 60	RAPID ROLL 11 \ 120
ELECTRICAL SPECIFICATION			
PV TECH	CIGS	CIGS	CIGS
NO OF MODULES	12	24	36
MODULE POWER	300 W	300 W	300 W
TOTAL PV POWER	**3.6 kWp**	**7.2 kWp**	**10.8 kWp**
INVERTER SYSTEM			
Electrical specification (split phase also available)	Single Phase 120 V / 60 Hz or 230 V / 50 Hz**	Single Phase 120 V / 60 Hz or 230 V / 50 Hz**	Three Phase 208 V / 60 Hz or 400 V / 50 Hz
Maximum output power (30 second peak/3 sec surge)	8.0 kW (9.1 kW / 11 kW)**	8.0 kW (9.1 kW / 11 kW)**	24 kW (27.3 kW / 33 kW)
Max rated continuous output power	6 kW**	6 kW**	18 kW

Figure 5-59 Specification of Rollable and Portable Solar Panel

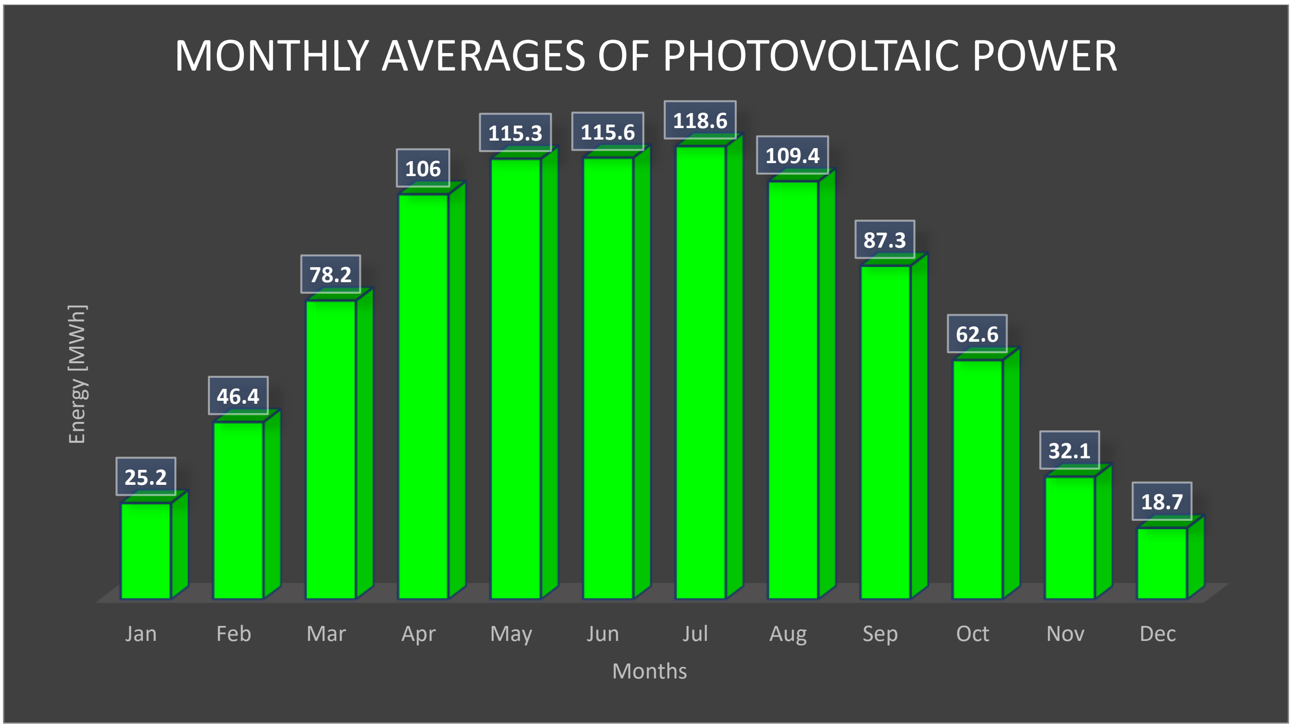


Figure 5-60 Produced Energy by Fixed and Portable Solar Panels During a Year

These energy values have been calculated with the irradiance levels and sunshine hours in the North Sea Region. The detail of solar system design as well as battery sizing will be attached as an appendix to this document. The comprehensive research for solar system design has been conducted by one of master students at Dalarna University. In this report, it will be shown how much the solar system can contribute to reduction of cost and mitigation of emission.

5.17.5 Ballast Pump

One of the most important equipment onboard the Decom Tools vessel is ballast pump since it plays colossal role in pile extraction operations. Comprehensive study regarding the size and number of ballast pump is conducted

Pump Data Sheet - IRON Pump

ironpump
world class water pumps

Company: Iron Pump A/S
Name:
Date: 2/16/2021

Pump:
Size: 600-500/630-1
Type: QHGV / QVKGV — Speed: 1480 rpm
Synch speed: 1500 rpm — Dia: 536 mm
Curve: 40620104BX — Impeller: 4062
Specific Speeds: nq: — S: —
Dimensions: Suction: 600 mm Discharge: 500 mm

Search Criteria:
Flow: 3000 m³/hr — Head: 70 m
Near miss: 7 % of Head

Fluid:
Water — Temperature: 20 °C
Density: 998.3 kg/m³ — Vapor pressure: 2.339 kPa a
Viscosity: 0.9946 cP — Atm pressure: 101.4 kPa a
NPSHa: —

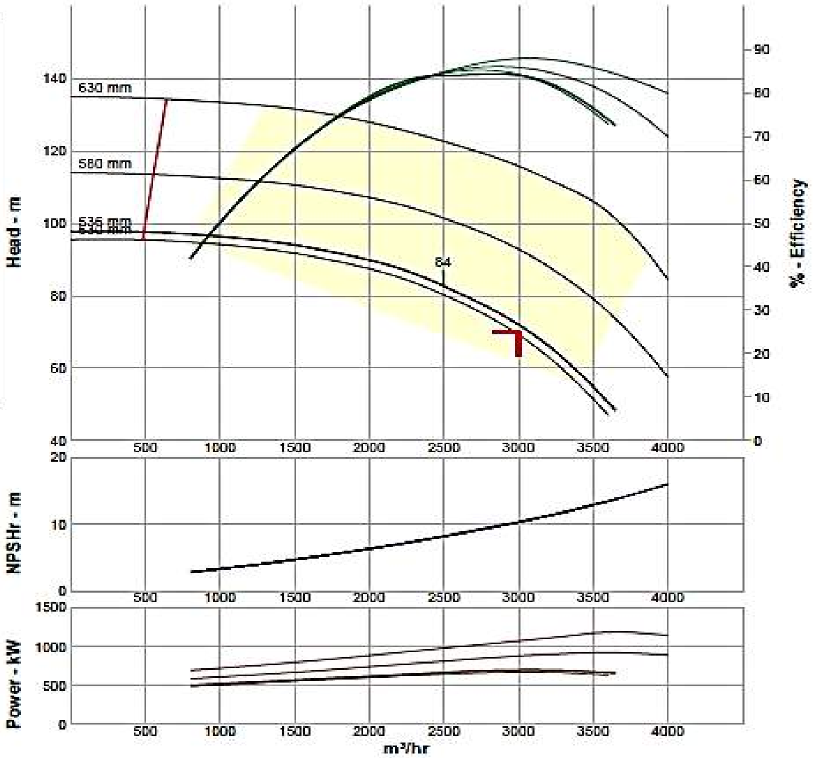
Pump Limits:
Temperature: 120 °C — Power: —
Pressure: 1600 kPa g — Eye area: —
Sphere size: 10 mm

Motor:
Standard: — —
Enclosure: — Speed: —
Frame: —
Sizing criteria: Max Power on Design Curve

— Data Point —
Flow: 3000 m³/hr
Head: 70.5 m
Eff: 82.4%
Power: 688 kW
NPSHr: 10.4 m

— Design Curve —
Shutoff head: 97.7 m
Shutoff dP: 957 kPa
Min flow: 499 m³/hr
BEP: 84% @ 2496 m³/hr
NOL power: 698 kW @ 3248 m³/hr

— Max Curve —
Max power: 1188 kW @ 3600 m³/hr



Performance Evaluation:

Flow m³/hr	Speed rpm	Head m	Efficiency %	Power kW	NPSHr m
3600	1480	50.2	73.6	665	13.5
3000	1480	70.5	82.4	688	10.4
2400	1480	84.5	83.9	657	7.8
1800	1480	91.1	73.4	600	5.7
1200	1480	95.1	55.9	542	3.9

Figure 5-61 Specification of Ballast Pump

The final design is to use 10 number of ballast pumps with flow capacity of 3000m^3/hr. Figure 5-61shows specification of a ballast pump with above-mentioned capacity. The size and quantity of ballast pumps are crucial since it changes the pile extraction operation.

5.18 Propulsion System

As it stated in the previous chapter the design of propulsion system depends on various factors. The ship needs to be empowered by a specific thrust to be sailed with specific speed. The most influential factors for calculation of required power are speed, geometry, and draft of the vessel. In other words, the geometry and draft identify the vessel resistance with respect to different speeds. However, environmental loads (dynamic loads) such as wind, wave, current water and so forth impact the required power. Not only the propulsion system can be used in sailing mode, but also it can be used if the vessel wants to maintain the position is a specified location for a particular operation. In this situation, the vessel needs dynamic positioning (DP) in order to resist against the loads. During the DP operation, normally the propellers and bow thrusters need to work around the clock in order to keep the position of the vessel.

The question of why to implement DP system in the Decom Tools vessel is explained in the following sections.

5.19 Correlation Between Draft, Speed, Resistance and Power

Regardless of how to keep the position of Decom Tools vessel in the field, we would like to see what the relation between the draft of the vessel, vessel speed and the required power for the propulsion system is. To find out this result, a simulation has been made in the MAXSURF module resistance. The results are selected for following two scenarios:

a) When the vessel is at minimum draft. The minimum draft of the Decom Tools vessel is 6 meters. The minimum daft can happen when there is not any cargo onboard the vessel and ballast tanks are partially ballasted.
b) When the vessel is at maximum draft. The maximum draft of the Decom Tools vessel is 19.76 meter. It is evident that the higher draft will result in more hull resistance. More resistance requires more power for the propulsion system to provide the thrust for sailing.

Table 5-4 provide the vital information for calculation of the resistance of the vessel. This information is based on the design of the ship, and all are extracted from MAXSURF Resistance.

Table 5-4 Parameters to Design Propulsion System

Decom Tools Vessel Parameter	Value	Unit
LOA	195	m
Beam	48	m
LBP	177	m
lightship	20 741.78	t
Designed water line (Max Draft)	19.762	m
Displacement	155 563	t
Volume (displaced)	151 768.494	m^3
Prismatic Coefficient[51] (Cp)	0.863	
Block Coefficient (C_b)	0.836	
Waterplane area coeff. (Cwp)	0.921	
Length: Beam ratio	3.989	
Beam: Draft ratio	2.429	
TPC[52] @ draft 10 m	84.086	Ton/cm
TPC @ draft 18 m	86.868	Ton/cm

Table 5-5 shows the resistance and required power at various speed at two-mentioned draft. The maximum speed of the vessel is 12.62 knots. This speed can be achieved when the vessel is at draft of 6 meter. The orange cells show the values of resistance and power in the speed of 12.62 knots.

When the vessel is fully loaded, the maximum speed can be 9.5 knots. The cells which are highlighted in yellow shows the value of power and resistance when the vessel sail at draft of 19.76 meters and the speed of 9.5 knots.

Figure 5-62 shows the relation between Decom Tools speed (knot) and the resistance (KN) at draft of 6 meter (minimum draft).

In addition, Figure 5-63 illustrates the correlation between Decom Tools speed (knot) and the power (kW) at draft of 6 meter.

Figure 5-63 depicts that relation between speed and required power for propulsions system is nonlinear. The required power is increasing exponentially with respect to the speed. In particular, after speed of 7.57 knots, huge amount of power is needed for the propulsion system.

[51] Prismatic Coefficient is used to define how displacement is distributed along a hull, or how fine or full the ends of the hull are.

[52] TPC (Tons per Centimeter): the number of tons required to sink the ship one centimeter.

Table 5-5 Correlation between Speed, Resistance and Power

Min & Max Draft	Decom Tools Vessel at 6m Draft		Decom Tools Vessel at 19.79m Draft	
Speed (Knot)	**Holtrop Resistance (KN)**	**Holtrop Power (KW)**	**Holtrop Resistance (KN)**	**Holtrop Power (KW)**
1.000	15.8	10.822	17.9	12.305
1.500	43.6	44.896	40.3	41.480
2.000	86.2	118.266	72.1	98.905
2.500	140.5	240.903	113.7	194.911
3.000	202.6	416.912	165.4	340.254
3.500	269.1	646.141	227.4	545.987
4.000	337.5	926.104	300.1	823.310
4.500	406.1	1253.381	383.4	1183.427
5.000	473.6	1624.437	477.4	1637.396
5.500	539.7	2036.039	582.1	2196.006
6.000	603.9	2485.434	697.3	2869.664
6.500	666.2	2970.393	822.8	3668.314
7.000	726.7	3489.208	958.3	4601.367
7.500	785.4	4040.645	1103.6	5677.665
8.000	842.6	4623.900	1258.4	6905.461
8.500	898.5	5238.551	1422.3	8292.423
9.000	953.2	5884.520	1594.9	9845.654
9.500	1007.0	6562.045	1775.8	11571.737
10.000	1060.1	7271.672	1964.8	13476.808
10.500	1112.7	8014.254	2161.4	15566.653
11.000	1165.1	8790.975	2365.3	17846.837
11.500	1217.4	9603.379	2576.4	20322.875
12.000	1270.0	10453.423	2794.3	23000.440
12.500	1323.0	11343.525	s3019.1	25885.605
12.62	1336.41	11574.512	3250.5	28985.138
13.000	1376.8	12276.629	3488.9	32306.822
13.500	1431.6	13256.274	3734.2	35859.811
14.000	1487.7	14286.654	3987.1	39655.013
14.500	1545.6	15372.693	4247.8	43705.504
15.000	1605.6	16520.061	4517.3	48026.905
15.500	1668.1	17735.357	4796.2	52637.613
16.000	1733.6	19026.129	5085.8	57560.362
16.500	1802.5	20399.921	5387.4	62820.987
17.000	1875.2	21865.917	5702.0	68444.538
17.500	1952.6	23438.000	6031.3	74466.656
18.000	2035.3	25128.653	6378.9	80945.342
18.500	2122.9	26939.328	6747.0	87930.812
19.000	2215.2	28869.819	7134.2	95423.815
19.500	2313.5	30944.018	7538.1	103412.078
20.000	2421.3	33216.681	2637090.09	27132.7269

Figure 5-63 and Table 5-5 shows that the required power for the speed of 16.62 knots is 11574.512 kilowatt.

The required power for the speed of 17 knots at draft of 6 meters is 21865.917 kilowatt which is approximately two time more than speed of 12.62 knots. It means sailing with 4.3 knots more than 12.62kn demand double power for the propulsion system.

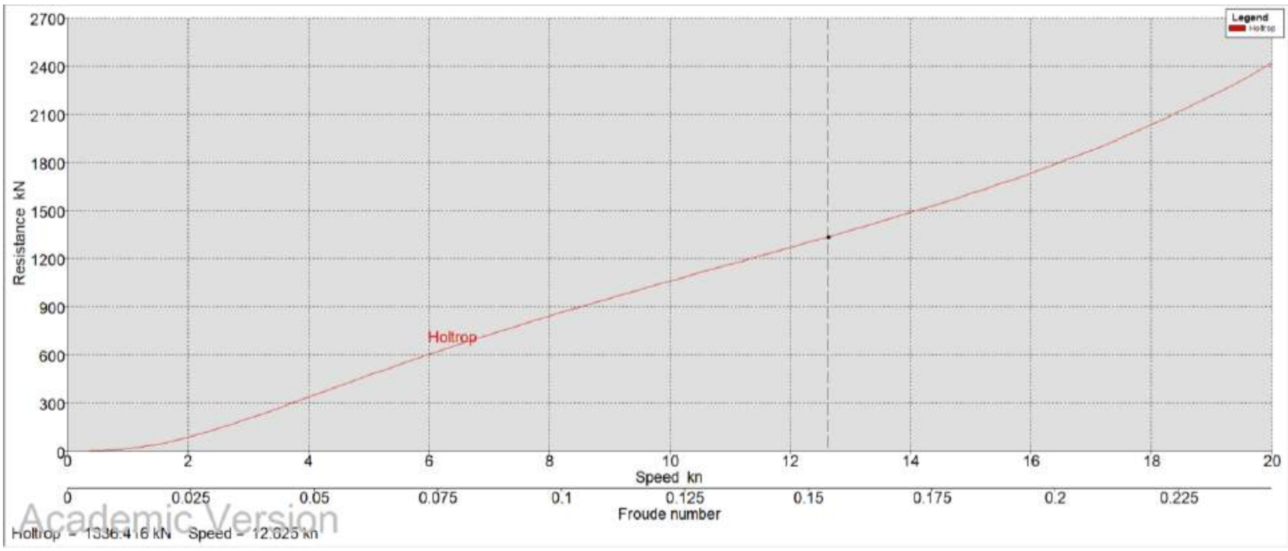


Figure 5-62 Correlation Between Speed and Resistance at Draft of 6 meters

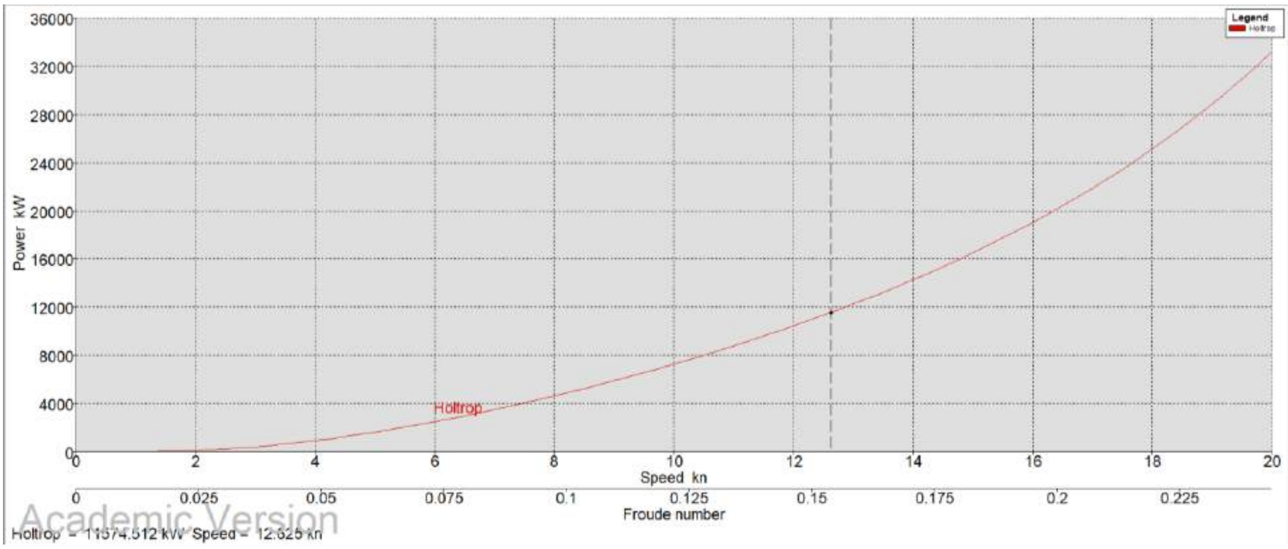


Figure 5-63 Correlation Between Speed and Power at Draft of 6 meters

Figure 5-64 illustrates the correlation between speed (knot) and Resistance (KN) at draft of 19.79 meters which is the maximum draft of the Decom Tools vessel. Referring to above figure, the resistance also is increasing exponentially with vessel speed. In the speed of the 9.5 knots, the resistance is 1775.8 kn. However, for the speed of 13 knots the resistance is 3488.9 which is two times more than speed of 9.5 knots. Table 5-5 shows the exact value of the resistance and power for the range of speed between 0 to 20 knots.

Moreover, Figure 5-65 depicted the correlation between the power and the speed at draft of 19.79 meters.

Table 5-5 shows that for the speed of 9.5 knots, the required power for the propulsion system should be 11570.623 kW. However, for the speed of 12 knots the required power is 23000 KW. It means 2.5 knots extra speed need approximately double power and ultimately consume double fuel which will pave the way for non-sustainable operation.

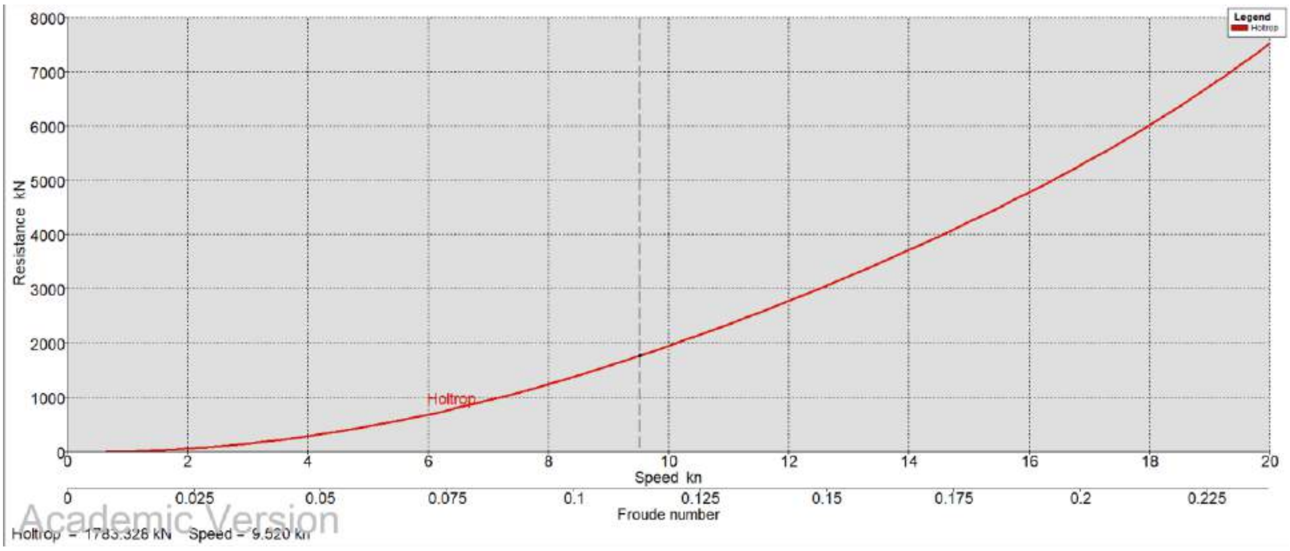


Figure 5-64 Correlation Between Speed and Resistance at Draft of 19.79 meters

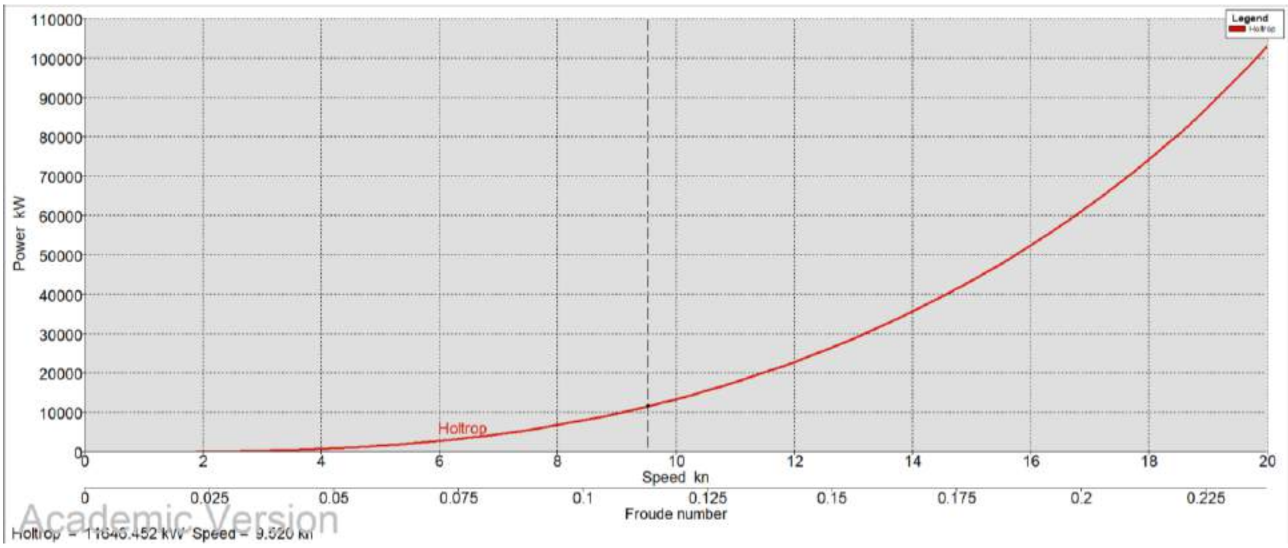


Figure 5-65 Correlation Between Speed and Power at Draft of 19.79 meters

Comparison of the Decom Tools at different draft shows that in minimum draft, with the power of 11571 kilowatt the vessel can sail with speed of 12.62 knots. However, with the same power the vessel can sail with speed of 9.5 knots at draft of 19.79 meters.

5.20 Selection of Propeller

With having this result, five numbers of thrusters have been engineered for the Decom Tools vessel. Three of them are Voith Schneider propeller which are located in the aft of the vessel. In addition, two of them are tunnel thruster as bow thrusters. Bow thrusters are used for low-speed manoeuvring. It should be noted that VSP does not need the bow thrusters during sailing since the VSP can provide the thrust as well as change the heading simultaneously.

According to the Voith Schneider Propulsion system manufacturer data sheet, we can select the VSP 36 for the Decom Tools vessel. Three numbers of this propeller can provide 11700 kW which is enough for the Decom Tools vessel with the speed of 12.62 knots. Consequently, three number of VSP 36 suffice the demand of Decom Tools Vessel.

Propeller type/ size	Control system ME/ECA*	Control system EC**	VRS*** option	Blade orbit diameter A [mm]	Blade length B**** [mm]	Housing heigt C [mm]	Housing diameter D [mm]	Number of gearsteps	Weight without oil [abt. kg]	Oil filling [abt.l]	Max. propeller input power [kW]
VSP 12		x		1200	912	1185	1660	1	3800	380	260
VSP 16		x		1600	1215	1372	2145	1	6700	680	540
VSP 18		x		1800	1512	1480	2405	1	9500	1000	780
VSP 21	x			2100	1766	1755	2815	1 or 2	16000	1600	1000
VSP 26	x			2600	1965	1980	3435	2	27500	2700	1500
VSP 28	x	x	x	2800	2355	2168	3790	2	38500	4300	2000
VSP 30	x			3000	2666	2380	4000	2	47000	4000	2450
VSP 31	x	x	x	3100	2666	2300	4200	1	48000	4000	2500
VSP 32	x	x	x	3200	2666	2371	4250	2	50000	5200	2600
VSP 36	x	x	x	3600	2872	2985	4765	2	75000	7700	3900

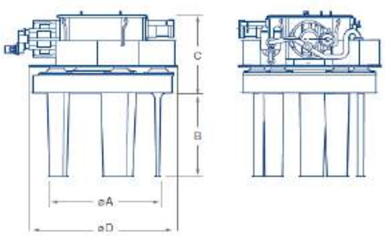


Figure 5-66 Data Sheet of Voith Schneider Propulsion System

There are a couple of reasons why the designers of the Decom Tools vessel selected Voith Schneider propulsion system for this vessel as following:

1. Decom Tools Vessel must need high precision manoeuvring due to pile extraction system. Furthermore, moving inside an OWP and approaching to a wind turbine need accurate manoeuvring. Having considered that VSP has the highest precision of manoeuvring among all types of propulsion systems, this propulsion type is devised for this vessel.

2. In the feeder configuration, the Decom Tools can keep the position in the field beside the construction vessel in three different methods which directly depends on the site condition as well as types of the construction vessel.
    A. If the construction vessel is jack up vessel, the Decom Tools Vessel cannot tie up itself to the jack up vessel. The jack up vessel stability is just designed to withstand the forces which is exerted by the environmental load as well as construction forces such as lifting operation. Therefore, no types of vessels can be tied up to the jack up vessel. In this case, there are two possible scenarios for Decom Tools Vessel as a feeder vessel to maintain the position beside jack up vessel.
        I. The first possibility is to drop mooring lines and keep the position by mooring anchors. In this case vessel can move in each direction approximately 500 meters (depending on the length of anchor wire, water depth, the sea state, the soil characteristic etc.). in some cased, dropping anchor in the fields is not possible, for example, where there are lots of subsea asset in the field or where the depth is high.
        II. The second possibility is to keep the vessel position by DP mode. So, in this case, the Decom Tools Vessel need to be equipped with DP system. DP system includes DP module, DP reference systems, suitable propellers for DP system, engines and so forth. The problem with DP system is that fuel consumption is relatively high in this mode. However, the fuel consumption should be calculated for overall project including sailing, DP mode, port mode etc. On the other hand, it should be noted the operation on DP is so smoother and easier and also manoeuvrability will be so easier and accurate. The VSP is the only propulsion types that does need extra thruster to be installed for DP system. In other propulsion system, if the vessel is designed to work on DP mode, the retractable thrusters need to be installed in addition to bow and transit (Main) thrusters. But in the VSP these three propellers can be used for steering, transit and manoeuvring.
    B. If the vessel is floating vessel, the Decom Tools vessel can maintain the position besides the construction vessel in three different modes.
        I. Keep the position in DP mode (advantages and disadvantages explained above).

II. Use mooring line and dropping anchors. In order to maintain the position of this large vessel at least six number of anchors need to be deployed. Running of each anchor takes at least three hours which means just dropping anchor takes 18 hours. Anchor running is time consuming and is not recommended to conduct, if better option is available.

III. Tie up to the construction vessel. This mode is the best way to keep the position of feeder vessel alongside the construction vessel. In this mode, the construction vessel keeps the position either in DP or anchor and the feeder vessel will tie up to the construction vessel. The construction vessel directly lifts the components and load onto the Decom Tools Vessel.

5.21 Advantage and Disadvantages of DP mode

There are some advantages and disadvantages with operating the vessel in DP mode. The advantages are listed in below:

- ☑ The manoeuvrability of the vessel in the DP mode is very flexible and precise.
- ☑ In addition to the high manoeuvrability of the vessel, in some fields, due to existence of subsea assets like cables, pipelines etc., the field owner do not allow the vessels to drop anchors. So, the only method of positioning is DP mode.
- ☑ Employing anchors in deep water is not a safe and effective means of positioning the vessel.
- ☑ Regardless of type of construction vessel, the cargo vessel can maintain the position via DP easily without any conflict. It means that conduction of simultaneous operation (SimOps) is so easy, if the cargo vessel run on DP.

However, keeping the vessel in the DP mode has some disadvantages as following:

- ☒ The propulsion system should work around the clock which will result in large fuel consumption (the loads are discussed in the next sections).
- ☒ High fuel consumption leads to high CO_2 emission.
- ☒ For DP operation, DP officers need to be mobilized which they have high wage. So, the charter rate of vessel will increase in the DP mode.
- ☒ DP need more machineries to be in operation which means more maintenances are needed.

The following figures (Figure 5-67 and Figure 5-68) show importance of equipping the cargo vessel with DP in the wind industry.

The below photos show one of the reasons why equipping the cargo vessel with DP system is vital in the wind industry. The monopiles of Hornsea 1 which are constructed in Rostock in

Germany were transported to the Able Seaton ports and Tees Port which are close to the wind farm in the UK. Also, the installation vessel sailed toward the port in order to load the monopile. See Figure 5-69 .If the cargo vessel was equipped with DP system (or position anchor winches), then it was possible to directly transport the monopile in the site rather than both sailing to the mentioned port for discharging and loading the monopiles.

Figure 5-67 Loading of Monopile from Cargo Vessel to the Installation vessel (SAL 2019)

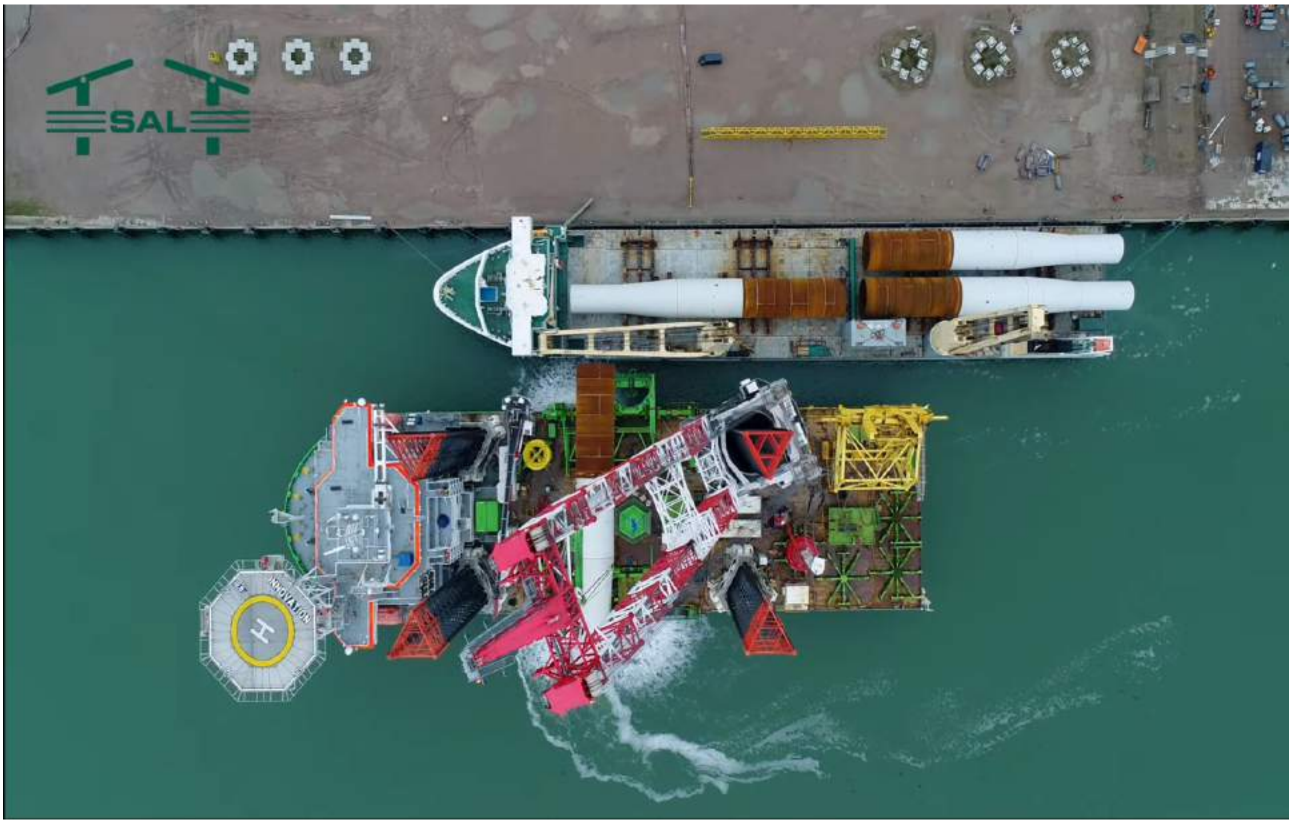


Figure 5-68 Loading of Monopile from Cargo Vessel to the Installation vessel (SAL 2019)

The omission to equip the cargo vessel with DP system result in increase in the offshore operation, more cost to the project and finally more fuel consumption as well as more emission. Therefore, in the design of Decom Tools vessel, 3 number of VSP is considered at the stern of the vessel plus two numbers of tunnel as bow thrusters. This combination of propellers allows safe and precise manoeuvring of the vessel for the mention offshore operations.

Figure 5-69 Loading of Monopile from Cargo Vessel to the Installation vessel (SAL 2019)

Figure 5-70, Figure 5-71 and Figure 5-72 demonstrate the location and number of mentioned propellers in the Decom Tools vessel.

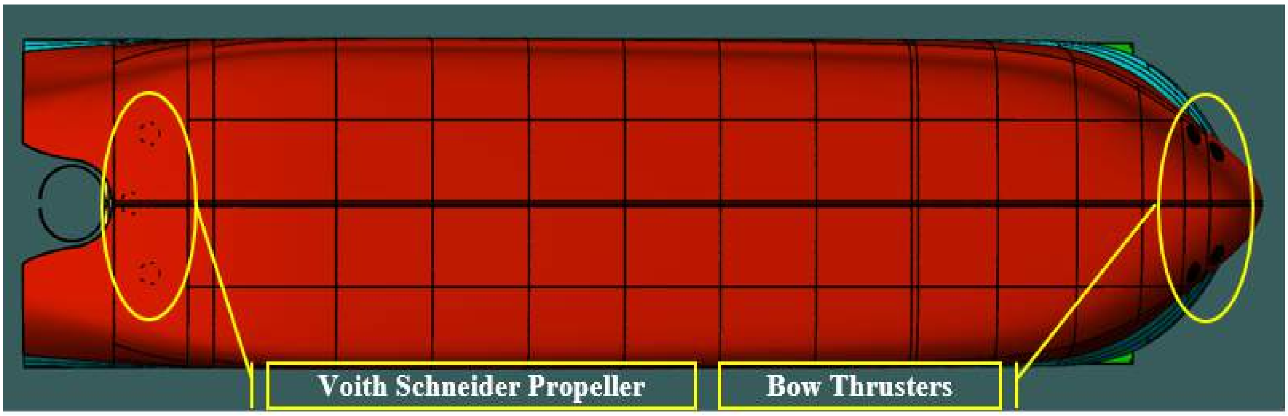


Figure 5-70 Bottom View of Decom Tools Vessel

Bow thrusters are added to increase the manoeuvrability of the vessel on DP mode. During the transit mode, the VSPs are able to steer the vessel to the desired heading. Figure 5-72 shows the bow thrusters of the Decom Tools vessel. As it shows the vessel is equipped with two bow thrusters which each of them is 1000 Kw. They can be used when the vessel operates on DP, during pile extraction, cable recovery as well as TP removal.

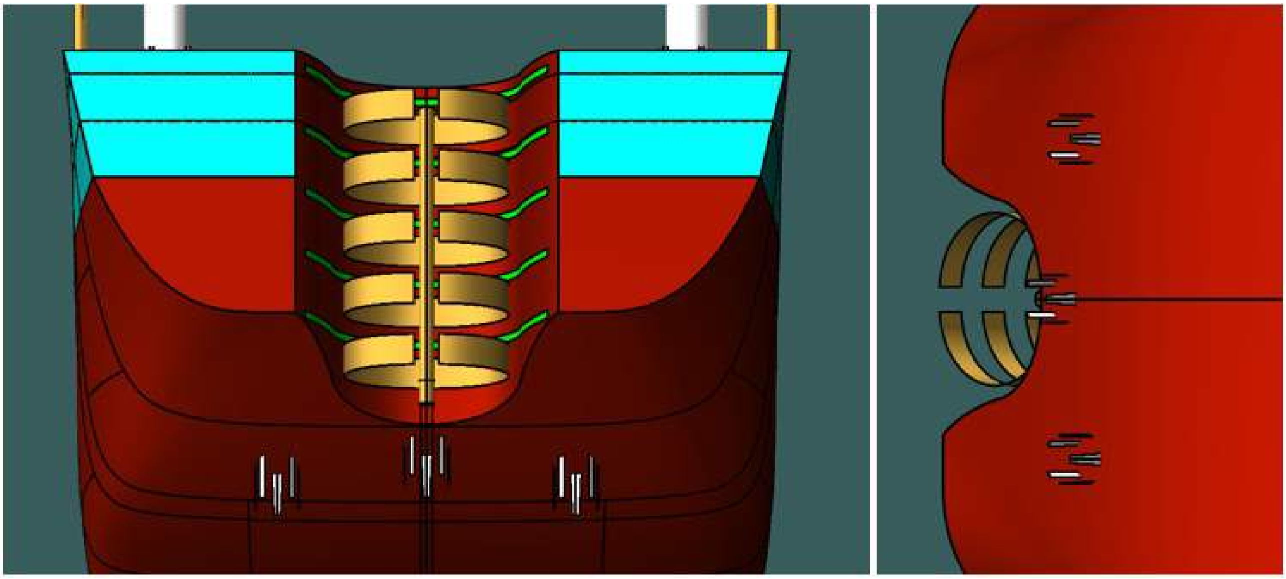


Figure 5-71 Voith Schneider Propeller System

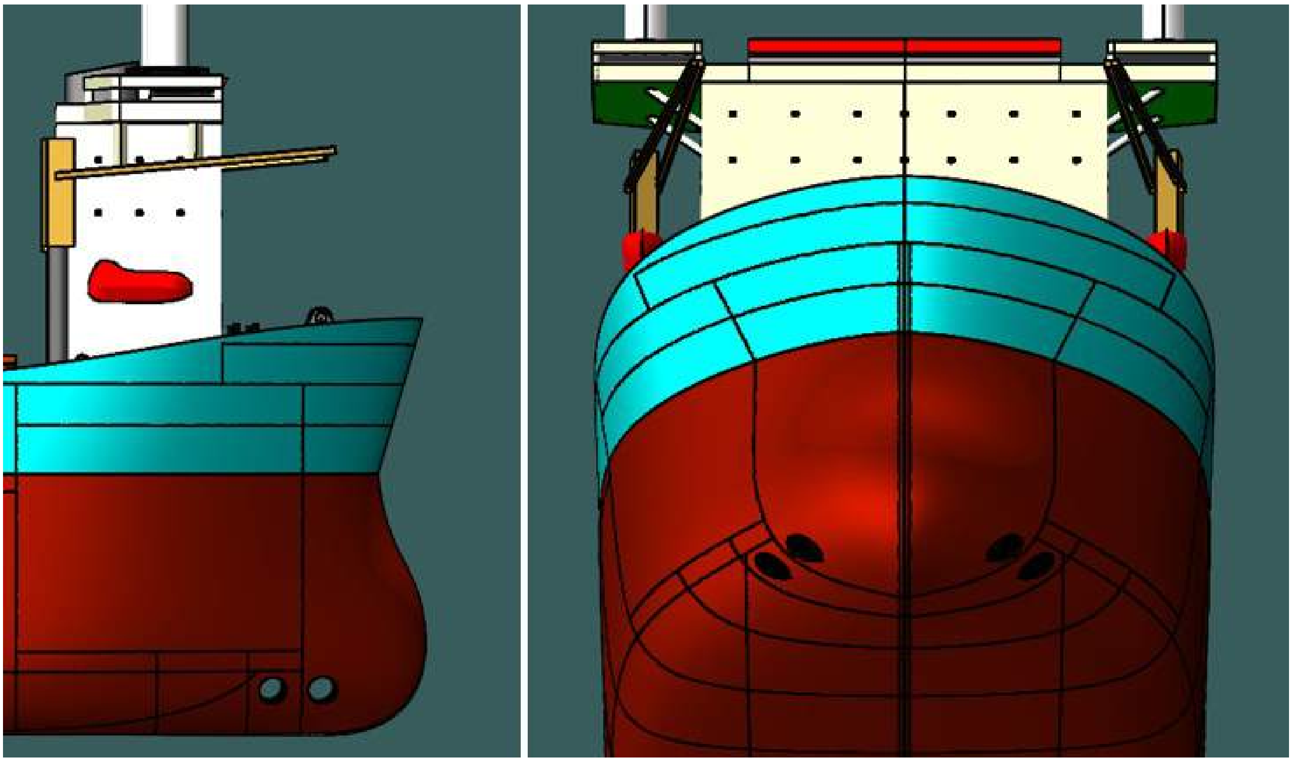


Figure 5-72 Bow Thrusters of Decom Tools Vessel

5.22 Machineries and Power Consumption of Decom Tools Vessel

There are lots of equipment and machineries onboard the Decom Tools vessel. These machineries are considered as loads which require power and electricity to run. As it stated earlier, one of the biggest consumers of electricity is propulsion system. Nevertheless, there are other equipment which consume electricity considerably. Table 5-6 shows the list of the equipment along with the quantity of them and their power consumption. In the following table, loads of accommodation includes water maker, the cooling pumps, HVAC and so on.

Therefore, the above-mentioned equipment considered as one load with consumption of 200 Kilo watt. It should be noted that vessel has different load profile during different modes of operation. It means that all of the equipment will not be in service simultaneously. In order to calculate the loads, first we have to define the various modes of the ship during different operations and specify which equipment will be in the service in that mode of operation. The loads for the three different operation modes of Decom Tools Vessel are classified as following:

I. Loads in the cable removal operation.
II. Loads in the loading, transportation and offloading of wind turbines.
III. Loads in the pile extraction, cutting and marine growth removal phase of the project.

Table 5-6 List of Main Equipment and Power Consumption

Load List			
List of Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System (3 X VSP 36)	11571	1	11571
Bow Thruster	1000	2	2000
Crane 750 tones	1100	2	2200
Crane 30 tones	288	2	576
HPU for Cutting the blades	55	32	1760
HPU for Pile Grippers	100	3	300
HPU for Cutting the cable	15	2	30
HPU for Cable Grippers	15	1	15
Winch Number 1 (362 Kn)	130	1	130
Winch Number 2 (147 Kn)	37	1	37
Ballast Pump	688	10	6880
Mooring Anchor	630	6	3780
Accommodation & Bridge	200	1	200

5.22.1 Loads During Cables Removal Operation

The Decom Tools vessel is able to extract the cable with basic tools. These tools include roller, two winches, hydraulic clamp and cutting tool. The Decom Tools vessel can move above the route of the cable in 2 different ways. The first way is by employing positioning anchor winch (PAW) and the second mode can be using the vessel in DP mode.

The cable extraction/recovery should be conducted by using a winch that must pull the cable out of the trench. According to one study which made in one of the offshore wind parks in the

North Sea Region, the maximum forces that need to be exerted to extract the cable without trenching top of the cable is about 150 kN. In the design of the Decom Tools vessel, the maximum force that the first winch can pull the cable is about 360 KN which demand approximately power of 130 KW. In addition, the second winch has the pulling force of 147KN which consume the power of about 37 KW approximately.

The list of major equipment along with their consumption for cable removal are listed in the following tables when the vessel is in DP mode as well on the position anchor winches.

According to the Table 5-9 and Table 5-10, the required power on the DP mode for the operation of cable extraction is three times more than the same operation on the positioning anchors. It means, if client agree to deploy the anchors for cable extraction, huge amount of energy can be saved.

In this document, the authors assume that 4 different campaigns for decommissioning of an offshore wind farm need to be conducted. The first campaign is mobilization of vessel for the cable removal operation. It means that the vessel should be mobilized with equipment and personnel for the removal of inter-array and export cable. The load profile in this part of this document is calculated based on two cases study. In this section, the offshore wind farm by the name of Hornsea 1 is our case study for disassembly of wind turbine, Transition piece and monopile removal. For the cable removal, the Anholt offshore wind farm is the case study of the cable recovery operation.

For the cable removal, five different modes of operations are considered. The modes are as following:

5.22.1.1 Loads in the Sailing Mode of the Cable Removal Operation

Having considered the size and volume of holds of the Decom Tools vessel, the vessel can remove all the cables both inter array and export, loads all of them onboard the vessel and then after entire removal, transport them ashore for further process and recycling.

The most left column of the Table 5-7 illustrates the equipment which are onboard of the vessel. The second column shows the nominal power for running the equipment at full load and the last column shows the overall power that need to be in-service since the quantity of the machines can be more than one. In this phase of the operation, the Decom Tools vessel need to sail to the OWP just one time, remove whole the cables and return.

The required time of the sailing are shown in the last row which is 0.07 (Day).

In the last row of the table, the percentage shows (the green cell), how much of the time of removal of cable recovery is associated to the sailing. Also, the last cell of the last row (the yellow cell) shows the overall loads during sailing mode.

In this calculation, we assume the average speed of sailing is 7.57 knots. Calling Table 5-5, the required power for propulsion system at the speed of 7.57 knots is 5785 KW.

This is the output of MAXSURF software for the Decom Tools vessel.

Table 5-7 The Load Profile for the Sailing Mode for The Cable Removal Operation

Sailing Mode (For the Cable Removal Operation)			
In-Service Equipment	**Nominal Power (kW)**	**Quantity**	**Overall Power (kW)**
Propulsion System (60%max speed=7.57kn)	11571	0.5	5785.5
Bow Thruster	1000	0	0
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads at 7.57 knot (50% load)	**0.04 Days**	**0.04%**	**5985.5 KW**

5.22.1.2 Loads in the Stand-By Mode of the Cable Removal Operation

The stand-by mode of the Decom Tools vessel during cable extraction of Anholt project is about 42.47 days. Since the vessel is floating and work in the NSR, 35% of operational working time is considered as stand by modes.

Having considered that in this case study, the cable extraction including stand-by time is 159.16 days. This means during course of operation, the vessel will be faced with bad weather condition or mechanical breakdown or waiting on client over 42 days. The exact figure will be presented in the next chapter under the section of Time-Cost Analysis of Anholt OWP Cable Retrieval with Decom Tools Vessel6.30.

It is evident that during stand-by mode, the vessel can be operated on the anchor. In this case, just accommodation and the necessary equipment such as bridge instruments, water maker etc.

will come to the service. The green cell shows the percentage that vessel goes to stand-by mode and the yellow cell shows the load in this mode of operation.

Table 5-8 Loads in the Stand-By Mode for the Phase of Cable Removal

Stand-By Mode (anchor) (For the Cable Removal Operation)			
In-Service Equipment	**Nominal Power (kW)**	**Quantity**	**Overall Power (kW)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**42.47 (Day)**	**26.68%**	**200 KW**

5.22.1.3 Loads in the Cable Removal Operation on DP Mode and Anchor Positioning Winch

During removal or extraction of the cable, the Decom Tools vessel can be operated in two different methods.

I. The first scenario is to keep the position of the vessel by deploying position anchor winch (PAW). In this case, minimum 4 anchors need to be deployed. But in this document, we consider 3 anchors work around the clock. Maintaining the position of the vessel on either DP or PAW has some advantages and disadvantages as following:

- ☑ The first advantage is the fuel consumption is lower than DP mode which results in less emission.
- ☑ The wages of DP officers are higher that anchor operators which result in less charter rate of the vessel.

The disadvantages are as following:

- ☒ For deploying anchors, there is demand for anchor handling tug (AHT) and positioning team.

- ☒ It is not possible to drop the anchor in water depth more than 70m.
- ☒ In some fields, the field owner (main client or government) does not allow to deploy the anchors due to existence of subsea asset in the field and the risk of accident of anchors with existing subsea assets.
- ☒ Anchor running is lengthy operation. Deploying each anchor takes 3 hours approximately and retrieving them the same. So, the preparation time of the vessel is lengthy and time consuming.

II. The second method is to maintain the position of the vessel by dynamic positioning (DP). In this mode of operation there are some advantages and disadvantages as following:

- ☑ The vessel can be operated without anchor handling tug.
- ☑ The controlling and manoeuvrability of the vessel is more convenient, flexible and quicker.
- ☑ Regardless of subsea assets and water depth, the vessel can keep the position.
- ☑ For the scenario of DP mode, DP officers can tune and set with which loads the propulsion system should work. This depends on the precision of positioning; the vessel drafts as well as weather condition. Therefore, the propulsion system does not need to work on 100% loads all the time. If the environment loads are high, the propulsion systems need to work on more load to maintain the vessel in the position. In this calculation, we considered that the propulsion system works in average on 60% of full load. However, we consider both bow thrusters work on 100% load. The disadvantages of running the vessel on DP are as following:
  - ☒ The fuel consumption is higher which will result in more emission.
  - ☒ DP officers need to be mobilized which has higher wage.

Important Note: During this calculation, it is considered for recovery of inter array cable, the vessel operates on DP mode and for recovery of export cable, the vessel run on PAWs.

Thus, the equipment which need to be in-service during cable extraction are listed in the Table 5-9 and Table 5-10.

Table 5-9 shows that the maximum loads during cable extraction if they run the vessel on DP mode is about 9584 kilowatts. It should be noted that average loads of propulsion system are considered 60% in average. Recovery of inter array cables, cutting and other preparation takes about 85.65 days which constitute 53.81% of cable recovery operation of Anholt wind farm. The explanation regarding the timing is given under section Time-Cost Analysis of Anholt OWP Cable Retrieval with Decom Tools Vessel.

Table 5-9 Loads in the Cable Removal Mode (on DP Mode)

Cable Extraction (DP Mode)			
In-Service Equipment	**Nominal Power (kW)**	**Quantity**	**Overall Power (kW)**
Propulsion System	11571	0.6	6942.6
Bow Thruster	1000	2	2000
Crane 750 tones (Hoist 30 tones)	1100	0.25	275
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Cable Grippers	15	0	0
HPU for Cutting the cable	15	0	0
Winch Number 1 (362 Kn)	130	1	130
Winch Number 2 (147 Kn)	37	1	37
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**85.65 Days**	**53.81%**	**9584.6 KW**

Table 5-10 Loads in the Cable Removal Mode (on Position Anchor Winch)

Cable Extraction (Position Anchor Winch)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	0.25	275
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Cable Grippers	15	0	0
HPU for Cutting the cable	0	0	0
Winch Number 1 (362 Kn)	130	1	130
Winch Number 2 (147 Kn)	37	1	37
Ballast Pump	688	0	0
Mooring Anchor	630	3	1890
Accommodation & Bridge	200	1	200
Overall Loads	**29.03 Days**	**18.24%**	**2532 KW**

Table 5-10 shows that that the maximum loads during cable extraction if they run the vessel on 3 numbers of anchor positioning winches is about 2532 kilowatts. It means that the loads of the vessel on the mooring system is 26% of the loads on the DP mode.

As it stated before, another vessel for running anchor all the time should be in the field. So, the fuel consumption, the emission and charter rate of AHT should be calculated as well.

5.22.1.4 Loads in the Cutting Operation of the Cable Removal Operation

After extraction of the cable, cable should be suspended by the hydraulic clamp for cutting operation and so on. In this period, some other equipment should come to the service including hydraulic clamp, the cutting tools and the second winch.

The consumption of mentioned equipment is not so much. The only difference is under which operation mode, the cable maintains the position. In other words, when the cutting is cutting, the vessel run on DP or the PAWs. In this specific case study, the cutting of inter array cables constitute 0.639% of cutting and cutting of export cable constitute 0.361% which is directly depends on the cable length. Therefore, loads during cutting is a combination of loads on PAWs and on DP modes.

The details of cable extraction procedure and sequence are described in the next chapter.

So, in this case, again the propulsion system works on 60% load. The maximum load on this part of the operation is 9600 Kilowatts based on the Table 5-9 and the minimum load is about 2532 KW according to Table 5-10.

5.22.1.5 Loads in the Offloading Mode of the Cable Removal Operation

After recovery of the inter array and export cable, the vessel needs to sail towards the port for offloading the cables. The procedure of cable cutting, loading and offloading are mentioned in under section Cable Extraction Procedure 6.28.

Table 5-11 shows the list of the equipment which need to be in-service during offloading of the cables. It is considered that the cables are loaded inside the container for easier transportation and recycling process. The time for offloading each container is considered 15 minutes which normally in the port, lifting of the container takes within 5 minutes or less.

According to the load profile, it is considered that one of the gantry cranes and the accommodation works around the clock. In this case the overall, load is 1300 KW. Also, offloading all the container takes about 1.93 days.

Table 5-11 Loads in the Cable Removal Mode (Port Mode/Offloading the Cables)

Port Mode (Tie Up to Port)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	1	1100
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Cable Grippers	100	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**1.93 Days**	**1.21%**	**1300 KW**

5.22.1.6 Load Profile During Cable Extraction Operation

An algorithm has been devised for calculation of load profile based on the in-service equipment in each sequence of the operation, the equipment consumption and the time that vessel operate in each sequence. The method and duration of operation are explained under section Time-Cost Analysis of Anholt OWP Cable Retrieval with Decom Tools Vessel 6.30 . However, the quantity of loads and load profile are mentioned here in this chapter in order to select the right Genset for the Decom Tools vessel.

In the Figure 5-73, the vertical axis depicts the consumption in kilowatt. In addition, the value of consumption in each bar is in the red colour.

Furthermore, the horizontal axis illustrates the various modes of operation during cable removal. As it shows, the highest consumption will be during cable extraction process, if the vessel operates on DP. Not only does the maximum power consumption is related to the cable extraction mode on DP, but also, the cable extraction time is most time-consuming operation. The yellow number in the chart shows the time that the vessel spends on each process of cable recovery operation. The rightest bar in the graph shows the duration for offloading the cable into the port which here is considered 1.93 days for approximately 185 km of inter-array and export cable.

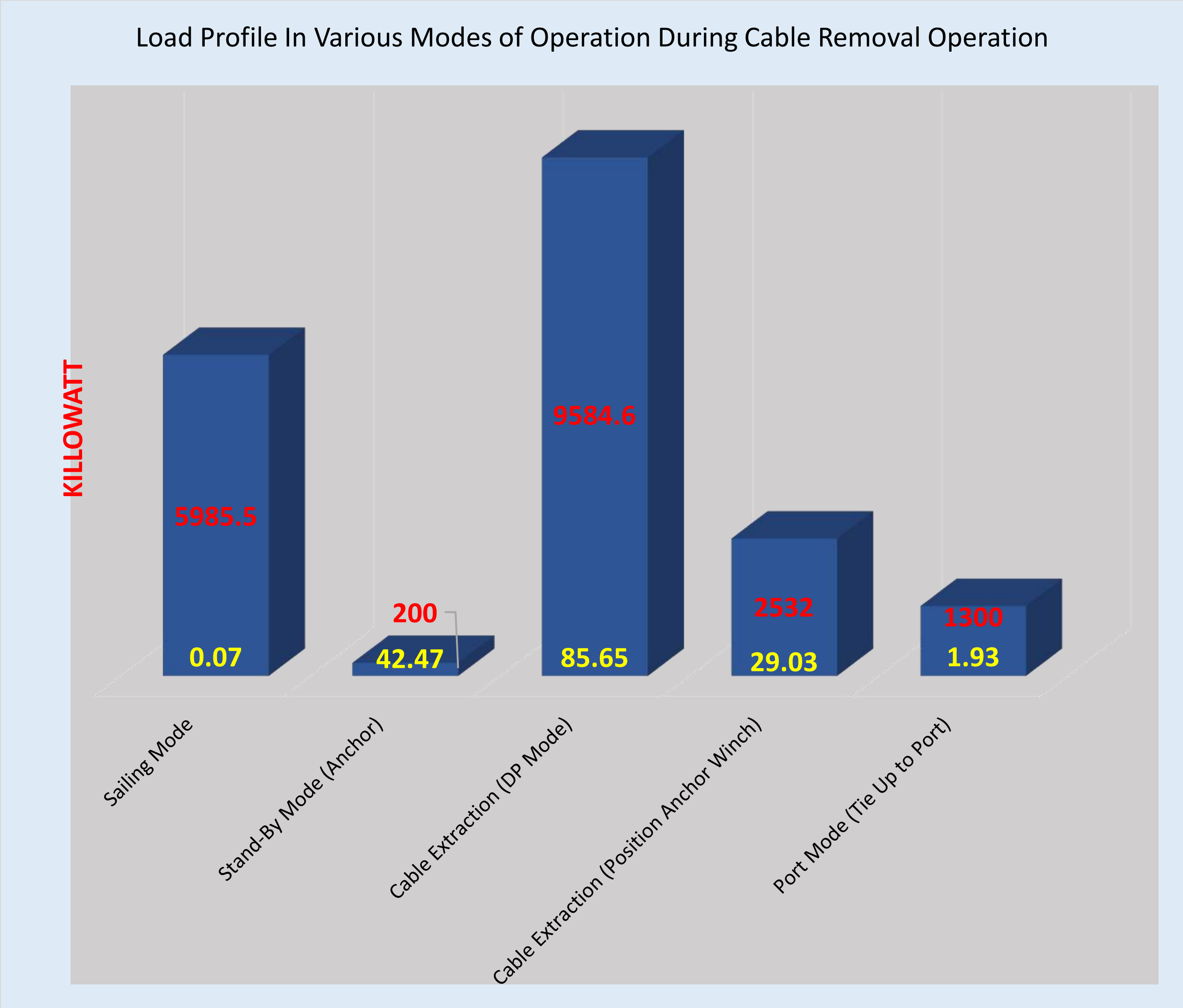


Figure 5-73 Load Profile for Cable Removal Operation

Table 5-12 Summary of Load profile During Recovery of Export and Inter-array Cables

Required Power During Cable Extraction of Anholt Offshore Wind Park			
List of Modes of Decom Tools Vessel	**Duration (Day)**	**%**	**Power (kW)**
Sailing Mode	0.07	0.045%	5985.5
Stand-By Mode (Anchor)	42.47	26.687%	200
Cable Extraction (DP Mode)	85.65	53.815%	9584.6
Cable Extraction (Position Anchor Winch)	29.03	18.242%	2532
Port Mode (Tie Up to Port)	1.93	1.211%	1300
Estimation of Loads In one Project	**159.16**	**100%**	**3920.42 KW Avg.**

5.22.2 Loads During Disassembly of Wind Turbines

Based on the findings of chapter 3, section 3.10.3, Conclusion of Time-Cost-Consumption-Emission Analysis , the optimum configuration was using a heavy lift vessel along with Decom Tools vessel (feeder configuration). Duration of each operation and the percentage was illustrated in the mentioned section. Seven modes of operation are defined for the Decom Tools Vessel for being as feeder vessel to transport the wind turbine components namely, rotor, nacelle and tower to the port. The equipment that needs to be in-service in each mode of operation differ which will result in load profile and ultimately will impact the genset capacity.

5.22.2.1 Loads in the Sailing Mode of the Disassembly of Wind Turbine

The Decom Tools vessel has two different sailing modes during disassembly of wind turbine components. When the vessel sail between the turbines, the vessel speed cannot exceed 1 knot. On the other hand, when the vessel sail between port to OWP or vice versa, two different scenarios for the speed can be considered as following:

I. When the vessel sail towards the offshore site, it does not load with any cargos, so the vessel sail at draft of 6 meters.

II. When the vessel is fully loaded and sailing from OWP to port, it is considered that the vessel sail at the draft of 19.6 meter.

Table 5-13 Equipment and Loads in the Sailing Modes

Sailing Modes (During Disassembly of Wind Turbines)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System (60%max speed=7.57kn)	11571	0.5	5785.5
Bow Thruster	1000	0	0
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	32	1760
HPU for Pile Grippers	100	0	0
HPU for Cable Grippers	15	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads at 7.75 knots (50% load)	**4.99 (Days)**	**3.39%**	**7745.5 KW**
Overall Loads at 1 knot	**1.89 (Days)**	**1%**	**500 KW**

So, in the calculation, we consider that the average vessel speed is 60% of maximum speed which is 7.57 knots. Based on Table 5-5, at the speed of 5.75 knots, the required power is 5780 kw. The above scenarios impact the consumption of the vessel remarkably. Therefore, two different loads are considered for each speed based on the chart of speed versus the engine power. The list of equipment and the necessary machineries which need to be in-service during sailing are mentioned in the Table 5-13.

Furthermore, in the sailing mode, neither the cranes nor ballasting pumps are in the operation. Instead, the Decom Tools vessel are designed to cut the blades into small pieces when the vessel is under voyage. Therefore, the consumption of cutting tools is calculated in the above mentioned- table.Table 5-13 shows that the load during sailing mode is about **7745.5** kilowatts.

5.22.2.2 Loads in the Stand-By Mode of the Disassembly of Wind Turbines

Decom Tools vessel goes to the stand-by mode in some cases. Some reasons of stand-by are mentioned as following:

- ☒ Due to failure of equipment.
- ☒ Due to stand-by of the construction vessel.
- ☒ Due to weather condition.
- ☒ Waiting on client (WOC)
- ☒ Lack of job for the vessel and so on.

Table 5-14 Equipment and Loads in the Stand-by Mode

Stand-By Mode (anchor) (During Disassembly of Wind Turbines)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Pile Grippers	100	0	0
HPU for Cable Grippers	15	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**39.72 (Days)**	**27.01%**	**200 KW**

In this case just accommodation and required equipment to run the accommodation and bridge instruments need to be in-service. In this case, we consider that the vessel can drop the anchor in the field or nearby the OWP.

5.22.2.3 Loads in the Operation Modes of the Disassembly of Wind Turbines

Operation modes is considered as the time the vessel is alongside the construction vessel and relocate the cargos on the deck or load them inside the holds.

Depending on the type of construction vessel, the Decom Tools vessel can maintain the position alongside the construction vessel by different methods as following:

I. The most economy way to maintain the position of the cargo vessel is by fastening the cargo vessel to the construction vessel, See Figure 5-74. In this case, the floating construction vessel is maintaining the position by using either DP or mooring winch, then the cargo vessel ties up itself to the construction vessel. This method is so common in the oil and gas industry. The following figure shows two cargo barges are fastened both to the port and starboard of the construction vessel. The construction vessel maintained the position by DP.

Figure 5-74 Feeder Barges are Fastened to the Construction Vessel

II. If the construction vessel is jack up vessel, neither the Decom Tools vessel nor any other vessel can tie up to the jack up. In this case the Decom Tools vessel can either drop the positioning anchor or use the DP mode. One of the reasons that the DP system is incorporated in the Decom Tools vessel is due to the fact that none of the vessels can tie up to the jack up vessel and more importantly, most of wind turbine installation vessels are jack up type.

III. The last method to maintain the position of cargo barge is to deploy the position anchor winches.

Each of above-mentioned scenarios has some merits and demerits which are explained below.
For the operation mode, the load profile has been calculated for all above scenarios. The following tables show the load and require equipment in each type of positioning.
So, in this mode, we consider one of the gantry cranes are in-service 18 hours per day or both of gantry cranes work 9 hours daily. In addition, one of the pedestal provision cranes are in service 12 hours per day.
Table 5-15 shows the load profile when the Decom Tools vessel are alongside the construction vessel, and it keeps the position by fastening to the installation vessel. As you can see in the table, neither the propulsion system nor the position anchor winches are in service. If the installation vessel is a floating vessel and capable to maintain the position when the Decom Tools vessel are tied up to it, the maximum loads of Decom Tools vessel with mentioned assumption is about 1169 kilowatt.

Table 5-15 Equipment and Loads in the Operation Mode (Tie Up to the HLV)

Operation Mode (Tie Up to HLV) (During Disassembly of Wind Turbines)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	0.75	825
Crane 30 tones	288	0.5	144
HPU for Cutting the blades	55	0	0
HPU for Pile Grippers	100	0	0
HPU for Cable Grippers	15	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**74.89 (Days)**	**50.92%**	**1169 KW**

Table 5-16 shows the load profile of the Decom Tools vessel when it maintains the position by DP system. The loads of DP system heavily depend on the weather condition. In this document, it is considered for reliable positioning alongside the construction vessel, the propulsion system needs to be in-service with 60% of its maximum power.

Table 5-16 Equipment and Loads in the Operation Mode (DP)

Operation Mode (DP) (During Disassembly of Wind Turbines)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0.6	6942.6
Bow Thruster	1000	2	2000
Crane 750 tones	1100	0.75	825
Crane 30 tones	288	0.5	144
HPU for Cutting the blades	55	0	0
HPU for Pile Grippers	100	0	0
HPU for Cable Grippers	15	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**0 (Days)**	**0.00%**	**10111.6 KW**

According to Table 5-16, if the Decom Tools vessel plan to maintain the position alongside the construction vessel by its DP system, the required load is about 10111KW.

Table 5-17 shows the load profile of the Decom Tools vessel, when it maintains the position alongside the construction vessel by position anchor winches.

In the positioning by use of position anchor winch (PAW), we consider 5 numbers of PAW are deployed but three of the electric motors of the winches works around the clock.

Thus, in this case the overall load profile is about 3059 kilowatts.

In the above section, the loads have been calculated for three different scenarios of keeping the position of the vessel. Having considered the dimension of Decom Tools vessel, tie up to small-sized construction vessel may not be possible due to the force that the Decom Tools vessel can exert to the construction vessel, in particular, when the weather is rough or very rough, however, it depends on the stability of the construction vessel.

In this document, it is assumed that the construction vessel is floating DP vessel and the Decom Tools vessel moored to the construction vessel. The main reason for this selection is reduction of fuel consumption which lead to lower charter rate of the vessel as vessel' emission.

Table 5-17 Equipment and Loads in the Operation Mode (Position Anchor Winch)

Operation Mode (Position Anchor Winch) (During Disassembly of Wind Turbines)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	0.75	825
Crane 30 tones	288	0.5	144
HPU for Cutting the blades	55	0	0
HPU for Pile Grippers	100	0	0
HPU for Cable Grippers	15	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	3	1890
Accommodation & Bridge	200	1	200
Overall Loads	**0 (Days)**	**0 %**	**3059 KW**

As it shows in the above tables, the load of the Decom Tools vessel is 1169 KW, 10111 KW and 3059 KW when the vessel maintain the position by fastening to the floating construction vessel, by DP system and by position anchor winches respectively. Therefore, in the fuel consumption calculation during disassembly of wind turbines, the Decom Tools are moored to the construction vessel for the sake of fuel consumption, mitigation of mission as well as charter rate.

5.22.2.4 Loads in the Port Modes for Offloading of the Wind Turbines

After disassembly of wind turbine with construction vessel and loading them into the Decom Tools vessel, the vessel has sail toward the port or decommissioning yard in order to offload the materials. In order to offload the materials from Decom Tools vessel into the port, the port crane or crawler crane need to lift the materials from the Decom Tools deck to the quayside. Normally the port crane or mobile crane can lift and transfer the cargos that are near the quayside. In order to increase the time of operation as well increase the safety of lifting operation, it is considered that one of the gantry cranes work around the clock to transfer the materials from holds to the accessible location (top of hatch coves) for the safe lifting of the port cranes.

Table 5-18 shows the required power when the vessel is fastened to the port for offloading operation. As it stated before, the time and the percentage in the last row is based on the devised algorithm. These figure shows the duration and percentage of the vessel in this mode during decommissioning of Hornsea 1 project. For this mode of operation, it is assumed just accommodation and one of the gantry cranes are in service or two gantry cranes work 12 hours daily.

Table 5-18 Equipment and Loads in the Port Mode (Tie Up to the Port)

Port Mode (Tie Up to Port) (During Disassembly of Wind Turbines)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	1	1100
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Pile Grippers	100	0	0
HPU for Cable Grippers	15	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**25.59 (Days)**	**17.4%**	**1300 KW**

5.22.2.5 Load Profile During Disassembly of Wind Turbines

An algorithm has been devised for calculation of load profile based on the in-service equipment, the equipment consumption and the time that vessel operate in each sequence.

The duration and analysis of different logistic configuration for disassembly of the wind turbines are explained in the third chapter under section Time-Cost Analysis of Hornsea 1 OWP Decommissioning with Feeder Configuration (DP2 HLV + Decom Tools Vessel)3.10.2.2.2. However, the quantity of loads and load profile are mentioned here in this chapter in order to select the right Genset for the Decom Tools vessel.

Figure 5-75 depicts the load profile during the disassembly of the wind turbine components.

In the Figure 5-75, the vertical axis depicts the consumption in kilowatt. In addition, the value of consumption in each bar is in the red colour.

Furthermore, the horizontal axis illustrates the various modes of operation during disassembly of rotor, nacelle and towers. As it shows, the highest consumption belongs the DP mode, however, we made decision to fasten the vessel to the floating construction vessel to minimize the cost, fuel consumption as well as emission.

Yellow values in the chart shows the time that the vessel spends on each mode during loading and transportation of wind turbines. Therefore, in this analysis, the time that vessel run on DP or position anchor winches is zero, however, the vessel maintains the position by mooring to the construction vessel.

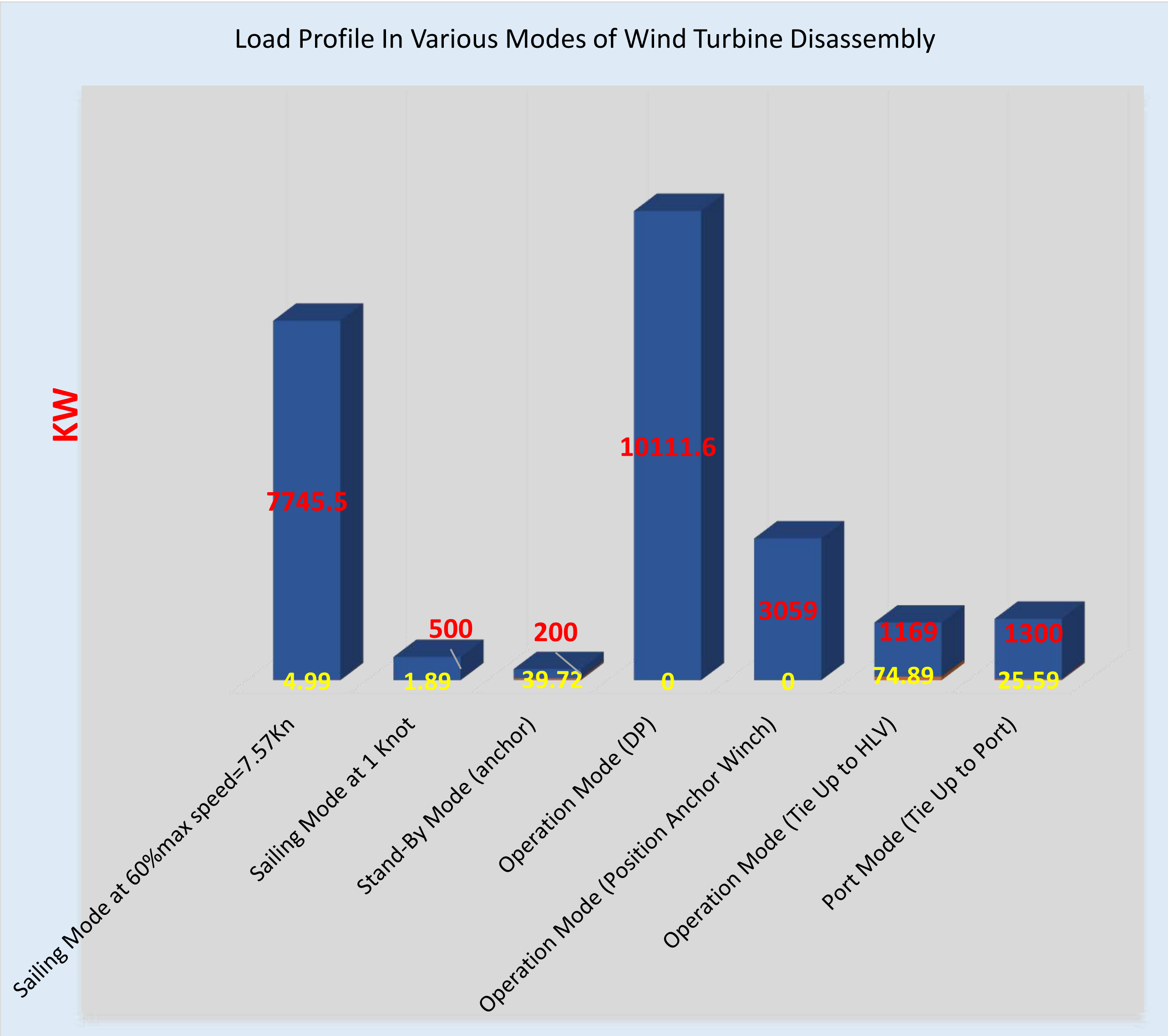


Figure 5-75 Load Profiles During Disassembly of Wind Turbines

The results of above figure show that in the operation mode, the most economy method is maintaining the Decom Tools vessel position by fastening the Decom Tools vessel to the construction vessel followed by using positioning anchor and lastly by DP system. However, the fuel consumption and emission are very crucial factors, but the safety, execution of operation and technical issues need to be considered too. Therefore, in order to select the best method of positioning the Decom Tools vessel in operation mode, all aspect including safety, the impact of cargo vessel to the construction vessel, fuel consumption, the CO_2 emission, duration of operation and so forth need to be studied well. There is not one answer fit all the situations. But it is clear that if there is not any technical issue to fasten the Decom Tools vessel to the construction vessel, there will be huge saving in terms of project cost as well as emission mitigation. Also, running the vessel on the position anchor winches or DP system need extra crew which means the charter rate of the vessel will be increased too.

Table 5-19 Summary of Load profile During Disassembly of Wind Turbines

Required Power During Wind Turbine Disassembly			
List of Modes of Decom Tools Vessel	**Duration (Day)**	**%**	**Power (kW)**
Sailing Mode at 60% of max speed=7.57Kn	4.99	3.39%	7745.5
Sailing Mode at 1 Knot	1.89	1.29%	500
Stand-By Mode (anchor)	39.72	27.01%	200
Operation Mode (DP)	0	0.00%	10111.6
Operation Mode (Position Anchor Winch)	74.89	50.91%	3059
Operation Mode (Tie Up to HLV)	0	0.00%	1169
Port Mode (Tie Up to Port)	25.59	17.40%	1300
Estimation of Loads In one Project	**147.09**	**100%**	**3440.72 KW Avg.**

5.22.3 Loads During Piles Extraction Operation

The Decom Tools vessel is designed to extract the monopile. The explanation about the pile extraction is provided in the next chapter, under section 6.18.4. Now in this section, just the list of equipment that are necessary for pile extraction are mentioned along with their consumption. The cutting system for pile extraction operation should be a fast-cutting method. So far, the quickest cutting method for this component is oxy fuel cutting. The other methods are so time consuming, expensive etc. which are not suitable for Decom Tools vessel. The more offshore duration means more fuel consumption of the involved fleet and more CO_2 emission. The calculated time for various modes of operation during pile extraction is based on the case study. In general loads and duration of operations are considered for Hornsea 1 offshore wind farm. The installation of wind turbines is executed with two contractors, Bold Tern jack up vessel installed 91 turbines and the Sea Challenger installed 83 numbers of wind turbine. The diameter of pile is 8.1 meters, and they have average length of 63 meters with maximum weigh of 1039 tones. Having considered that the water depth in the field vary between 20-40 meters, it is assumed that the length of penetration into the seabed is about 32.5 meters (SAL 2020).

5.22.3.1 Loads in the Sailing Mode of the Pile Extraction Operation

An algorithm has been devised for calculation of the time that the Decom Tools vessel has to spend in different mode. Then in order to evaluate and verify the algorithm, a case study has been selected in order to check the precision of algorithm. As it stated before, the case study is Hornsea 1 project. The wind farm consists of 174 wind turbine which the installation of 91 number of wind turbine has been conducted by Bold Tern vessel and the rest are installed by Sea Challenger. But in our calculation, we calculate the timing for 91 number of turbine and substructure.

As it states before, we calculate two sailing time. The first sailing time is the duration the vessel sail between port and the offshore wind farm. In this case, the distance is 120 km, and the average speed of the vessel is 60% of the maximum speed of the vessel.

The second sailing time is the time the vessel sails between wind turbines.

Table 5-20 Equipment and Loads in the Sailing Mode

Sailing Mode (During Pile Extraction Operation)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System (60%max speed=7.57kn)	11571	0.5	5785.5
Bow Thruster	1000	0	0
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads at 7.75 knots (50% load)	**2.85 Days**	**1.76%**	**5985.5 KW**
Overall Loads at 1 knot	**1.89 Days**	**1.17%**	**500 KW**

We presume that the distance between the wind turbine is 6 times greater that than the rotor diameter. Having considered that the rotor dimeter of 7 MW Siemens Gamesa Wind turbine is

154 meters, then the distance between wind turbines is 924 meters. Also, the maximum speed that the vessel can sail inside the field is considered 1 knot. The Decom Tools vessel can load and transport 24 number of monopile of Hornsea 1 project which has average length of 63 meter and diameter of 8.1 meter.

5.22.3.2 Loads in the Stand-By Mode of the Pile Extraction Operation

The duration of stand-by is fraction of duration of working mode of the vessel. It is considered that 35% of working hours is stand-by time. Having this fact, the duration of stand-by mode and the load in this mode can be seen in the following table.

Table 5-21 Equipment and Loads in the Stand-By Mode

Stand-By Mode (anchor) (During Pile Extraction Operation)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**43.71 (Days)**	**27.01%**	**200**

5.22.3.3 Loads During Positioning Around Pile

Prior to extraction of monopiles, the Decom Tools vessel has to be positioned around monopile. In this stage, the DP system has to be in-service with the highest precision. Therefore, in this stage, it is considered that propulsion system along with the bow thrusters are in-service with 100% load.

Table 5-22 shows the loads in this mode along with timing and percentage. As it shows, the overall load in this mode is about **14071 KW**. The vessel spends about 7.58 days for extraction of 91 numbers of monopile which constitute about 4.6% of overall extraction operation.

Table 5-22 Equipment and Load During Positioning Around Monopile

Positioning Around Monopile (During Pile Extraction Operation)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	1	11571
Bow Thruster	1000	2	2000
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	3	300
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**7.58 (Days)**	**4.6%**	**14071 KW**

5.22.3.4 Loads in the Pile Extraction Operation of the Pile Extraction

During pile extraction operation, the DP should be deactivated and just bow thrusters should come to the service in order to maintain the heading of the vessel since the positioning of the vessel are maintained by grippers and monopile.

Table 5-23 Equipment and Loads During Pile Extraction Mode

Pile Extraction			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	2	2000
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	3	300
HPU for Cutting the cable	15	0	0
Ballast Pump	688	10	6880
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**69.78 (Days)**	**43.12%**	**9380 KW**

One of the most energy demanding equipment which need to come to the service for the pile extraction are ballast pumps. 10 numbers of ballast pumps which each has consumption of 688 KW are considered for this vessel. During pile extraction operation, all the pumps need to run in order to ballast and deballast the vessel. The explanation of how the Decom Tools vessel can extract the monopile are described in the next chapter under section Design of Pile Extraction System of the Decom Tools Vessel6.18.4.

Table 5-23 shows the loads in this mode along with timing and percentage. As it shows, the overall load in this mode is about **9380 KW**. The vessel spends about 69.78 days for extraction of 91 numbers of monopile which constitute about 43.12% of overall extraction operation.

5.22.3.5 Loads During Cutting the Monopile of the Pile Extraction

The detail explanation regarding the pile extraction is described in the next chapter. Here we just briefly explaining the operation in order to identify which equipment need to be in-service for calculating the loads for genset selection.

Table 5-24 Equipment and Loads During Cutting the Monopiles

Cutting the Monopile After the Extraction			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	2	2000
Crane 750 tones	1100	2	2200
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	3	300
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**30.33 (Days)**	**18.74%**	**4700 KW**

After extraction of the monopiles, both gantry cranes need to hold the monopile before the grippers become open. Then, after lifting the monopile with gantry cranes, the cutting can take place. The monopile need to be cut into length of 12 meters. Thus, to hold and transfer the cut piece, gantry cranes need to be in-service. The loads and equipment which need to be in-service during this operation are listed in the Table 5-24. As it illustrates, the load in this part of operation is about **4700 kilowatts**.

5.22.3.6 Loads During Offloading the Monopiles to the Port

After extraction of the monopiles, they have to be transported to the port for further recycling process. During offloading operation, it is estimated that one of the gantry cranes work around the clock to lift the monopile from holds to top of the hatch covers and to load them in a location to be accessible for the shore-based crane for offloading them. Therefore, in this part of operation only one of the gantry cranes as well as accommodation along with bridge equipment need to be in operation. It is calculated for offloading 91 numbers of monopile with length of 65 meters, approximately 5.69 days is needed which account 3.5% of pile extraction operation.

Table 5-25 Equipment and Loads During Offloading The Monopiles

Port Mode (Tie Up to Port) (During Pile Extraction Operation)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	1	1100
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**5.69 (Days)**	**3.5%**	**1300 KW**

5.22.3.7 Load Profile During Disassembly of Wind Turbines

Figure 5-76 depicts the load profile during extraction of 91 numbers of monopile of Hornsea 1 OWP. In this figure, the vertical axis depicts the consumption in kilowatt. Furthermore, the horizontal axis illustrates the various modes of operation during pile extraction. As it shows, the highest consumption belongs to the positioning around monopile which takes 7.58 days. Extraction operation is the most time-consuming operation which takes about 69.78 days. Yellow values in the chart shows the time that the vessel spends on each mode.

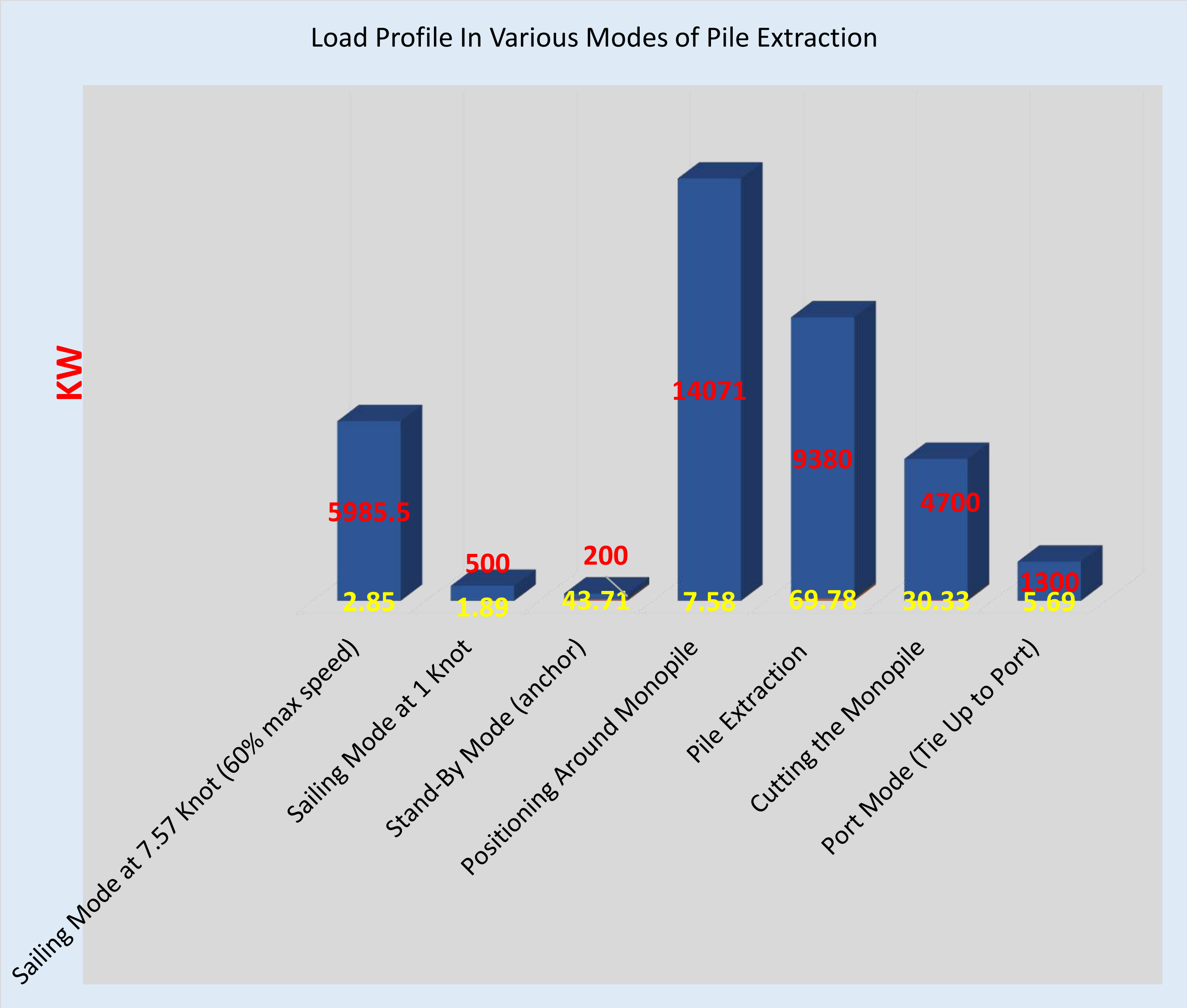


Figure 5-76 Load Profiles During Pile Extraction

Table 5-26 Summary of Load profile During Pile Extraction

Required Power During Pile Extraction			
List of Modes of Decom Tools Vessel	**Duration (Day)**	**%**	**Power (kW)**
Sailing Mode at 7.57 Knots	2.85	1.76%	5985.5
Sailing Mode at 1 Knot	1.89	1.17%	500
Stand-By Mode (anchor)	43.71	27.01%	200
Positioning Around Monopile	7.58	4.69%	14071
Pile Extraction	69.78	43.12%	9380
Cutting the Monopile	30.33	18.74%	4700
Port Mode (Tie Up to Port)	5.69	3.51%	1300
Estimation of Loads In one Project	**161.84 days**	**100.0%**	**5162.36 KW Avg.**

5.22.4 Loads During Transition Piece Removal

Cutting and removal of transition pieces has to be made in separate campaign regardless of the vessel that is planned to decommission the OWP. So, under any circumstances this component should be cut above the top of the monopiles.

The Decom Tools vessel is designed to cut and transport the transition pieces (TP) in a sustainable method. In our analysis, it is supposed that the first piece of cutting take place above the monopiles' level. As it stated above, the cutting method is oxy fuel cutting since it is quick and reliable. The various modes of operation for the Decom Tools vessel are considered for TP removal which each mode required specific power. The detail explanation about removal of transition pieces is explained under section Procedure of Transition Piece Removal with Decom Tools Vessel, 6.17.4.

5.22.4.1 Loads in the Sailing Mode of TP Removal

The selected case study includes 91 numbers 7 MW wind turbine with pile diameter of 8.1 meter and they are located approximately 120 km from shore. 56 pieces of top section of TP can be loaded on the Decom Tools Vessel. As it explained before, the vessel is considered to sail with 60% of maximum speed in average between the offshore wind park and the port which is 7.57 knots. Also, inside the wind turbines, it sails with speed of 1 knot. Table 5-27 shows the loads in these two speeds along with their duration.

Table 5-27 Equipment and Load in the Sailing mode of TP Removal

Sailing Mode (During Removal of Transition Pieces)			
In-Service Equipment	**Nominal Power (Kw)**	**Number**	**Overall Power (Kw)**
Propulsion System (60%Max speed=7.57kn)	11571	0.5	5785.5
Bow Thruster	1000	0	0
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads at 7.75 knots (50% load)	**1.43 days**	**3.99%**	**5985.5 KW**
Overall Loads at 1 knot	**1.89 days**	**5.30%**	**500 KW**

5.22.4.2 Loads in the Stand-By Mode of TP Removal

The loads in the stand-by mode, in any kind of operation are the same. The only difference is duration of the stand-by mode since it is fraction of operation time. Since the Decom Tools vessel is floating vessel and has high freeboard, it is considered that 35% of operation time is stand-by mode due to bad weather condition and 2% is stand-by mode due to waiting on clients and mechanical breakdown. The duration of stand-by mode during TP removal based on calculation is about 9.65 days.

Table 5-28 Equipment and Load in the Stand-By mode of TP Removal

Stand-By Mode (Anchor) (During Pile Extraction Operation)			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**9.65 days**	**27.01%**	**200 KW**

5.22.4.3 Loads in the Positioning Mode of TP Removal

In order to hold the transition pieces with the grippers, the vessel require precise positioning. It is considered that the propulsion system along with bow thrusters are in-service with full load. Also, the pile grippers should be in service in order to hold the transition pieces. Table 5-29 shows the list of in-service equipment along with their consumption.

The last row of the tables shows removal of 91 transition pieces takes about 7.58 days which constitute about 21.2% of overall TP removal operations. The maximum load on the Genset on this mode of operation is about 14071 kilowatts.

Table 5-29 Equipment and Loads in the Positioning Mode of TP Removal

Positioning Around TP			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	1	11571
Bow Thruster	1000	2	2000
Crane 750 tones	1100	0	0
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	3	300
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**7.58 Days**	**21.2%**	**14071 KW**

5.22.4.4 Loads in the Cutting Mode of TP Removal

As it stated above, the TP need to be cut above the monopile. The TP of this wind farm has dimeter of 6.21 meters.

Table 5-30 Equipment and Loads in the Cutting Mode of TP Removal

Cutting the Transition Pieces			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	2	2000
Crane 750 tones	1100	2	2200
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	3	300
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**9.48 (Days)**	**26.5%**	**4700 KW**

Cutting of TP with diameter of 6.21 meter is assumed takes 2.5 hours. The required loads and the time of cutting is mentioned in the Table 5-30. The loads in this mode of operation is 4700 KW.

5.22.4.5 Loads in the Offloading Mode of TP Removal

After cutting of the TP, they need to be transported to the port for further recycling. The time that the TP need to be transferred from vessel to the quayside is listed in the following Table 5-31.

Table 5-31 Equipment and Loads in the Offloading Mode of TP Removal

Port Mode (Tie Up to Port) During removal of TP			
In-Service Equipment	**Nominal Power (Kw)**	**Quantity**	**Overall Power (Kw)**
Propulsion System	11571	0	0
Bow Thruster	1000	0	0
Crane 750 tones	1100	1	1100
Crane 30 tones	288	0	0
HPU for Cutting the blades	55	0	0
HPU for Grippers	100	0	0
HPU for Cutting the cable	15	0	0
Ballast Pump	688	0	0
Mooring Anchor	630	0	0
Accommodation & Bridge	200	1	200
Overall Loads	**25.59 days**	**17.40%**	**1300 kW**

5.22.4.6 Load Profile During Disassembly of Wind Turbines

Table 5-32 and Figure 5-77 depicts the load profile during extraction of 91 numbers of transition pieces of Hornsea 1 OWP. In this figure, the vertical axis depicts the consumption in kilowatt. Furthermore, the horizontal axis illustrates the various modes of operation during transition pieces removal. As it shows, the highest consumption belongs to the positioning around transition pieces which takes 7.58 days. Stand by mode is the most time-consuming mode which takes about 9.65 days. Yellow values in the chart shows the time that the vessel spends on each mode. The average loads on the genset during the course of transition piece removal is about 4460kilowatts.

Table 5-32 Summary of Load profile During TP Removal

Required Power During Transition Piece Removal			
List of Modes of Decom Tools Vessel	**Duration (Day)**	**%**	**Power (kW)**
Sailing Mode at 7.57 Knot	1.43	3.99%	5985.5
Sailing Mode at 1 Knot	1.89	5.30%	500
Stand-By Mode (anchor)	9.65	27.01%	200
Positioning Around TP (DP 100%)	7.58	21.23%	14071
Cutting the TP	9.48	26.54%	4700
Port Mode (Tie Up to Port)	5.69	15.93%	1300
Estimation of Loads In one Project	**35.71**	**100.0%**	**4459.42 KW**

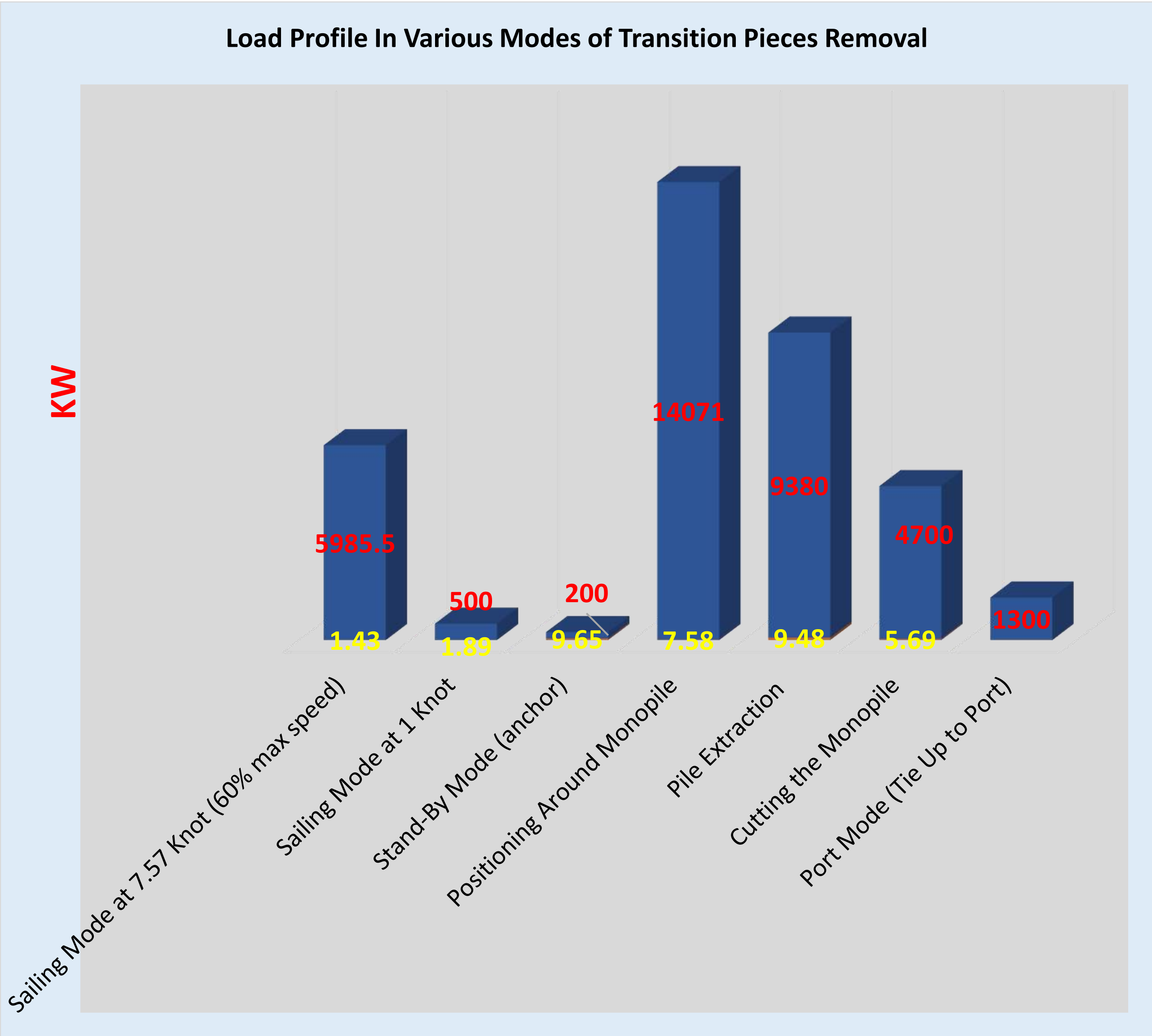


Figure 5-77 Load Profiles During Transition Piece Removal

5.22.5 Overall Load Profile During Decommissioning of an Offshore Wind Park

Table 5-33 shows the different modes of operation of the Decom Tools vessel in various modes and phases of operations. The overall time of decommissioning of this wind parks takes about 508.65 days.

The lowest portion of the project associate to the infield transit with the speed of 1 knot which constitute 1.13% of entire decommissioning.

The consumption of the vessel during operation on DP is the highest which is about 14071 kilowatts. But the vessel spend time on this mode about 3% on the entire project.

These results are achieved based on the algorithm which has been developed. The results are for decommissioning of 91 numbers of wind turbines, transition pieces and monopiles of Hornsea 1 offshore wind farm plus recovery of the infield and export cables of Anholt offshore wind farms.

According to Table 5-33 the overall time of decommissioning of above cables and structures takes about 508.65 if the same proposed method and assumptions applied.

Table 5-33 Overall Load Profile During Decommissioning of one Offshore Wind Farm

Overall Load Profile During Decommissioning of one Offshore Wind Farm			
List of Modes of Decom Tools Vessel	**Duration (Day)**	**%**	**Power (kW)**
Sailing Mode (60%max speed=7.57Kn)	9.34	1.84%	5985.5
Sailing Mode at 1 Knot	5.68	1.12%	500
Stand-By Mode (anchor)	136.47	26.83%	200
Operation Mode (DP)	15.17	2.98%	14071
Operation Mode (Position Anchor Winch)	31.43	6.18%	4949
Operation Mode (Tie up to HLV)	74.89	14.72%	1169
Cutting TP & MP	39.81	7.83%	4700
Pile Extraction, Cable Extraction/Cutting	155.44	30.56%	9547
Port Mode (Tie Up to Port)	40.43	7.95%	1300
Overall Duration and Load Profile	**508.65**	**100.00%**	

The load profile for various modes of operation is calculated precisely in order to select the right engines and size the batteries properly.

Figure 5-78 shows that the lowest demand of power is when the vessel is in the stand-by position. Also, the highest demand of power is when the vessel is on the DP mode for positioning around TP and MP. The blue value above the bar of the Figure 5-78 shows the duration that vessel needs those specific loads.

The engine consumption and emissions also strongly depend on the engine loads. Specific emissions are normally higher at low engine loads. This is particularly evident for unburned methane (CH_4) emissions. CH_4 is a very strong greenhouse gas (GHG) (at least 25 times more potent than CO_2). Moreover, a diesel engine (using either heavy fuel oil or low sulphur diesel) is expected to have significant particulate matter (PM) emissions, especially at low loads. The battery system is used to reduce emissions by allowing the engines to run at optimized loads with respect to emissions.

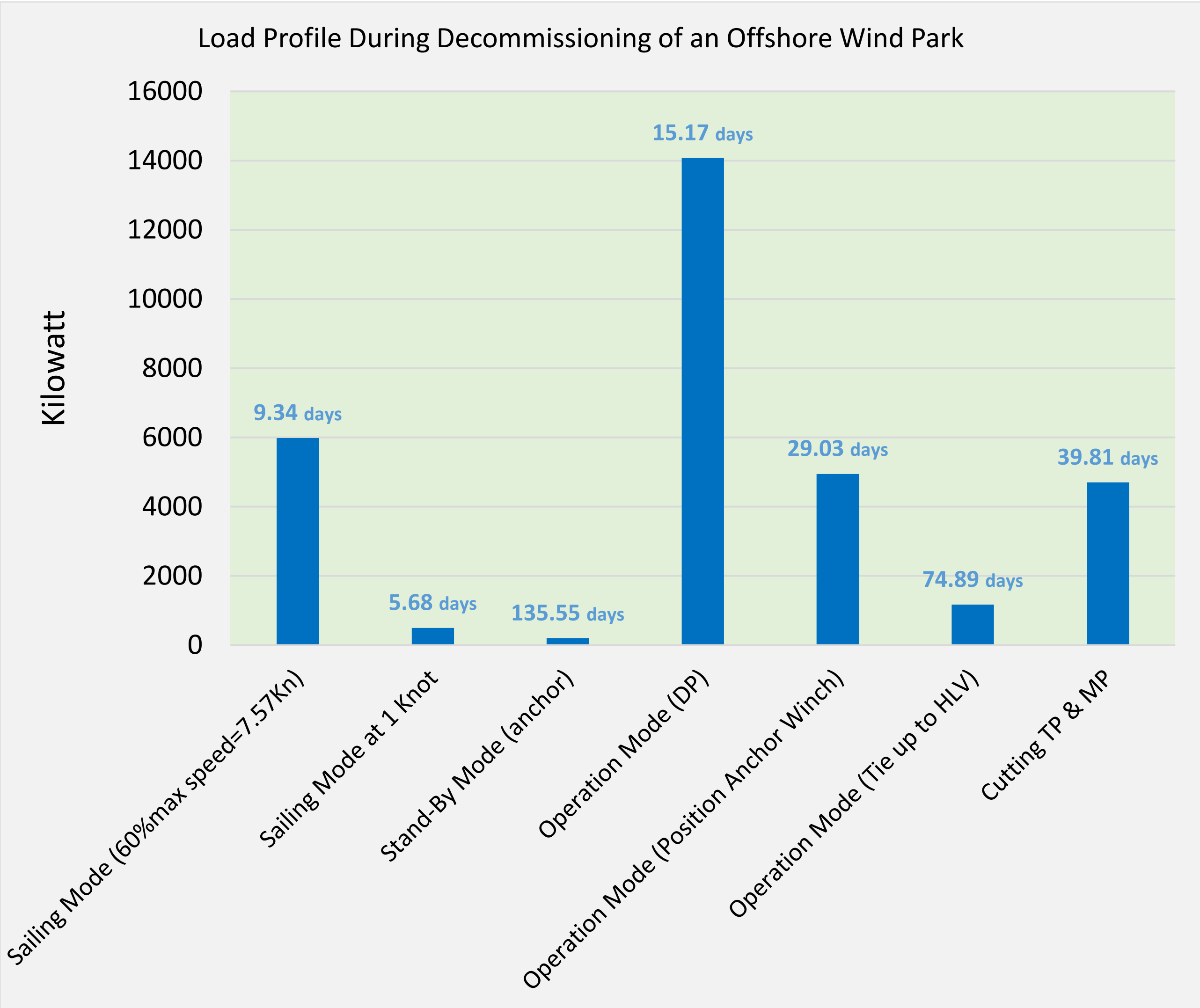


Figure 5-78 Load Profile During Decommissioning of an Offshore Wind Park

All in all, the above proves that selection of right engine can have significant impact on the efficiency of the vessel and the emission. Not only does the engine selection have profound impact, but also the right battery sizing can improve the efficiency of the vessel and reduce the emission considerably.

5.23 Engine Selection

After calculation of the required power for propulsion system and calculation of load profile of the Decom Tools vessel for various modes of operation engines can be selected. In selection of engine a couple of factors are considered as following:

- The emission should fulfil the latest emission regulation which set by IMO.
- The power should be sufficient based on the defined criteria and calculated resistance at full load condition.
- Given the fact that the electrical propulsion system is selected for this vessel, then the vessel should have a couple of engines equipped with generator sets to produce the electricity in order to be distributed to the loads. Obviously, one of the most important loads of the vessel is propellers and propulsion system.
- Having considered that the vessel equipped with batteries, shaft generator is required to charge the batteries when full loads are not exerted to the engines for example during in-field transit when the vessel has to sail with one knot (1 Kn) speed or in stand-by mode etc.
- In the feeder configuration, when the construction vessel is jack up vessel, the Decom Tools vessel cannot tie up to the jack up. It has to keep the position either via mooring system (dropping anchors to the seabed) or via DP. DP system is providing more flexibility and manoeuvrability to the Decom Tools Vessel (DP2 suffice the demand of a cargo vessel). In the case of DP, the vessel has to have reliability[53] and redundancy. Many research including Failure Mode Effects Analysis (FEMS)[54] has been conducted for the redundancy and reliability of DP vessels. To fulfil the redundancy and reliability level, 4 numbers of engines are considered for the Decom Tools Vessel. All are located in one room since class 2 DP rules allow all generators to be located in a single space (Germanischer Lloyd SE 2013).
- The engines should suffice the lowest demand of load, such as stand-by mode and suffice highest amount of load such as sailing mode.
- The engine should be dual fuelled powered, both LNG and MGO.

[53] The ability of a component or system to perform its required function without failure during a specified period of time. (Germanischer Lloyd SE 2013)

[54] A failure mode and effect analysis (FMEA) concerning availability of the DP system after a single failure shall be provided for the class notations DP 2 and DP 3 for the desired DP 2 or DP 3 power plant configuration. (Germanischer Lloyd SE 2013)

Having considered above, the engines are selected based on consultation with Wärtsilä specialist. After holding a couple of meetings and hours of discussion with the Wärtsilä specialist, the following engines are selected for this vessel.

I. 2 numbers of Wärtsilä 12V34DF
II. 2 numbers of Wärtsilä 6L34DF

These Wärtsilä engines are designed for continuous operation on fuel gas (natural gas) or Marine Diesel Fuel (MDF). It is also possible to operate the engine on Heavy Fuel Oil (HFO). However, our aim is to run the engine just on LNG and MDF. The 12V34DF engine has maximum output of 6000 kW at frequency of 50 hertz and at rpm of 750. Nevertheless, the output of generator in the frequency of 50 hertz and rpm of 750 is 5770 kW. This 230kW reduction is due to dissipation of energy during conversion from mechanical energy to electrical energy (Generator output based on a generator efficiency of 96%.).

The 6V34DF engine has maximum output of 3000 kW at frequency of 50 hertz and at rpm of 750. Nevertheless, the output of generator in the frequency of 50 hertz and rpm of 750 is 2890kW.

In overall, the maximum output of the electricity will be 17320 kW.

From an emission perspective, the Wärtsilä 34DF engines are Tier 2 compliant in diesel mode and Tier 3 compliant in gas mode. The engine operates efficiently and economically on low sulphur fuels (< 0.1 S) making it suitable for operation in emission-controlled areas (ECA) (Wärtsilä 2020).

Table 5-34 shows the maximum output of engines and generators.

In any modes of operation, the engines can be set to work on optimum load (between 80-90% depending on manufacturer specification), then the extra generated electricity can be saved in the batteries for other consumers. It should be noted that all loads will not be in the circuit at the same time as explained in the load profile tables. So, in this situation, the extra produced energy can charge the batteries. Thus, the battery can feed the accommodation and some of the machineries such as pumps, water maker, fuel purifier, fuel pumps, lighting etc.

The specification of the selected engine is extracted from the website of manufacturer. The normal frequency onboard the vessels is 50 hertz, however, many of the equipment can work either with 50 or 60 hertz. But in this document, the frequency of 50 hertz is selected.

Size of engines are shown in the Figure 5-79 and Figure 5-80. The size of engines and genset are important because the suitable engine room(s) need to be considered for the vessel. Figure 5-79 and Figure 5-80 shows the dimension of 12V34DF engine. For the other engines, please refer to the website of Wärtsilä.

This engine has maximum continuous output as following (Table 5-34):

Table 5-34 Maximum Continuous Output of Wärtsila Engines (Wärtsilä 2021)

Engine Model	Quantity	Generating Set @ 720 RPM		Generating Set @ 750 RPM	
		60 Hertz		50 Hertz	
		Engine (KW)	Generator (KW)	Engine (KW)	Generator(KW)
Wärtsilä 6L34DF	2	2880	2770	3000	2890
Wärtsilä 12V34DF	2	5760	5530	6000	5770
Overall Production of Electricity@ 750 RPM /50 HZ				**18000 kW**	**17320kW**

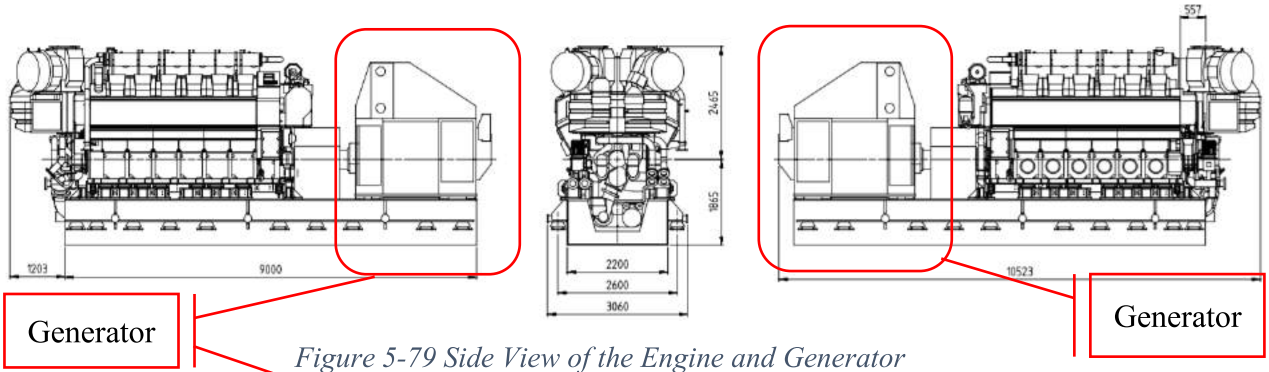


Figure 5-79 Side View of the Engine and Generator

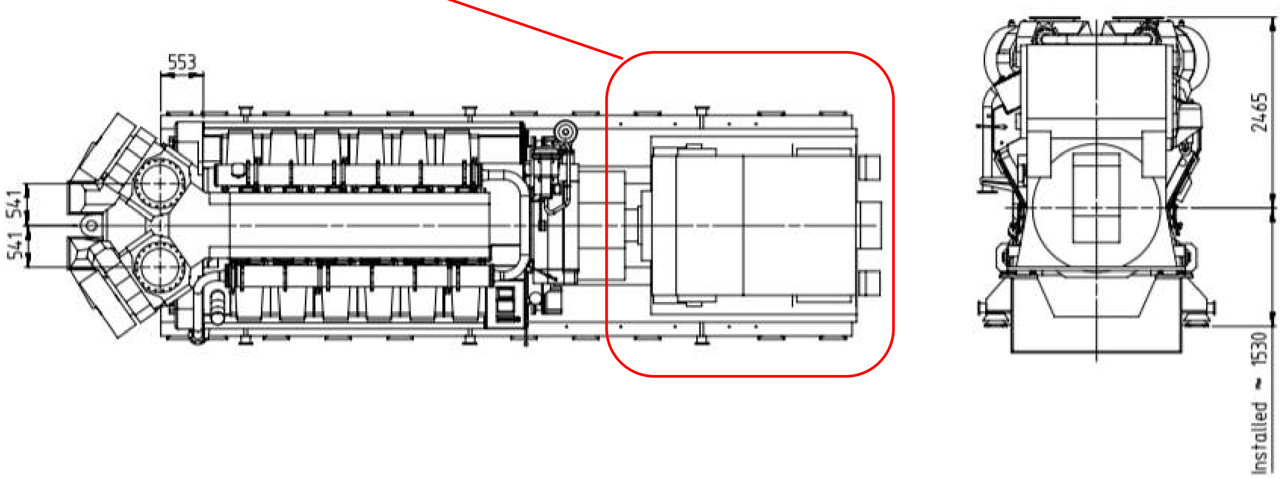


Figure 5-80 Plan of The Engine and Generator

Table 5-35 shows the weight of engines, the support structures plus the required oil. The weight of engines is crucial since it impacts the overall stability of the vessel. So, this weight is considered during stability analysis. Furthermore, the size of engines identifies how big the engine room should be. The weight of engines' components also impacts the installation of hoist and overhead cranes inside the engine rooms.

Table 5-35 Components and Weight of Wärtsilä 12V34DF Engine and Generator (Wärtsilä n.d.)

Weigh of all Engines and Generators of Decom Tools Vessel				
Sr.	**Components of Genset**	**Weight (KG)**	**Weight (KG)**	**Remark**
		12V34DF	**6L34DF**	
1	Engine with Liquid	62100	35400	
2	Common base frame	22600	18300	
3	Alternator ABB	22000	13000	
4	Coupling and Flywheel	6400	5000	
Total Weight of Engines & Genset		**113100 kg**	**71700 kg**	**369600 kg = 369tons** (total weight of engines)

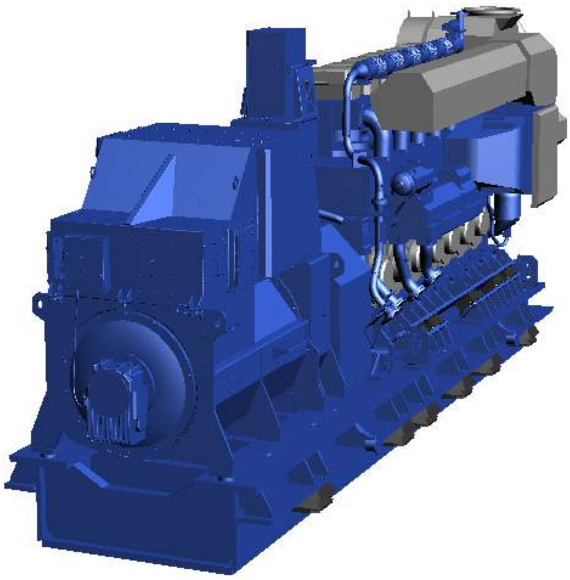


Figure 5-81 Perspective View of Wärtsilä 6L34DF

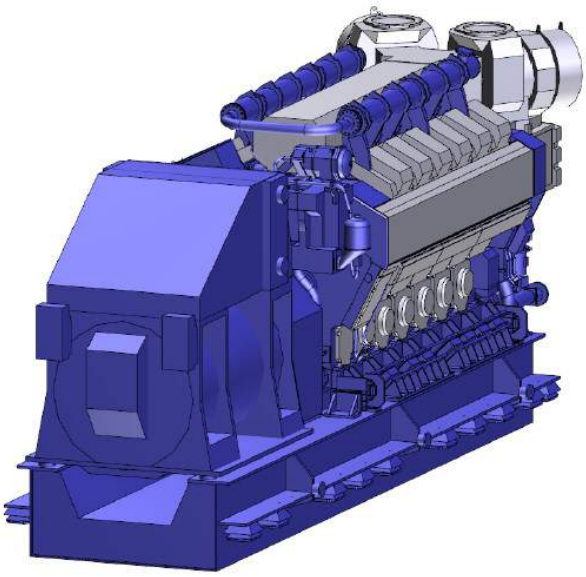


Figure 5-82 Perspective View of Wärtsilä 12L34DF

Table 5-36 shows the duration, consumption and emission of the Decom Tools vessel during decommissioning of 91 turbines of Hornsea 1 wind farm and all cables of Anholt wind farm.

It is calculated entire removal of all the turbines, foundations and cables take 508.65 days. The duration calculation has been carried out under chapter 3, section Time-Cost-Consumption-Emission Comparison of Various Logistic Configurations for Decommissioning of Hornsea 1 OWP.

Also the time calculation for removal of TPs, MPs and cables can be found in the chapter 6, sections Time-Cost Analysis of Transition Piece Removal with Decom Tools Vessel, Time-Cost Analysis of Pile Extraction with Decom Tools Vessel and Time-Cost-Consumption-Emission Analysis of Case Study for Cable Retrieval .

Table 5-36 shows the fuel consumption and emission of the Decom Tools vessel with considering the impact of Flettner rotors, the batteries and solar system for decommissioning of 91 numbers of wind turbines, transition pieces and monopiles of Hornsea 1 wind farm and infield and export cables of Anholt wind farm.

As you can see the above table, the required load on engines in different modes of operation are identified. Then the LNG and MGO consumption for each mode of operations are calculated. Finally, according to the Table 4-4 the emission is calculated.

It should be noted in this calculation, it is assumed that the Decom Tools vessel maintain its position during disassembly of wind turbines by fastening itself to the heavy lift vessel. During recovery of export cable, it maintains the position via position anchor winches. During removal of inter array cables, transition pieces and monopiles, the position maintained by the DP system

Table 5-36 Fuel Consumption and Emission for Decommissioning of Hornsea 1

List of Modes of Decom Tools Vessel	Duration (Day)	Power (kW)	LNG Consumption (T)	MGO Consumption (T)	Emission (T)
Sailing Mode (60%max speed=7.57Kn)	9.34	5985	23.8982	0.42852	67.09388512
Sailing Mode at 1 Knot	5.68	500	2.1951	0.098579	6.352569274
Stand-By Mode (anchor)	136.47	200	1.167289	0.082145	3.47340162
Operation Mode (DP)	15.17	14071	54.9199	0.788028	153.5561428
Operation Mode (Position Anchor Winch)	31.43	3059	13.4298	0.286322	37.84989833
Operation Mode (Tie up to HLV)	74.89	1169	5.1322	0.10941	14.46431846
Cutting TP & MP	39.81	4700	18.0448	0.258688	50.45255373
Pile Extraction, Cable Extraction/Cutting	155.44	9547	36.41818	0.517293	101.8084364
Port Mode (Tie Up to Port)	40.43	1300	5.698557	0.147466	16.14380775
Overall Duration, Consumption & Emission	**508.650**	**4503.444**	**8643.916**	**141.585**	**24224.689**

5.24 Batteries and Batteries Sizing

For ship types that experience large load variations during operation such as Decom Tools Vessel, the introduction of batteries may allow the engines to operate optimally with respect to fuel oil consumption and/or emissions. This can be achieved by selecting engine sizes that operate at optimal loads for most of the time, with additional power obtained from the batteries when required. When power requirements are low, the batteries can be charged using the excess energy generated by running the engine at the optimal load.

Under conceptual design phase of this study, seven numbers of batteries are engineered for this vessel. Each propeller needs one separate battery in order to increase the system reliability and avoid using one big battery onboard ship (three batteries for VSP and 2 batteries for bow thrusters). In addition, a battery is needed for major machineries likes crane and the other one just for accommodation. These seven batteries will be located in two different battery rooms. The battery sizing and relevant analysis will be attached as an appendix to this document in due course.

5.25 Battery Rooms, Engine Rooms, Winch Room and Propulsion Room

In the design of battery room, some consideration should be considered. For example, ventilation should be considered a measure to limit the formation of potentially explosive atmospheres in the battery space in the event of a serious fault condition (DNV.GL 2016). In addition, the class rules states that the battery space cannot be placed forward of the forward collision bulkhead (DNV.GL 2016). There are some other measures which need to be considered in the design of the battery rooms which are out of scope of this research. As it stated before, 7 batteries will be installed in two battery rooms onboard Decom Tools vessel. One of the battery rooms is below the accommodation, on top of the engine room. The other battery room is above propulsion room on the aft of the vessel to feed the VSPs.

Engine room is located on the forward of the vessel below the accommodation. Also, the MGO and LNG tanks need to be in vicinity of the engine rooms. Figure 5-83 and Figure 5-84 show the location of propulsion room, battery rooms, LNG tank and control room (CR).

CR room in the following figure in the aft of the vessel shows the control room for the running of the blade seafastening. Having considered that seafastening of blade as well as cutting mechanism need operator, a room for the operator in the aft of the vessel is devised in order to have a view to both sections of hold number 2. In addition, during cutting of the blades, dust is produced which compel the operator to wear special PPE. By designing this control room, the operators are not expose to the space (hold) that cutting are conducted.

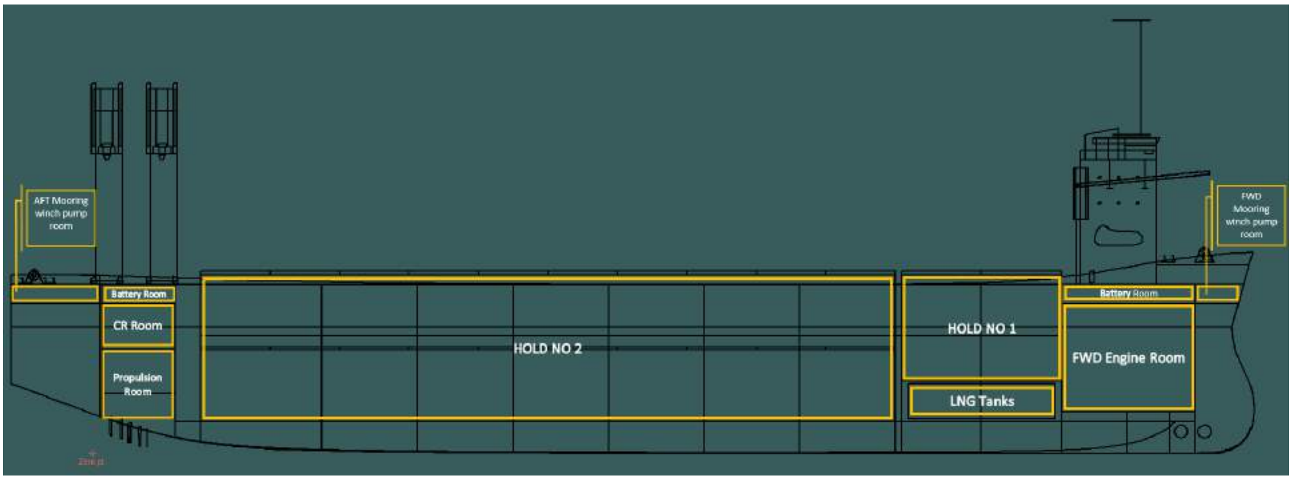


Figure 5-83 Engine room, Propulsion Room and Battery Room

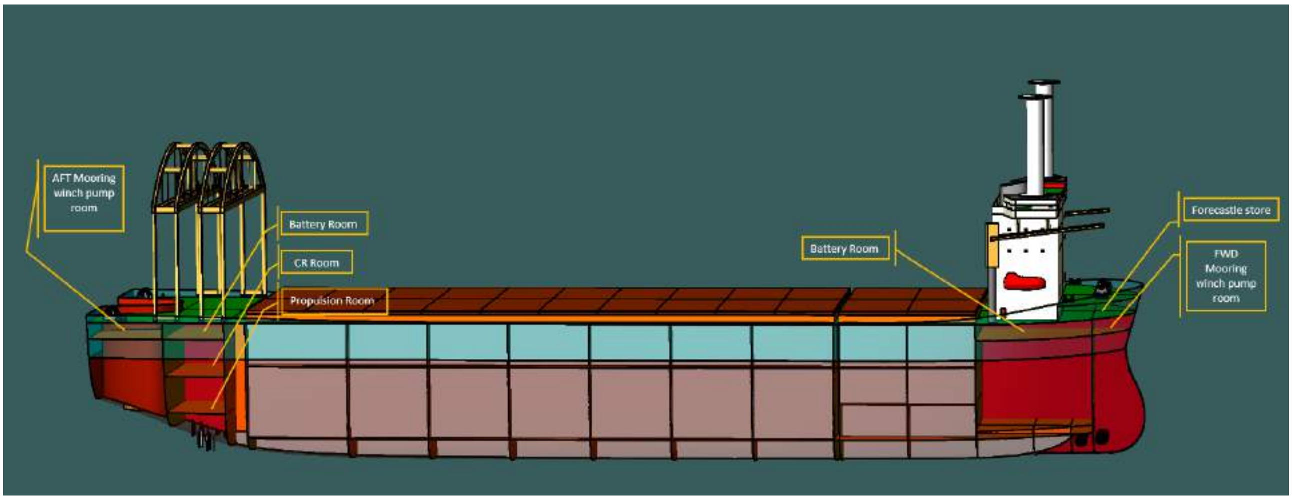


Figure 5-84 Engine room, Propulsion Room and Battery Room

In addition, every mooring winch need a hydraulic pumps and reel. Having considered that two mooring winches are devised at the aft of this vessel, the room for above-mentioned equipment is also considered in the aft.

5.26 Life-Saving Appliances (LSA)

Two lifeboats have been designed for this vessel in the forward portside and starboard side. Each of the lifeboat has a capacity of 100 person. The maximum personnel onboard (POB) of this vessel are 90 persons which in this design lifeboat for 200 persons are considered. In some special cases like mobilization or sea trial of the vessel (or in case of short-term visitors), more personnel than maximum POB get onboard the vessel. In this case, the shortage of LSA impede joining of necessary personnel. By overdesigning of lifeboat from 90 to 100 person we can ascertain that from a safety perspective, 100 personnel can be joined for a short period of time. The following figure shows the lifeboats of the Decom Tools vessel.

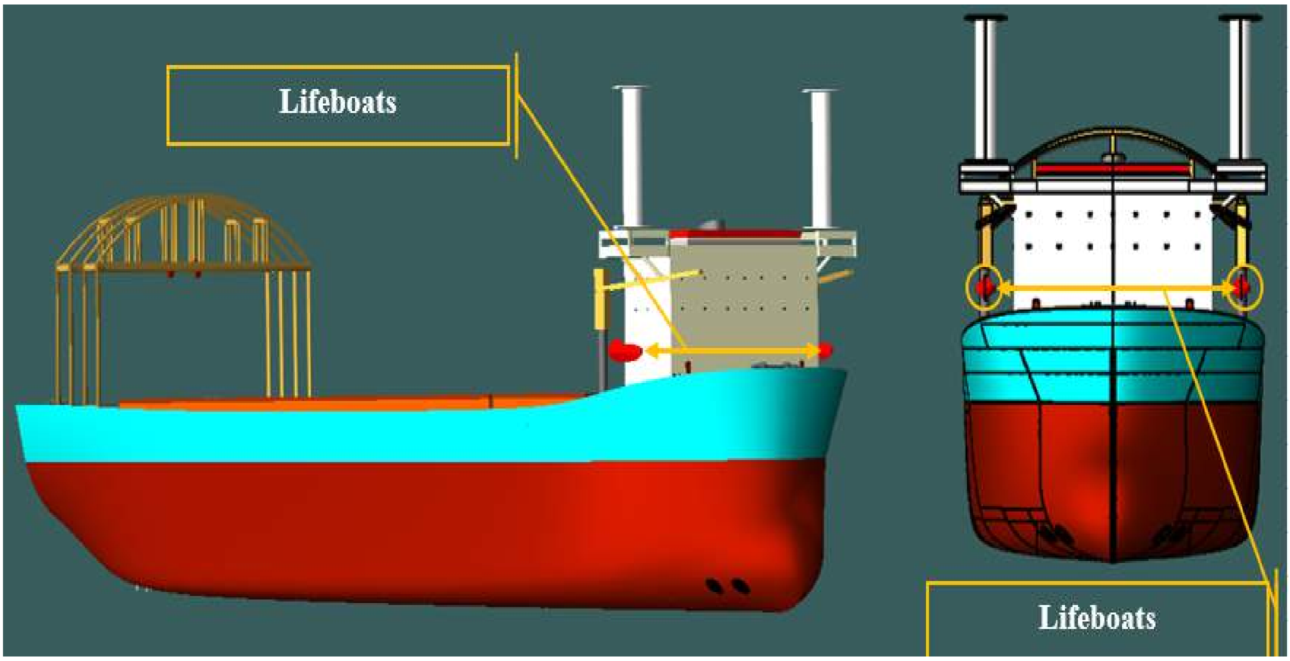


Figure 5-85 Perspective and Front (Bow) View of Lifeboats

5.27 Pile Extraction and Marine Growth Removal System

One of the functions of the Decom Tools vessel is pile extraction. In the next chapter, it is proved that pile extraction is possible by exploiting the potential of the floating vessel. The detail of pile extraction procedure is explained in the next chapter.

Moreover, the vessel is equipped with an automatic marine growth removal system. Again, the procedure how to remove the marine growth and fouling of the monopile and transition pieces are described in the next chapter. It should be noted that in this drawing the marine growth removal system and hydraulic pile grippers are designed for the pile with 10 meters diameter. Figure 5-87 shows the dimension of the pile grippes, the arrangement of the gripper and marine growth removal system.

However, the entire removal of marine growth cannot be achieved by using automatic marine growth removal system, but considerable area can be removed which pave the way for the entire removal on the deck. Therefore, manual removal of marine growth onboard the vessel deck is proposed.

All of the following drawings just demonstrate conceptual design. It means that the exact size, thickness, material, hydraulic power system and in general specification of these two devices are not designed.

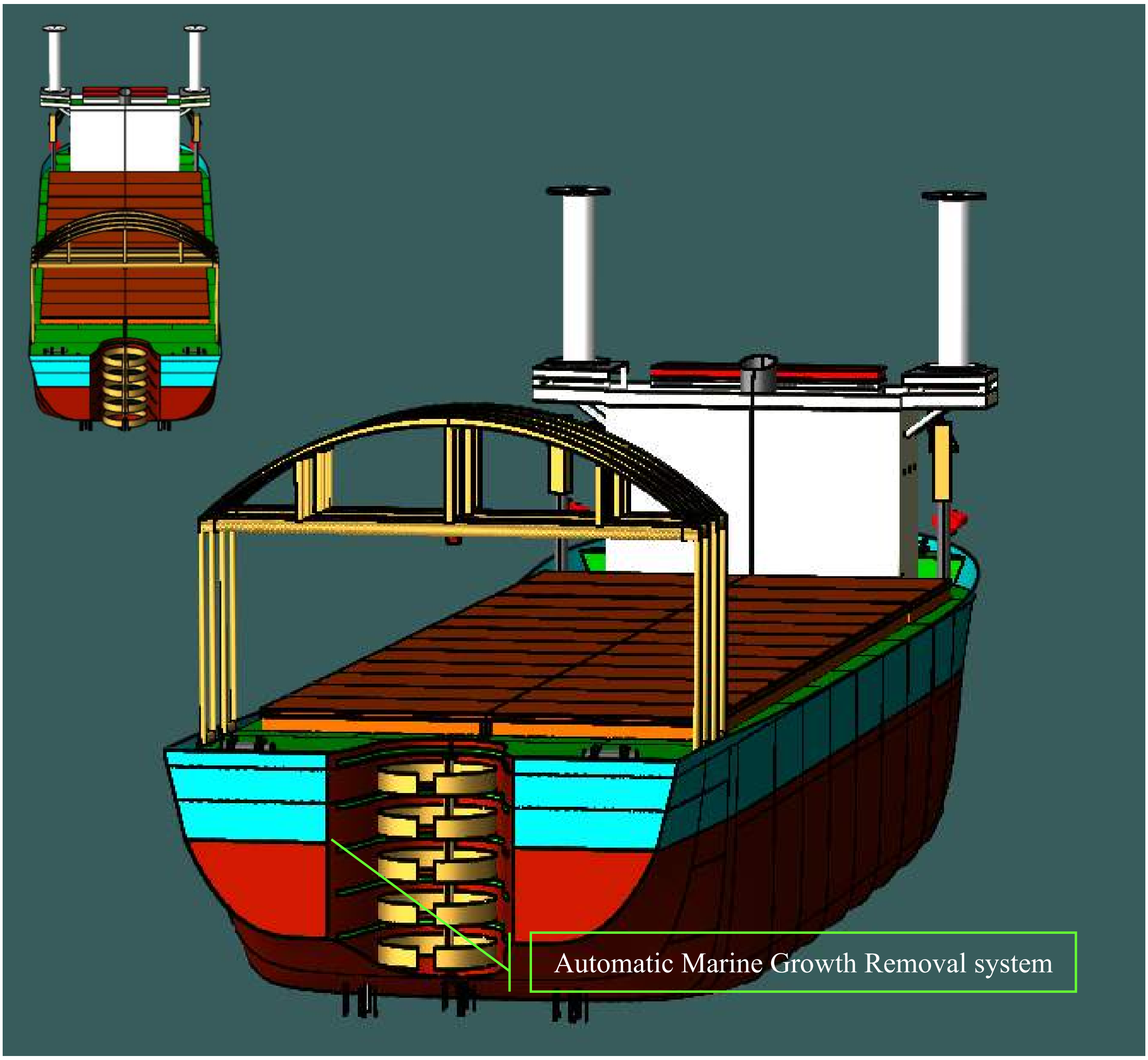


Figure 5-86 Perspective and Back View of Decom Tools Vessel

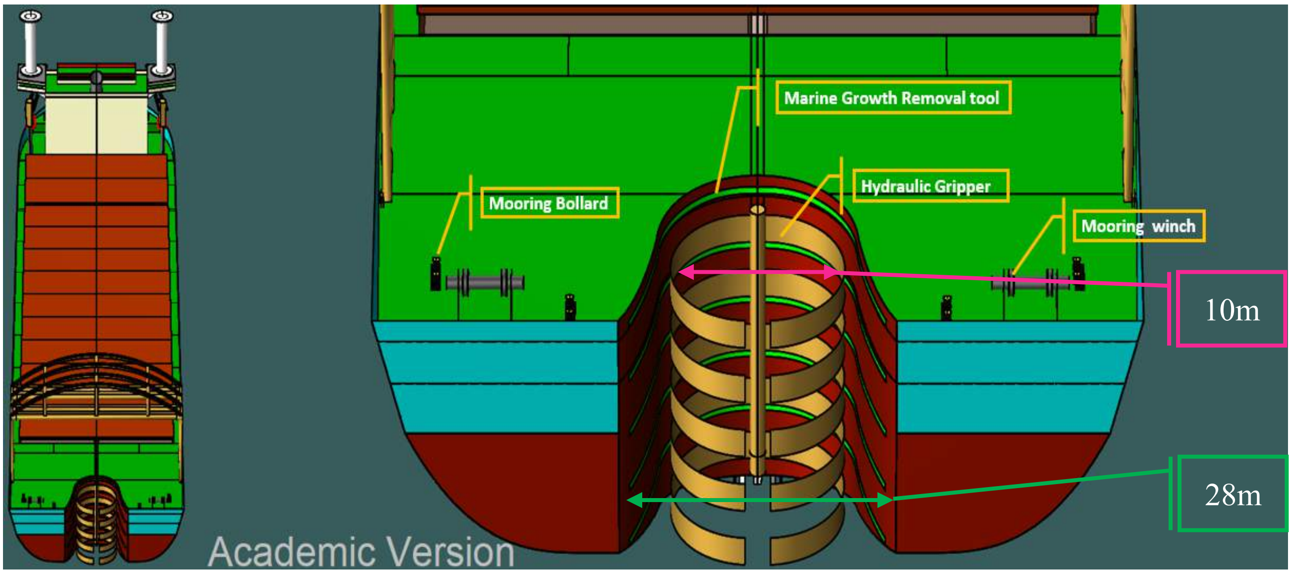


Figure 5-87 Details of Stern of the Decom Tools Vessel (Pile Gripper and MGR System)

5.28 Equipment on the Bow of the Vessel

Some of the equipment which are designed in the forward (bow) of the vessel are shown in the following figures. It includes mooring winches, bollards, the accommodation door.

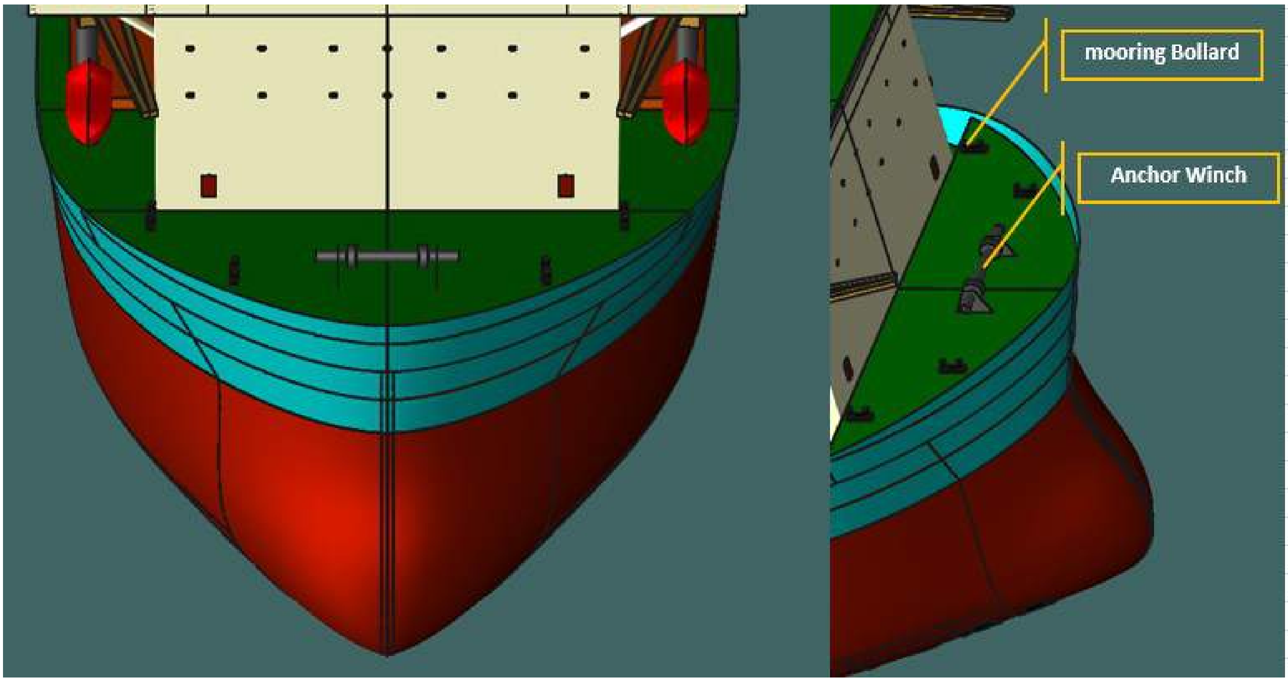


Figure 5-88 Details of Bow of the Decom Tools Vessel

In addition to above-mentioned items, the lifeboats, bridge, bridge equipment such as radar, VSAT, telecommunication instruments, barometer, anemometer, GPS and DGPS antenna, the HVAC of the accommodation, the funnel of engine rooms and so forth are located in the forward of the vessel on the top of the accommodation or on the monkey island.

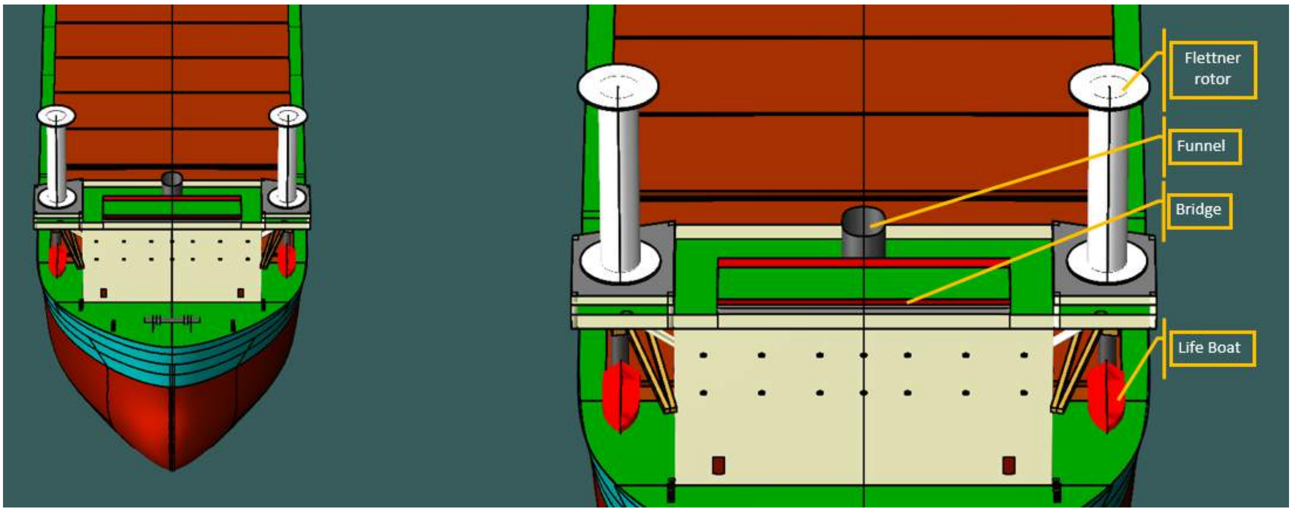


Figure 5-89 Details of Bow of the Decom Tools Vessel

The aim of this document is not illustration of this instruments since they are common equipment onboard vast majorities of the vessels. However, some of the equipment are needed for the DP vessel such as DGPS. The following figure shows some of mentioned equipment in the bow and accommodation of the vessel.

5.29 Hatch Cover and Hatch Cover Opening

As it stated before, the holds have hatch covers. The hatch covers are located on the top of holds. Besides, to segregate the height inside the holds number 2 and to place more cargos, the panels are designed to be placed inside the hold number 2 as tween deck.

The overall height of hatch cover plus hatch coaming is 2.1 meter. Figure 5-91 shows that the height of hatch coaming is 1.5 meter. Therefore, the hatch cover has heigh of 60 cm. The hatch cover from a structural perspective is not designed since it is not in the scope of this research. But it should withstand at least 16 tonnes per square meter.

In order to lift the hatch covers, we proposed a four-point adjustable lifting beam (Figure 5-93). This tool is widely used onboard the cargo vessel across the world. Evidently, for the lifting of the hatch covers, this lifting beam should be rigged to the gantry cranes according to the following figures.

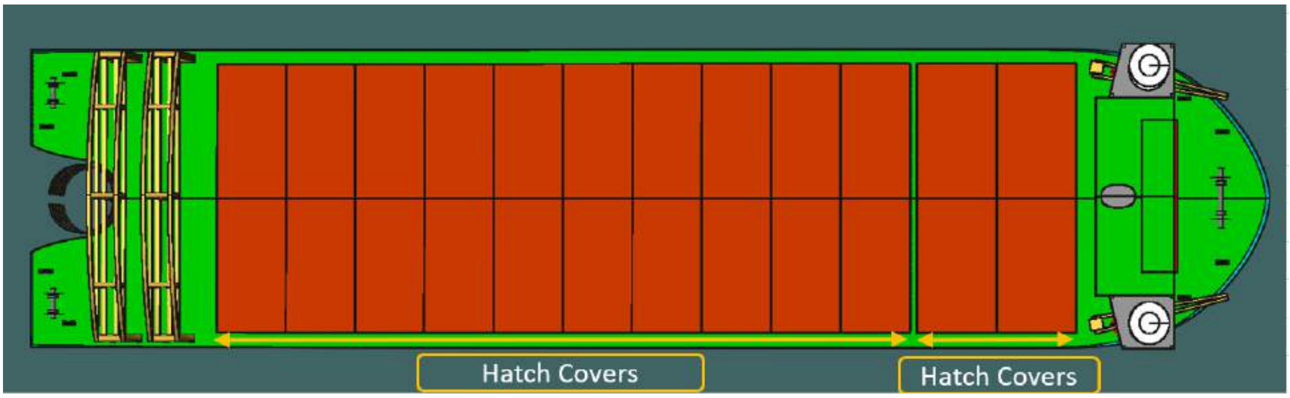


Figure 5-90 Top View of The Decom Tools Vessel

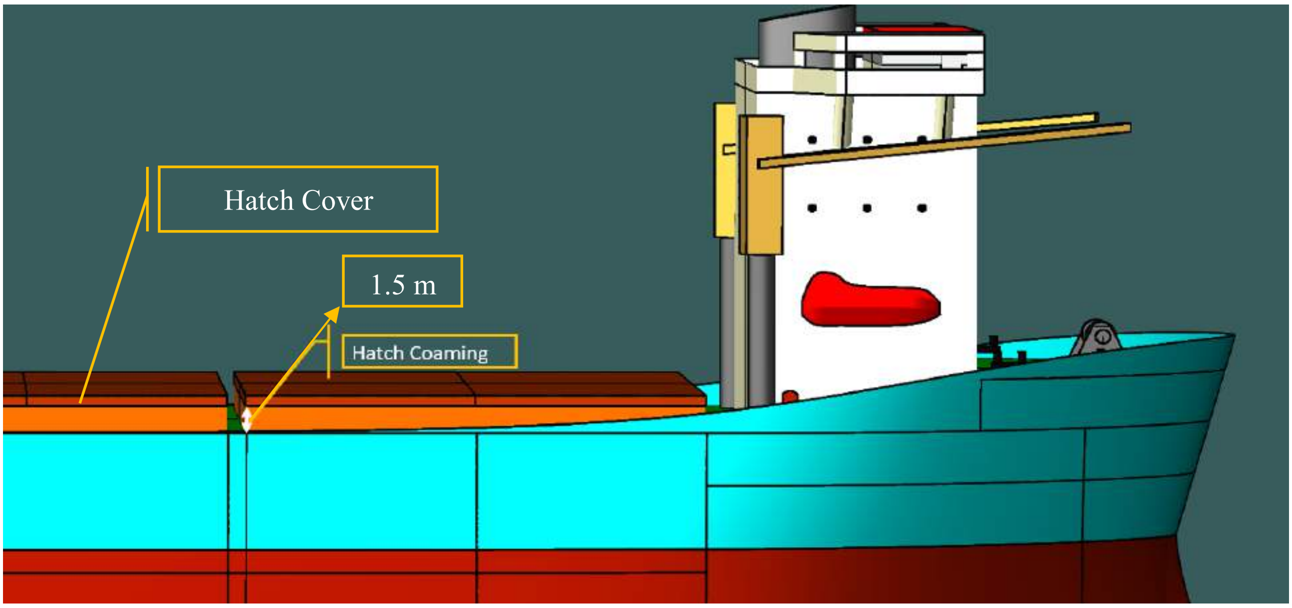


Figure 5-91 Hatch Coaming

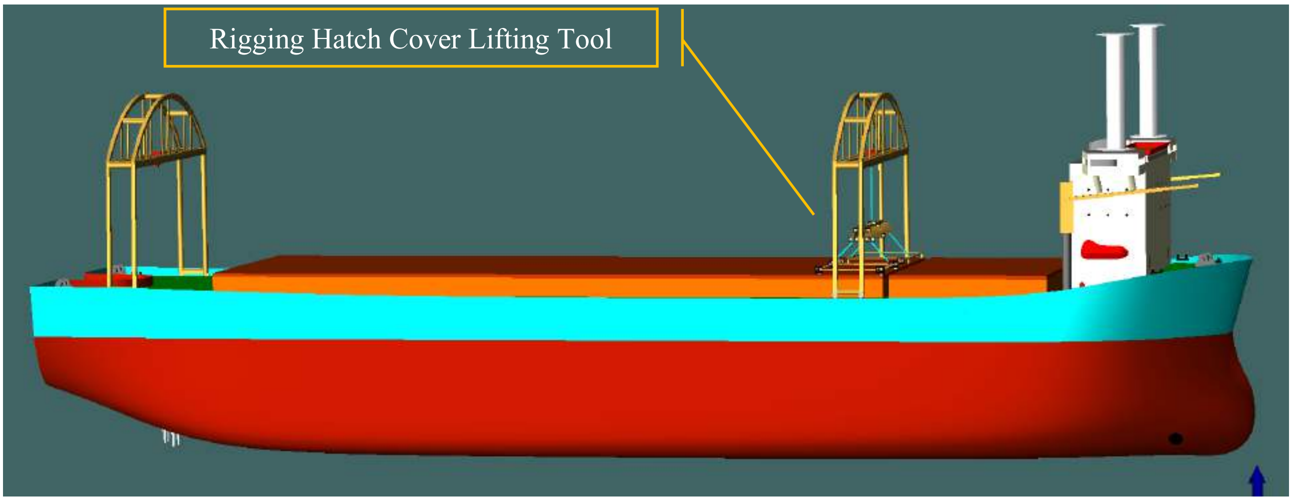


Figure 5-92 Procedure to open the Hatch Cover-Step 1 Rigging Lifting Tool

In order to lift the hatch covers, Figure 5-93 shows the suitable tool which is four-point adjustable lifting beam.

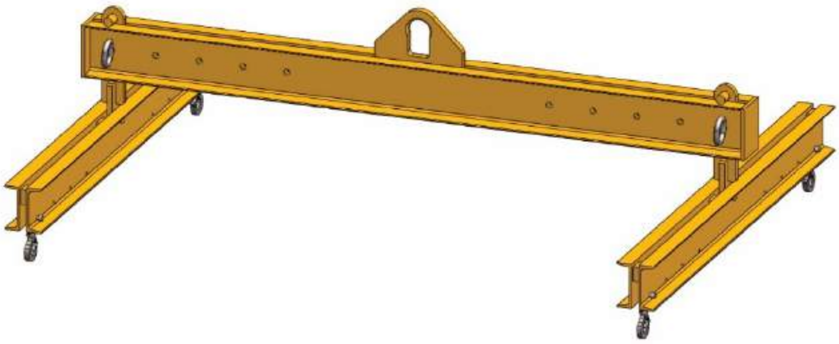


Figure 5-93 Hatch Cover Lifting Tool (TRI-STATE RIGGING EQUIPMENT n.d.)

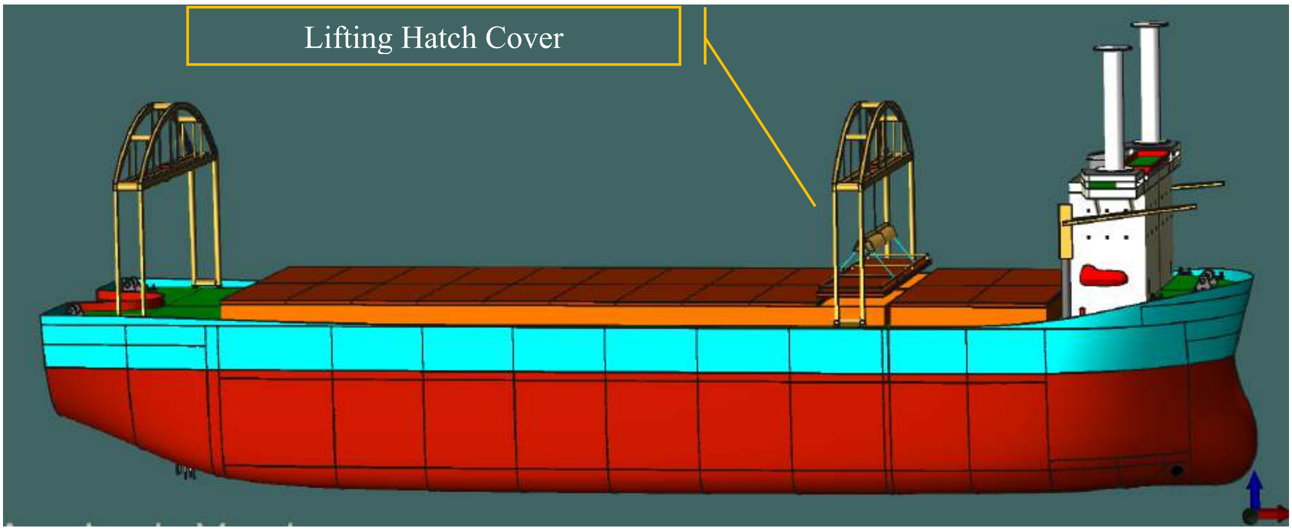


Figure 5-94 Procedure to open the Hatch Cover-Step 2 Lifting Hatch Cover

Figure 5-95, Figure 5-96 and Figure 5-97 shows the procedure of opening hatch covers. Also, it shows where the hatch covers need to be marshalled.

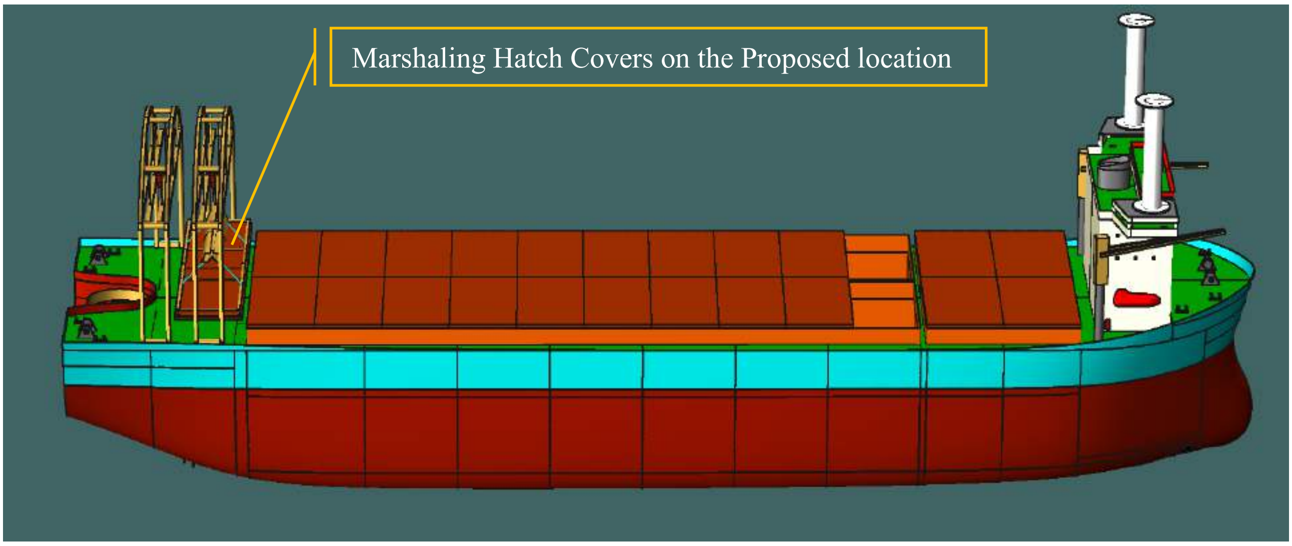


Figure 5-95 Procedure to open the Hatch Cover-Step 3 Placing Hatch Cover on the Proposed Location

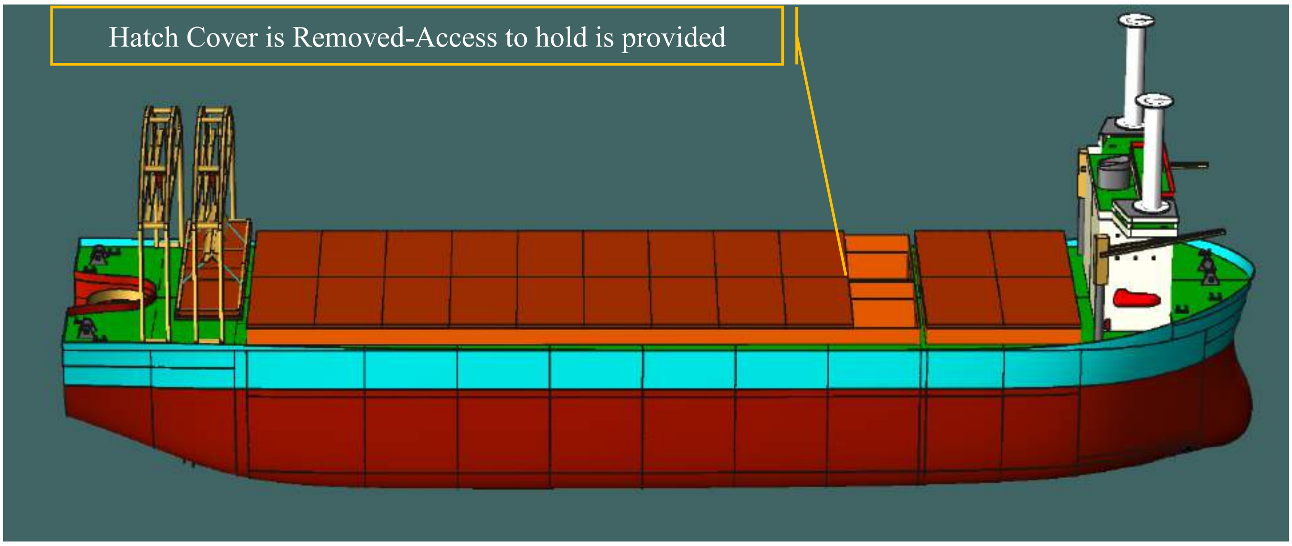


Figure 5-96 Procedure to open the Hatch Cover-Step 4 Access Provided to the Hold

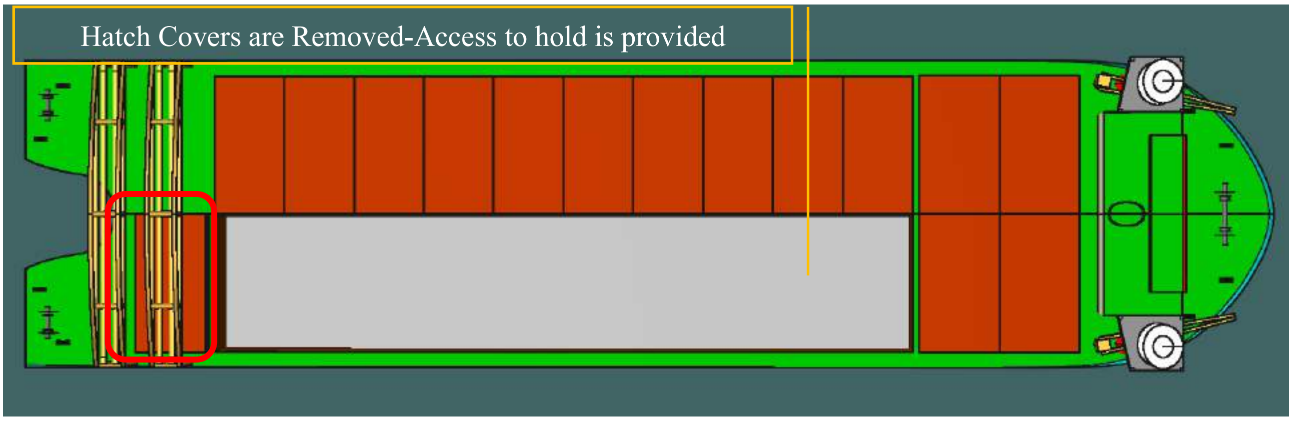


Figure 5-97 Procedure to open the Hatch Cover-Step 5 Access Provided to the Hold Entirely

Figure 5-97 shows the location where the hatch covers can be stored and marshalled.

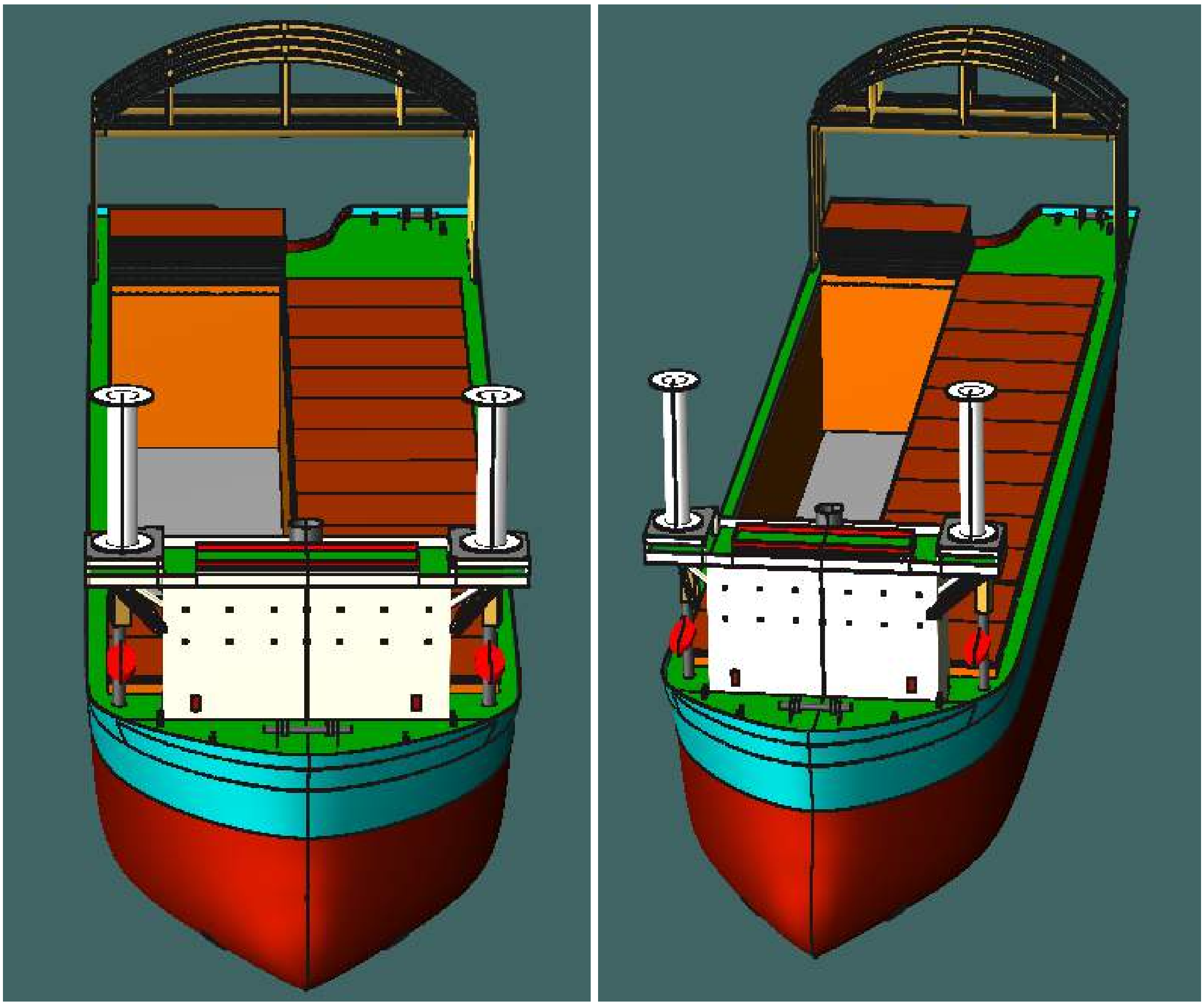


Figure 5-98 Bird's-eye view of the Vessel after Opening the Hatch covers

6 Offshore Operation Manual of Decom Tools Vessel

6.1 Crucial Factors in Disassembly of Offshore Wind Parks

In order to reduce the cost of decommissioning and mitigate the CO_2 emission resulting from decommissioning, a couple of measures can be taken to reach the Decom Tools targets. One of them is optimization of the marine operations. Marine operations consist of disassembly and lifting as well as transportation of components from offshore wind park to the port or decommissioning yard. The optimization of disassembly and lifting operation can be accomplished by following actions:

6.2 Project and Operation Management

In general, management and engineering of the project affect the duration, cost and CO_2 emission of operation. Some of the conspicuous decision that can be made by management team are as below:

- Proper planning such as execution of offshore operation in summer when the weather is more workable[55].
- Preparing the site before mobilization of construction vessel or other expensive fleet. This stage is called pre-decommissioning phase in that all the preparatory activities need to be done prior to mobilization of construction vessel and disassembly operations. In the Decom Tools document by the name of "Pre-Decommissioning Marine Operations of Offshore Wind Parks" with document number of "DECOMTOOLS-WP4-PDOWP-EDP-A3-001" all the actions which need to be carried out in this phase of project has been studied and identified. This document can be found in the appendix 1.

6.3 Optimizing Engineering

Having considered that offshore operations consist of several steps, therefore, comprehensive and detailed study need to be done in order to have optimum result. Apart from pre-decommissioning and post-decommissioning operations, there are two different stages namely disassembly and removal as well as transportation. Transportation here is just transportation from offshore wind farm to port/decommissioning yard and it does not include offloading from ship to quayside and further onshore or inland transportation. These two stages can be described as following:

6.4 Disassembly and Removal Methods

National and international regulation as well as availability of technology outline how to decommission a foundation. Some part of a foundation and cables can be kept in-situ under some

[55] In general, reducing the duration of offshore operation will minimize considerably the cost of project, the CO_2 emissions and improve the safety operation as well. However, it is not easy to book the vessel for summer. The vessels are booked 2-3 years in advance.

certain circumstances and whatsoever above seabed shall be decommissioned. Based on IMO resolution A.672(16), the default condition for decommissioning of disused or abandoned offshore structure is entire removal. However, under some certain circumstances, the developers can keep some parts of structure in situ which will have weighty responsibility for them until their existence or removal. Having considered this significant, authors consider in this research the entire removal as basis to design the ship.

There exist several methods and techniques to disassemble and remove a set of offshore wind turbine. Different designs, cost analysis and environmental impact caused by decommissioning should be studied for the various techniques of disassembly and removal of OWF in order to find the most optimum methods in term of cost, CO_2 emission and environmental impact. Conduction of such research is out of scope of this study, but very briefly the various removal methods is skimmed since they impact the offshore transportation enormously.

Regardless of addressing how to remove a set of OWT, the removal of a full set of OWT can be done in 1-piece[56], 2-pieces, 3-pieces, … and n-pieces. Obviously, foundation types, the height and weight of WT, the penetration of foundation[57] into the seabed and so forth influence how the disassembly should undertake. Each of methods comes with a plethora of advantages and disadvantages. For example, 2-piece removal of a wind turbine, means to remove a set of wind turbine in 2 campaigns. The first campaign is removal of rotor, nacelle along with tower. And the second campaign includes extraction of foundation along with transition piece. For this method of disassembly and removal, advantages and disadvantages are mentioned in the Table 6-1.

Generally, the basis of decommissioning, in particular, the Decom Tools project is to remove the component exactly reverse to the installation sequences. Referring to this fact, the baseline for disassembly and removal of an OWT is to remove the blades one by one, then remove the nacelle and finally to remove the tower. After conduction of this stage, transition piece and foundation need to be removed one by one respectively. This is a 7-piece removal of offshore wind turbine (OWT) which is reverse of installation of many wind farms across the world. The pros and cons of 7-piece removal are mentioned in the Table 6-2.

These two tables just show the advantage and disadvantage of these two methods. In order to see how cost-effective and CO_2-effective they are, analysis with different vessel need to be done which is out of scope of this work.

[56] 1-piece removal is possible when the foundation is floating, or gravity based. For other types of foundation, 1-piece removal is unfeasible currently.

[57] It should be noted that type of foundation has profound impact on the method of disassembly and removal. Having considered that about 82% of foundations are monopile, the basis of design to design this ship is a wind farm with monopile foundations.

Table 6-1 Advantage and Disadvantages of 2-Piece Removal of OWT

Advantage of 2-Piece Removal	Disadvantage of 2-Piece Removal
The duration of offshore operation takes less time since there is no need for many cuttings or disassembly.	Vessel with a large lifting capacity and large boom length is needed.
Less offshore duration may lead to less fuel consumption as well less CO_2 emission (not always).	Large vessel normally has higher fuel consumption
Less hinderance for other sea users, because the operation takes less time.	Large vessel normally has high CO_2 emission
Less manpower and other resources are needed.	Charter rate of big vessel is high.
Less offshore operation leads to facing with less weather down time which means more productive operation.	Transportation of this wind turbine is difficult and need more stable vessel for transportation.
	No wind Turbine is installed or decommissioned with this method so far. Therefore, all aspect should be considered.
	The lifting and transportation of large and heftier object is more dangerous than light weight and small objects.
	Just possible for monopile foundation

Table 6-2 Advantage and Disadvantages of 7-Piece Removal of OWT

Advantage of 7-Piece Removal	Disadvantage of 7-Piece Removal
Already technology is existed to handle and lift each component separately.	The duration of offshore operation takes more time since more cutting or disassembly of components are needed.
This method is proven concept since this method was used during installation, therefore, it is a reliable and safe method.	More offshore duration may lead to more fuel consumption as well more CO_2 emission (not always).
Smaller vessel or vessel with lower lifting crane capacity is needed.	More seafastening is needed since every single component needs to be secured for the safe transportation.
Normally smaller vessel has less charter rate.	More seafastening means using more resources including manpower as well as materials.

Advantage of 7-Piece Removal	Disadvantage of 7-Piece Removal
Normally, smaller vessels consume less fuel, eventually, emit less CO_2.	Number of transportations from field to shore will be higher since the WT components are bulky and cumbersome.
Seafastening and transportation of smaller pieces are easier, and technology is available.	More transportation leads to more fuel consumption and eventually more CO_2 emission.
Offloading smaller and lighter components to shore for further process is easier.	More transportation contributes to more waiting in a port for offloading the materials.
Less effort for shore disassembly is needed.	More waiting in the port leads to longer in duration of offshore operation
Transportation for further disassembly and recycling is easier onshore.	More waiting in the ports means more money should be paid to the port

As it stated earlier, the decision to make partial or entire removal of foundations and cables impact how to execute the decommissioning. For instance, if the decision is to carry out partial removal, the piles should be cut a couple of meters below seabed or the cables should be secured based on recommendation number one of ICPC which is about Recovery of Out of Service Cables (International Cable Protection Committee (ICPC) 2016). Keeping the cables and foundations in-situ not only affect the cost of operation but also does influence the legal responsibility of owners or developers in the long-term.

Also, selection of right equipment for disassembly, cutting and removal of different components based on their availability, safety of operation, rental cost of equipment etc. can impact the decommissioning. For example, in overwhelming majority of project, transition piece and the foundation have composite connection (they are connected with grout). Therefore, the available technology for disassembly of this joint can be cutting with abrasive water jet or diamond wire cutter and so forth.

6.5 Crucial Factors in Transportation of Wind Turbine Components

It is crystal clear that every wind park has different specification. Three different types of factors have profound impact in the decommissioning and transportation of wind turbine components as following:

6.5.1 Wind Farm Specification

1. Size of wind turbines.
2. Weight of wind turbine components.
3. Number of wind turbines in a wind park.

4. Topology of wind park, such as having offshore high voltage substation (OHVS) and metrological mast.
5. Number and length of submarine cables.
6. Burial depth of cables.
7. The distance of offshore wind park from the suitable port.
8. The water depth at wind park.
9. Types of structure and foundation.
10. The methods of installation such as number of segments of tower, the connection of transition piece to the foundation, the connection of rotor etc.

6.5.2 Shore Infrastructure

In addition to the specification of wind parks, other factors play significant role in decommissioning of wind park which includes:

1) The closet port or decommissioning yard which must have some parameters for the decommissioning such as:
    - Water depth at berth.
    - The seabed condition at berth, if the plan is to use jack up vessel.
    - Load bearing capacity of quayside.
    - Suffice area for storage and disassembly etc.
    - The load bearing capacity of storage area.
    - Space and infrastructure to mobilize workshop, warehouse, suitable area for cutting the materials like monopile, blades etc. for further processing and to disassembly of nacelle.
    - Port infrastructure to offload materials from vessel to the port. In case of lack of port infrastructure, the mobilization of cargo handling tools like cranes, self-propelled modular transporter (SPMT), truck, labour and so forth should be reasonable.
    - Access to the onshore facilities like recycling company, original equipment manufacturer (OEM) and so forth.

6.5.3 Waste Management and Recycling Process

After transportation of components to the decommissioning yard or port, a number of activities need to be done on the materials including:

- Waste management and management of hazardous materials.
- Function test of equipment in order to segregate the functional components.

- Disassembly of equipment such as nacelle or offshore high voltage substation or metrological mast.
- Sorting the materials.
- Decontamination and shredding the materials.
- Further transportation of goods to the necessary factory or plant for further process such as disassembly or recycling. This process needs onshore transportation or may need transportation via inland waters or offshore transportation.

The proximity and accessibility of the factories/plants for disassembly and waste management influence the selection of port. Obviously, the less transportation result in less CO_2 emission and less decommissioning cost.

Finding of one study demonstrates that transportation with ship is approximately 4 times more efficient than shore transportation with truck. The following compare the efficiency of shore transportation versus ship transportation.

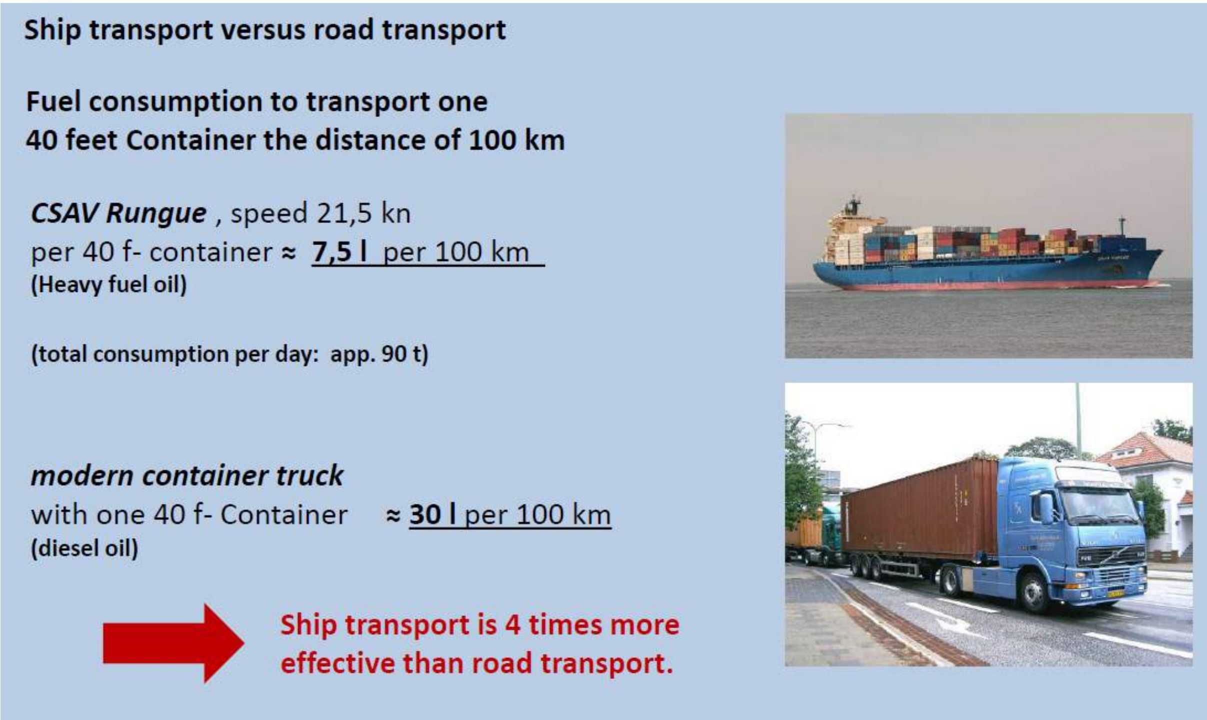


Figure 6-1 Shore Transportation VS offshore Transportation (Meyer 2019)

In conclusion, less onshore transportation will result in reduction of the cost as well as mitigation of CO_2 emission. Thus, the effort should be made in order to plan the transportation of the items to the final destination via vessel than trucks or other onshore logistic vehicle.

6.6 Comparison of Cutting Tools in a Glance

There are many types of cutting tools which each of them follows specific principal and techniques. Each of them has their own advantages and disadvantages. However, research about the cutting technics is out of scope of this research, but briefly some of the broadly used cutting methods along with their pros and cost are listed shortly as following:

6.6.1 Diamond Wire Saw

The advantages of this cutting techniques are as following:

- ☑ This tool is so environmentally friendly.
- ☑ It is reliable cutting tools for subsea cutting and surface cutting.
- ☑ It can cut any material and any joint. So, it can cut the composite joint, grout, metal and combination of them.
- ☑ It does not generate heat, fume, arc and relatively a low noise cutting technique.
- ☑ Does not need operator to be close to the cutting location, so it is safe.

The disadvantages of this cutting techniques are as following:

- ☒ It is time-consuming cutting technology. the cutting process for a monopile with a diameter of 3.5 m and a wall thickness of 78 mm can take up to 30 hours and more (Hinzmann, Stein and Gattermann 2018).
- ☒ More offshore time means the more day rate of the vessel, more fuel consumption and more emission resulted from the vessel.
- ☒ Cutting large size structure and monopile need 2 divers for installation of tool around the structure. The following figure shows the diamond wire cutter for cutting monopile with diameter of 6-8 meter.

Figure 6-2 Diamond Wire Saw for Large size monopile (Mirage Machine Tool)

6.6.2 Abrasive Water Jet

Abrasive waterjet cutting uses an abrasive particle (e.g. garnet) added to high pressure water to cut through hard materials. The abrasive particle is added to the water in the nozzle of a waterjet cutting machine (Resato n.d.)

The advantages of this cutting techniques are as following:

- ☑ It is reliable cutting tools for subsea cutting and surface cutting.
- ☑ It can cut any material and any joint. So, it can cut the composite joint, grout, metal and combination of them.
- ☑ It does not generate heat, fume, arc etc.
- ☑ Does not need operator to be close to the cutting location, so it is safe.
- ☑ Can be installed inside TP or MP without needing ROV or divers.

The disadvantages of this cutting techniques are as following:

- ☒ It is time-consuming cutting technology.
- ☒ More offshore time means the more day rate of the vessel, more fuel consumption and more emission resulted from the vessel.
- ☒ It needs about 4 tons of abrasive for 22 hours of cutting. It means cutting each TP needs more than 5 tons of abrasive, if cutting take place 30 hours. So huge amount of material is needed in the course of operation.

Figure 6-3 Cutting of 36 inches Twin well Conductor

Source: (James Fisher Offshore 2020)

6.6.3 Shear Cutting Tool

Shear cutting technique is also a proof of concept and suitable cutting tools for offshore operations. There are a couple of reasons why it is a good tool and why this tool is not suitable for cutting TP or MP as following:

The advantages of this cutting techniques are as following:

- ☑ It is fast cutting tool.
- ☑ It does not emit any pollutions.
- ☑ Can be used subsea and on the surface.
- ☑ Can cut the metal and composite joint.

The disadvantages of this cutting techniques are as following:

- ☒ Need divers to align the tool around the structure.
- ☒ Utilization of divers increase the cost of the project, makes the operation complex and riskier.
- ☒ The shear cutter tool for large size tubular like MP or TP is not designed/manufactured yet.
- ☒ It is not used so far for cutting the vertical structure, mostly used for cutting the pipelines.
- ☒ It is relatively expensive tools.
- ☒ There are limited number of shear cutter manufacturers.

Figure 6-4 Shear Cutting Tool

Source: (James Fisher Offshore 2019)

6.6.4 Oxy Fuel Cutting Technique

There are various oxy fuel cutting tools, but in general some of the general and common advantages and disadvantages are as following:

- ☑ It is a reliable cutting method.
- ☑ It is quick cutting techniques.
- ☑ Due to fast cutting, the duration that the fleet should be in operation are minimized. Then the overall cost of project, the emission and the risk can be minimized.
- ☑ It is relatively cheap cutting technique.
- ☑ It is so common technology in oil and gas, wind industry and ship construction etc.
- ☑ It can be a precise cutting tool which is not important for decommissioning.
- ☑ This cutting tool are widely available.

The disadvantages of this cutting techniques are as following:

- ☒ It is not a subsea cutting tool.
- ☒ It cannot cut the grouted and composite joint.
- ☒ It produces fume, heat, smoke, smell, and spark (however, it is producing many variants of pollutions, but because it is fast cutting techniques, the offshore operation become less. Thus, the emission of ship which is many times greater than cutting tool will be less).
- ☒ It is harmful for the operator. Therefore, the suitable PPE need to be used to prevent and minimize the harmful impact.

However, in this document we will show how cutting, removal and loading of transition piece has to undertake on board the Decom Tools vessel. In this document it is proposed to cut top section of the transition pieces above the sea level, where there is not overlap with the monopile. So oxy fuel cutting tool can be utilized to cut this section due to mentioned advantages.

6.7 Functions of Decom Tools Vessel

As it stated earlier, the Decom Tools Vessel has several functions which the most significant functions are listed below.

1. Transportation of materials such as blades, nacelle and towers, transition piece as well as foundation from offshore to port or decommissioning yard. However, the vessel is able to transport offshore high voltage substation, metrological mast and cables.
2. Extraction of monopile from seabed.
3. Cut the monopile into small pieces for easier offloading at port and further transportation and processing.
4. Automatic removal of marine growth.
5. Extraction of in-field (inter array) and export cable.
6. Cut the cables into small pieces.
7. Seafastening of all sizes of wind turbine blades from the first generation to 12 MW blades.

8. Cut the blades into small pieces for easier offloading, transportation, and further process.

6.8 Loading and Transportation Function

In installation of most of wind farms, the installation vessel has been used for the transportation of components. One of the main reasons is lack of suitable cargo vessel for transportation of components from base port or OEM to the offshore field. Noticing the high charter rate of installation vessels as well huge fuel consumption of this type of vessels, utilizing this vessel contribute to high fuel consumption and incur enormous cost to the project. To fill this gap in this industry, this cargo vessel has been designed in order to transport large number of components from offshore wind parks to the decommissioning yard or port. To accomplish this mission, the vessel should be dimensioned in a way to be suitable for various generation of wind turbines.

6.9 Criteria for Dimensioning the Decom Tools Vessel

Dimensions of Decom Tools vessel has been tailored based on the largest wind turbine that has been installed so far[58] which is 12 MW wind turbine. GE designed and manufactured 12MW X-Heliade wind turbine and launched it in 2019. However, two sets of this wind turbine have been installed in the Rotterdam port and Blyth for obtaining certificate for further offshore installation which means yet this size has not been installed at any offshore site[59].

Due to more efficiency of larger wind turbines, the industry is avid to install XL wind turbine in coming projects. There is 4.8 GW of orders for 12MW project in the pipeline of GE.

In addition, if the vessel can suit the requirement of the largest size of wind turbine, it can be suitable for smaller sizes as well. Figure 6-5 shows the trend of development and dimension of various size of wind turbines. As the figure shows, 6MW blade is about 34m shorter and about 20 tones lighter in weight than 12MW.

The 12MW wind turbine and larger ones which is launched by Siemens Gamesa necessitate rapid development of supply chain including ports and logistic namely on/offshore transportation as well as installation. One can expect larger and heftier wind turbine in near future based on trends in the development of this industry as well as numerous advantages of XL turbines. As it can be seen the transportation and installation contractors are behind the development of wind turbine.

Every year, larger and heavier wind turbine are unveiled by the wind turbine manufacturers, but the development of the transportation and installation vessels lag behind.

[58] January 30, 2021

[59] Until January 2021

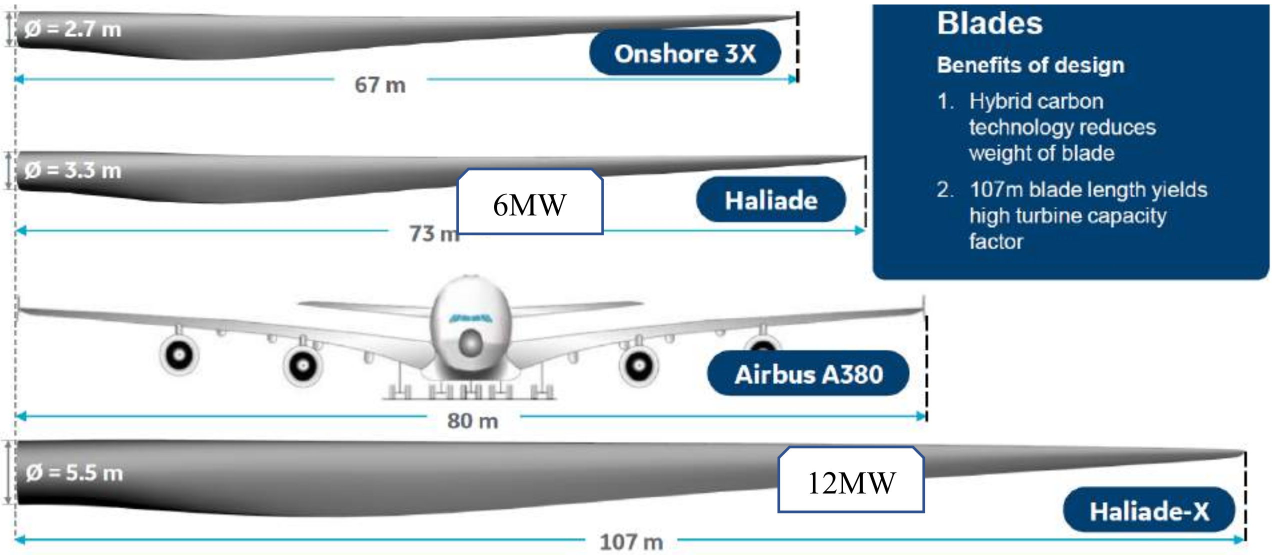


Figure 6-5 Dimension of blades of Various Wind Turbine sizes (LM Windpower 2020)

Before showing the loading of 12 MW wind turbine's components on the Decom Tools vessel, it is beneficial to see how the loading one set of this giant wind turbine took place in 2019 and how the installation conducted in the port of Rotterdam.

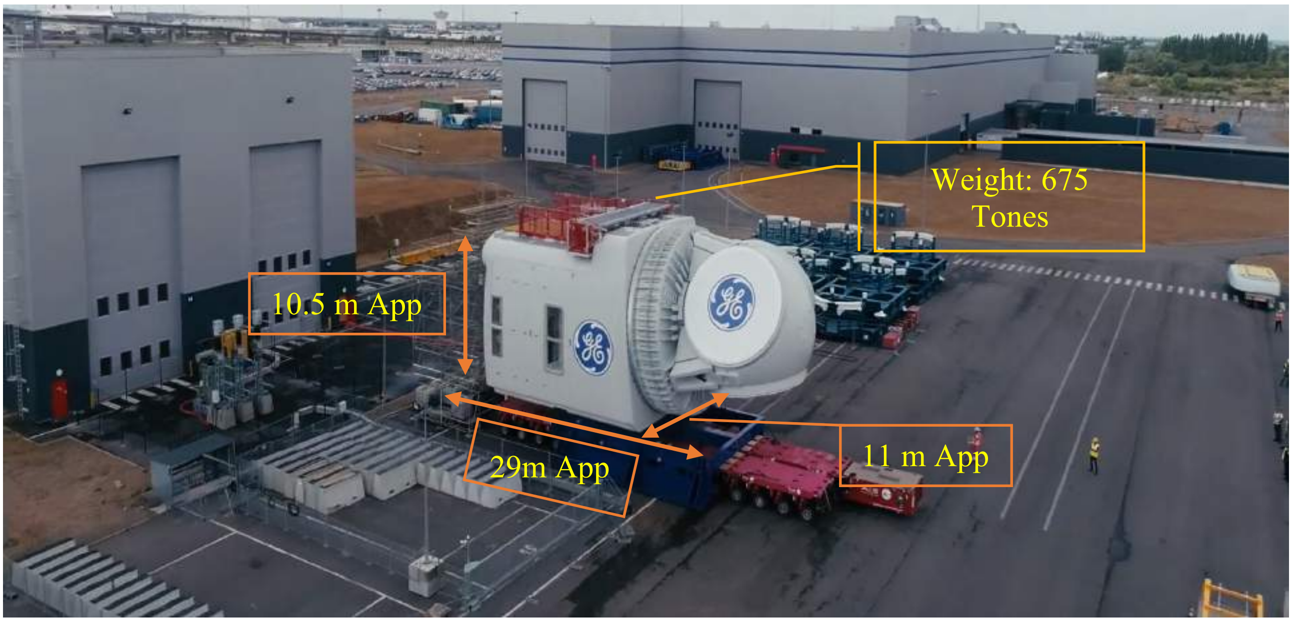


Figure 6-6 Transportation of 12MW GE X-Heliade Nacelle (Energyfacts.eu 2019)

Figure 6-6 shows transportation of 12MW nacelle from company to the berth for load out and transportation to the Rotterdam port. The weight of nacelle including the hub is approximately 675 tones. This nacelle has 10.5-meter height, 29 meter length and 11meter width.

Figure 6-7 and Figure 6-8 shows the transportation of the mentioned nacelle to the quayside and Figure 6-9, Figure 6-10 and Figure 6-11 shows lifting and load of the nacelle into the transportation vessel. As it shows, one SPMT has been used for transportation. Besides, the lifting was conducted by the vessel crane.

Figure 6-7 Transportation of 12MW GE X-Heliade Nacelle to Quayside

Figure 6-8 Preparation of 12MW GE X-Heliade Nacelle for Loading into the C/V

The transportation vessel has hold(s) which the nacelle loaded out inside the hold for transportation.

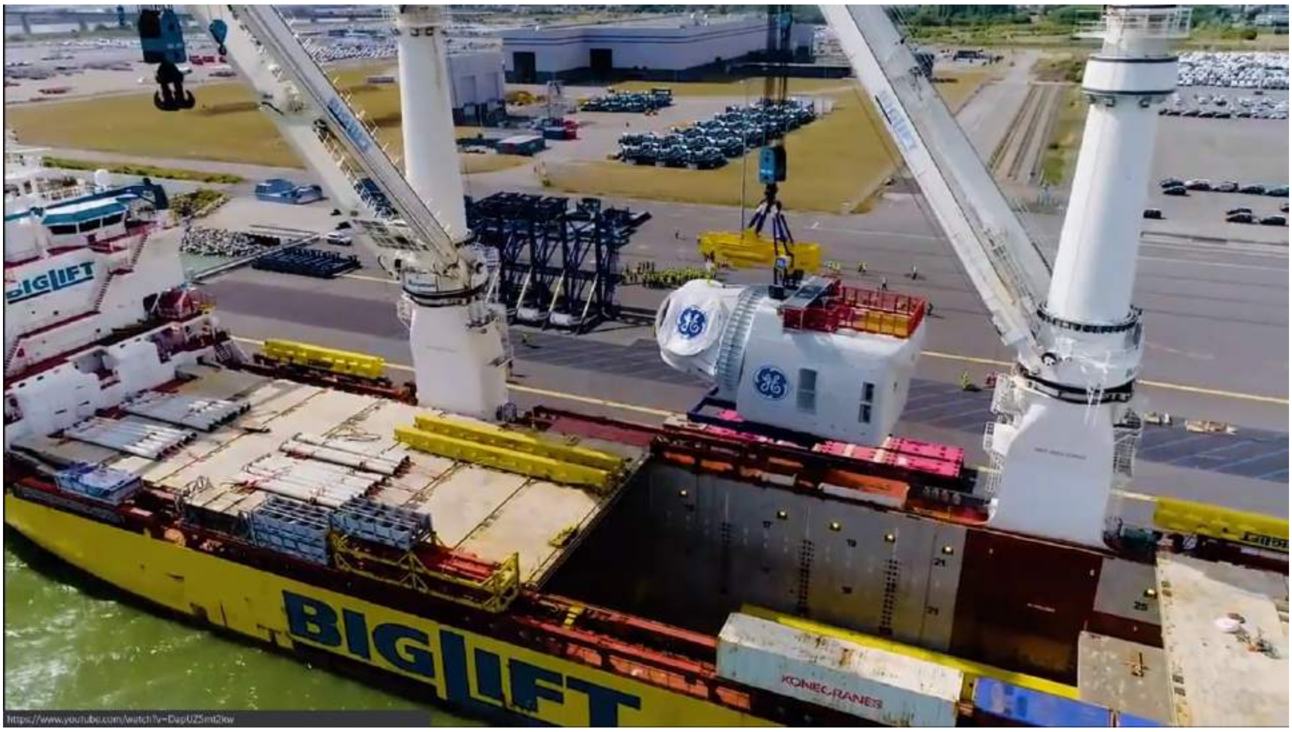


Figure 6-9 Lifting 12MW GE X-Heliade Nacelle into the C/V (Pondera 2019)

Figure 6-10 Lifting 12MW GE X-Heliade Nacelle into the C/V (Pondera 2019)

Figure 6-12 and Figure 6-13 shows transportation of the 12 MW blade from the factory via two SPMTs to quayside and transportation of it with the ship to the Rotterdam port. The ship transported just one blade from LM Wind Power factory in Cherbourg, France to Rotterdam port in the Netherlands which is about 290 nautical miles.

Figure 6-11 12MW GE X-Heliade Nacelle Loaded into the C/V (Pondera 2019)

Figure 6-12 Transportation of 12 MW GE X-Heliade Blade (LM Wind Power, 2019)

The omission or oversight to design and construct a cargo vessel for new and future generations of wind turbine can be seen in the Figure 6-13. The existing vessels are not suitable and are not tailored to the size of new generations of wind turbines which causing the transportation extremely inefficient. Not only there is lack of suitable cargo vessel for the transportation, but also the existing installation vessels are not mostly capable to install newly launched extra-large wind turbines.

Figure 6-13 Transportation of 12 MW GE X-Heliad Blade with Ship To the Rotterdam (LM Wind Power 2019)

Figure 6-14, Figure 6-15, Figure 6-16, Figure 6-17, Figure 6-18 and Figure 6-19 show sequences of installation of 12 MW GE X-Heliade wind turbine in the Rotterdam port. The steel tower for this size of wind turbine will have weight of approximately 880 tones. It should be noted that the installed tower in the Rotterdam port consists of 4 segments. In addition, the wight of monopile with diameter of 10 meter for the water depth of 50 meter will be around 2000 tones (Kellner 2018).

Figure 6-14 Installation of the Second Segment of 12 MW GE X-Heliade WT in the Rotterdam Port (GE Renewable Energy 2019)

Figure 6-15 Installation of the Third Segment of 12 MW GE X-Heliade WT in the Rotterdam Port (GE Renewable Energy 2019)

Figure 6-16 Installation of the Fourth Segment of 12 MW GE X-Heliade WT in the Rotterdam Port (GE Renewable Energy 2019)

Figure 6-17 Installation of 12 MW GE X-Heliade Nacelle in the Rotterdam Port (GE Renewable Energy 2019)

Figure 6-18 Installation of First Blade of 12 MW GE X-Heliade Nacelle in the Rotterdam Port (GE Renewable Energy 2019)

Figure 6-19 Installation of Third Blade of 12 MW GE X-Heliade Nacelle in the Rotterdam Port (GE Renewable Energy 2019)

6.10 Dimensions of Decom Tools Vessel

However, the vessel primarily designed for the largest and latest generation of offshore wind turbine which is 12MW GE X-Heliade, but optimization has been done on the dimensions of the Decom Tools vessel for transportation of other sizes of the wind turbines too. Having considered criteria and specifications of installed wind farms across the EU, authors designed the vessel with following specifications. Moreover, the hull optimization has been conducted in order to reduce the hull resistance which contribute to less fuel consumption.

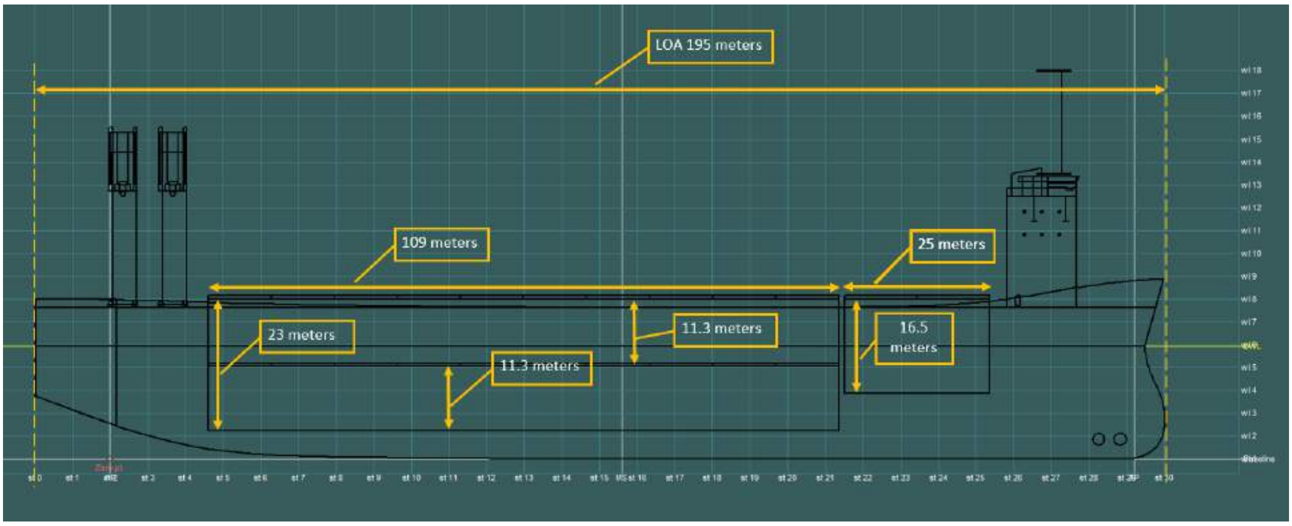


Figure 6-20 Dimension of Decom Tools Vessel

The final dimension of the vessel is as following:

- Length overall (LOA): 195 Meter
- Breadth overall: 48 Meter
- Moulded depth: 26.5 Meter
- Summer Draught: 19.7 Meter

Figure 6-20 shows the dimensions of Decom Tools vessel in general, holds and other sections. In addition, dimensions of different sections of Decom Tools vessel are mentioned in the Table 2-1 and Table 5-1.

However, in the last section of this document, the overall dimension and specification of the vessel can be found as an appendix.

6.11 First Method of Cargo Loading Arrangement (Full Set Load Out)

Loading and transportation of components directly depends on the sequences of disassembly and removal.

More importantly, the disassembly and removal sequence heavily depend on onshore waste management infrastructure, port specification as well as location of nacelle manufacturer.

It should be noted that three campaigns (the first three mentioned sequences) are needed for disassembly and removal of wind farm components which may increase due to installed components in a wind farm as following:

1. The retrieval and extraction of inter-array and export cables (if removal of the cable take place as first stage, jack up vessel can do the positioning without any concerns).
2. The next campaign is disassembly and transportation of towers, nacelles, and rotors.
3. The third campaign is removal of transition pieces and extraction of the monopiles or other types of foundation[60].
4. Removal of topside of offshore high voltage substation (OHS), if any.
5. Removal of jacket or other structure of high voltage substation (OHS), if any.

6.11.1 12 MW GE Turbines Loading Arrangement

Regardless of topology of wind farm and installed components, the first method of cargo loading is exactly reverse to the installation sequences of many installed wind farms. It means that the last stage of installation of a wind turbine was installation of blades. Therefore, the first sequence for the decommissioning is disassembly of blades from a wind turbine and loading of them into the vessel. Therefore, the blades should be loaded on the lowest part of the ship. Given this fact, the longitudinal holds are designed for the loading and securing the blades. The length of hold is 109 meters and the length of largest manufactured blade up to date[61] is 107 meters which is belong to GE X-Heilade 12 MW. The sizes of various generation of wind turbines blades are shown in the Figure 6-5.

So, one meter clearance is considered from tip and root of the blades from both end of the holds. With the designed holds, four number of 12 MW blades (4 x 107m blade) which weigh 55 tones can be loaded vertically on top of each other in each section of longitudinal hold. In addition, in each holds section, three number of them can be loaded adjacent to each other. It means that each holds section can load 4 sets of 12-MW wind turbines blades (12 number of 12 MW blades). In overall, the longitudinal hold is capable to be loaded by 8 sets of 12-MW wind turbines blades (24 number of 12 MW blades). Figure 6-21, Figure 6-22, Figure 6-23 and Figure 6-24 shows the holds when are loaded with 12MW wind turbines blades.

The weight and dimension of the major components of the 12 MW wind turbine is listed in the Table 6-3.

[60] The first two campaigns can be done in one run, in case the removal of wind turbines and foundations take place in one campaign. So far, this technology is available for the gravity base structure as well as floating wind turbine. There is not any proof of concept for removal of wind turbine and relative structure in one campaign.

[61] January 2021

Table 6-3 Weigh and Dimension of 12 MW Wind Turbine

Weight and Dimension of 12 MW Wind Turbine	
Component Name	**Size**
Blade length (m)	107
Blade Diameter	5.5
Blade mass (t)	55
Max. chord (m)	6
Hub mass (t)	75
Nacelle mass (t)	600
Nacelle + Hub mass (t)	675
Nacelle dimensions (m) (L x W x H)	20.6 x 11 x 10.4
Nacelle with hub dimensions (m) (L x W x H)	29 x 11 x 10.5
Tower Mass (t)	880
Tower Height (m)	129
Tower top diameter (m)	5.5
Tower bottom diameter (m)	10

This cargo loading plan does not limit to the loading of blades just and it consists of a complete set of wind turbine including nacelle and tower. Obviously after fully loading of the vessel with sets of rotor, nacelle and tower, the materials need to be transported to the nominated port or decommissioning yard for offloading the materials and further process. After completion of disassembly of towers, nacelles and rotors of the whole wind farm, the extraction and loading of transition pieces and foundations can be executed.

Figure 6-21 Perspective View of Load out of 12 MW Blades inside the holds

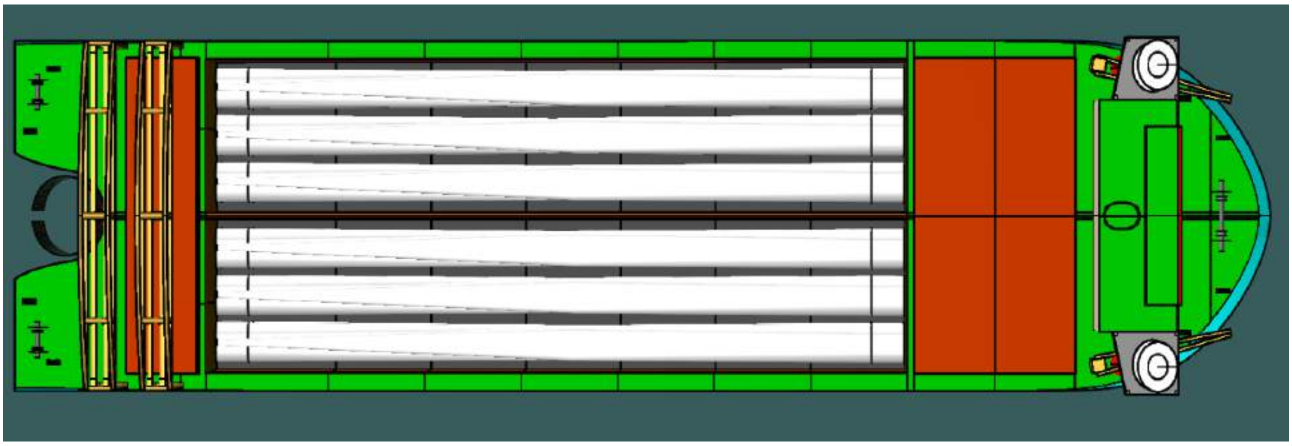


Figure 6-22 Top view of Load out of 12 MW Blades inside the holds

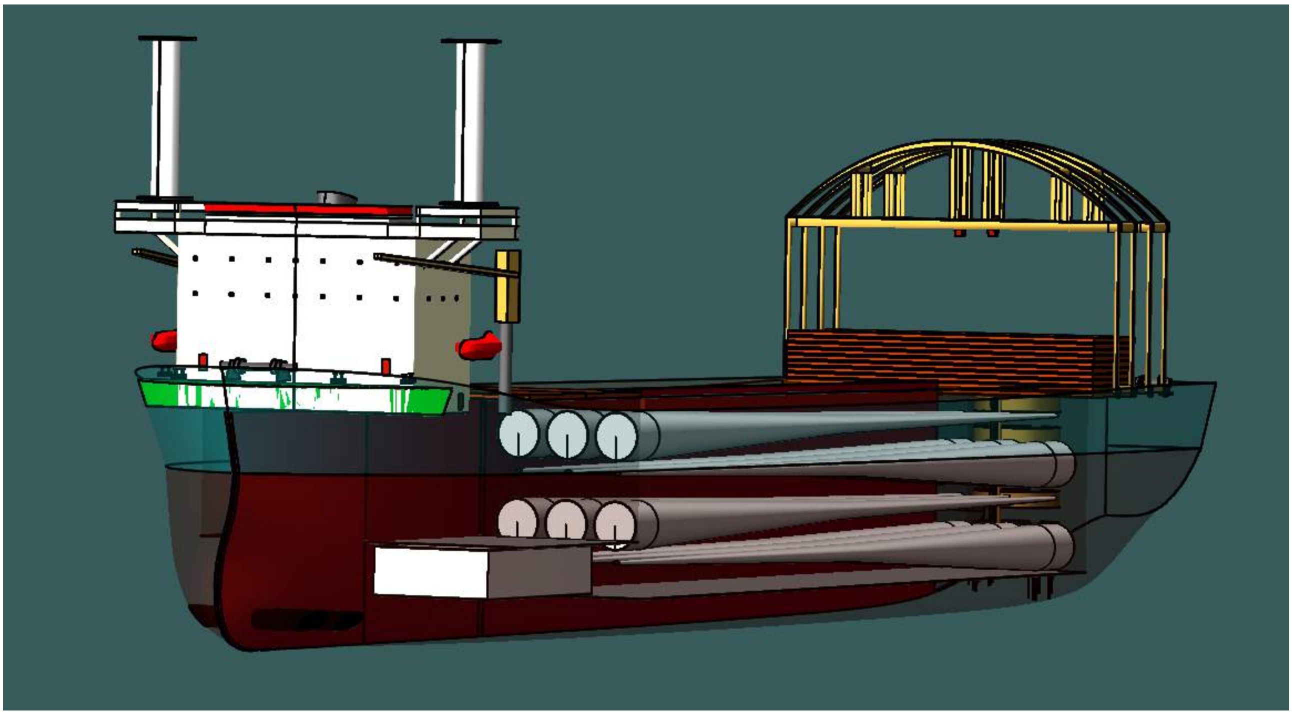


Figure 6-23 Perspective view of Load out of 12 MW Blades inside the holds

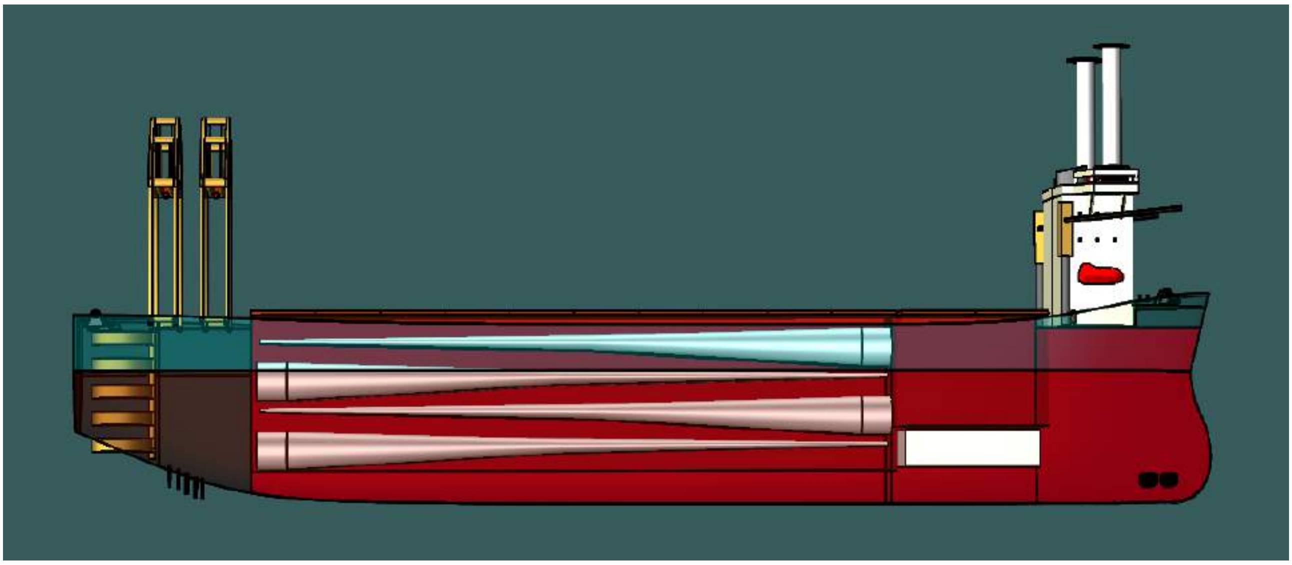


Figure 6-24 Side view of Load out of 12 MW Blades inside the holds

Figure 6-25 to Figure 6-29 shows that the 12 MW tower is made of 2 segments with the overall weight of 880 tons and length of 129 meter meaning each segment is about 65m. As it shows 8 full set of 12MW wind turbine can be loaded on the Decom Tools vessel. It means 24 number of blades, 8 towers (consists of 16 segments) and 8 nacelles plus hubs.

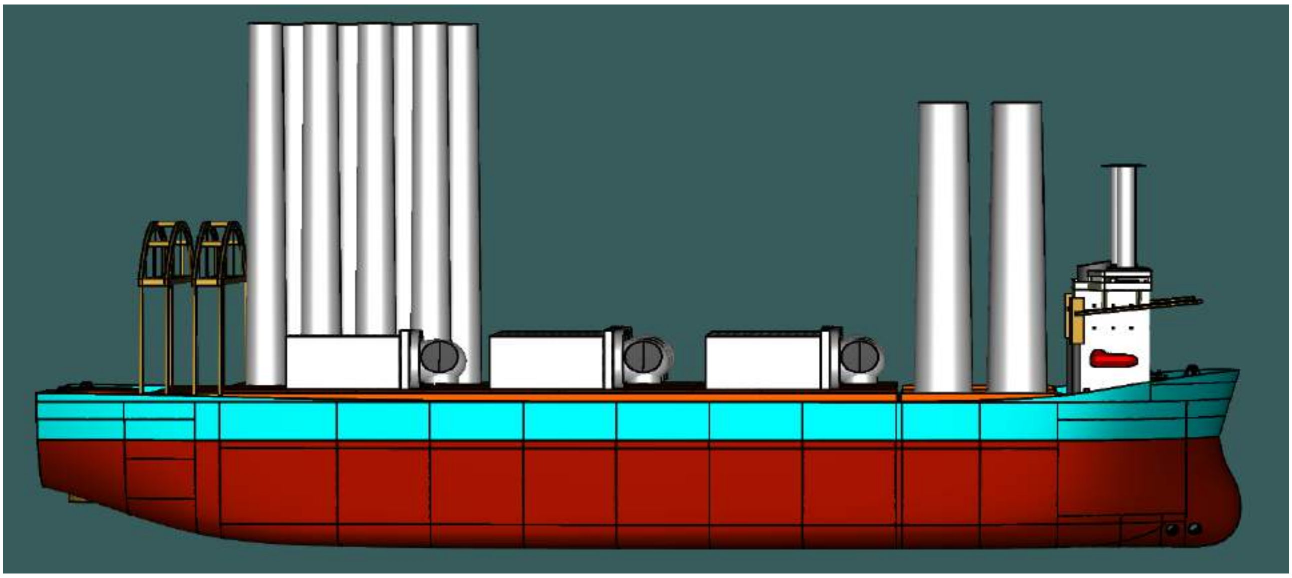


Figure 6-25 Side View of Load out of 12MW Blades, Nacelle & Tower

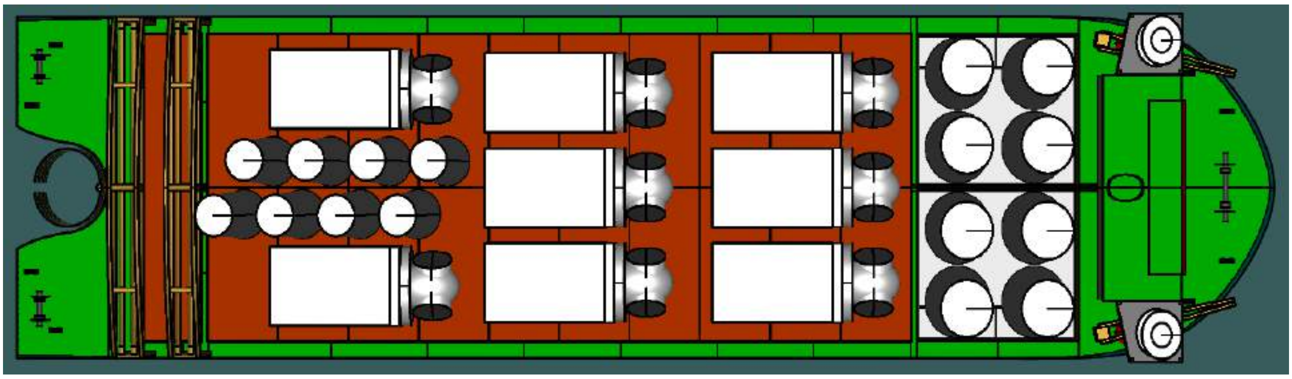


Figure 6-26 Top View of Load out of 12MW Blades, Nacelle & Tower

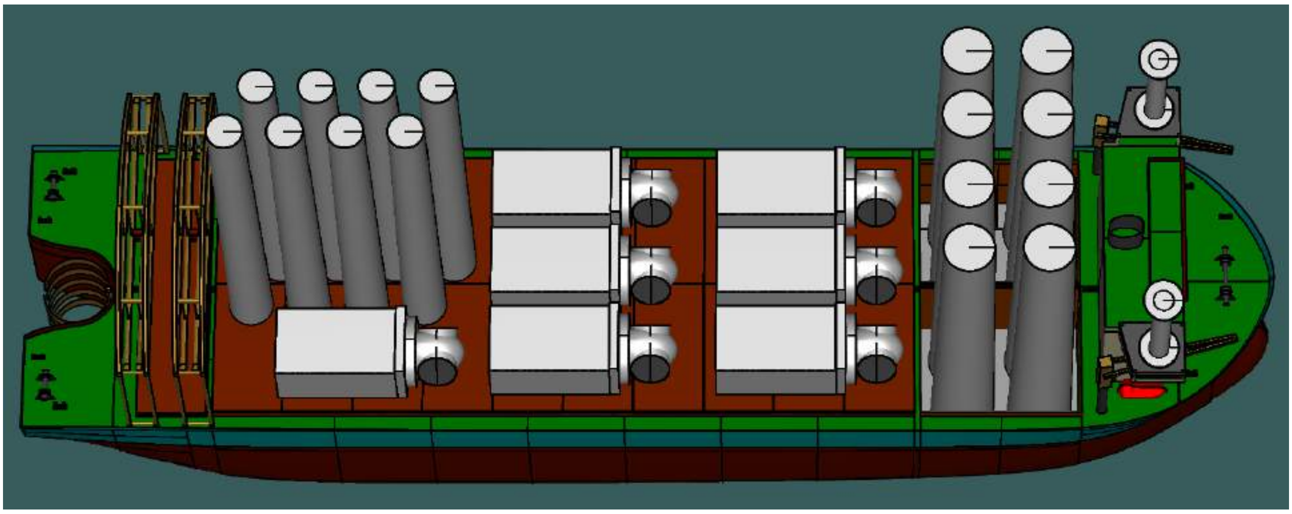


Figure 6-27 Top View of Load out of 12MW Blades, Nacelle & Tower

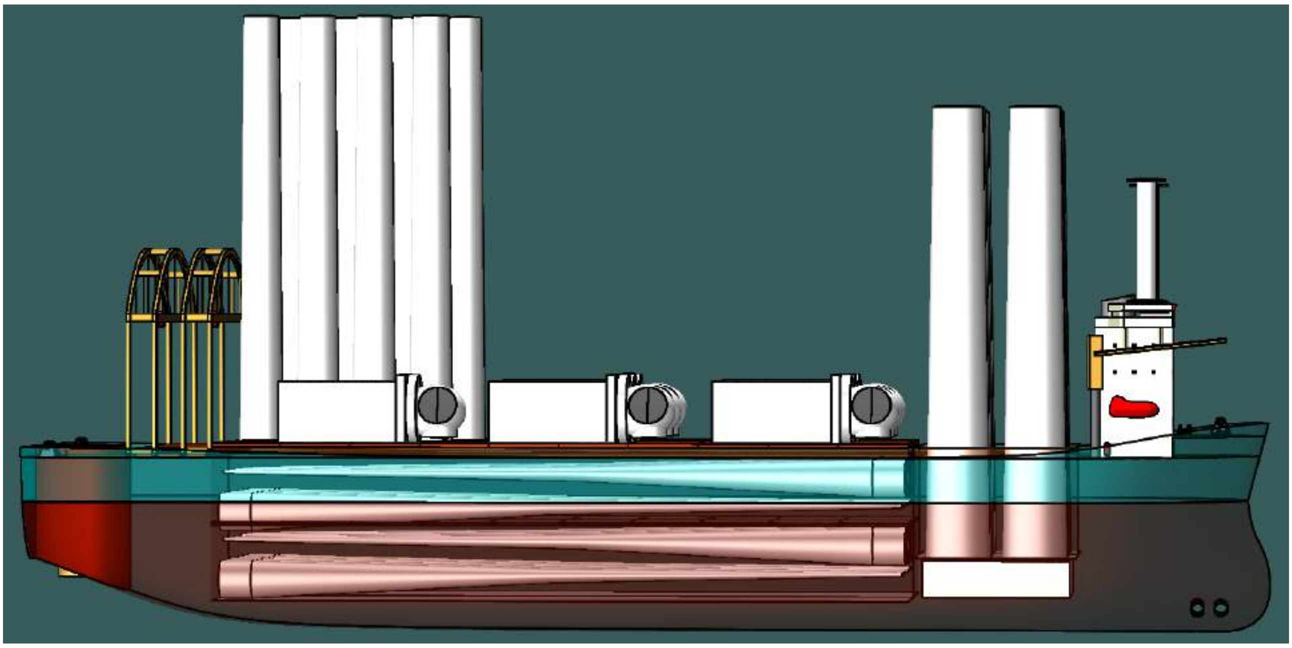


Figure 6-28 Side View of Load out of 12MW Blades, Nacelle & Tower

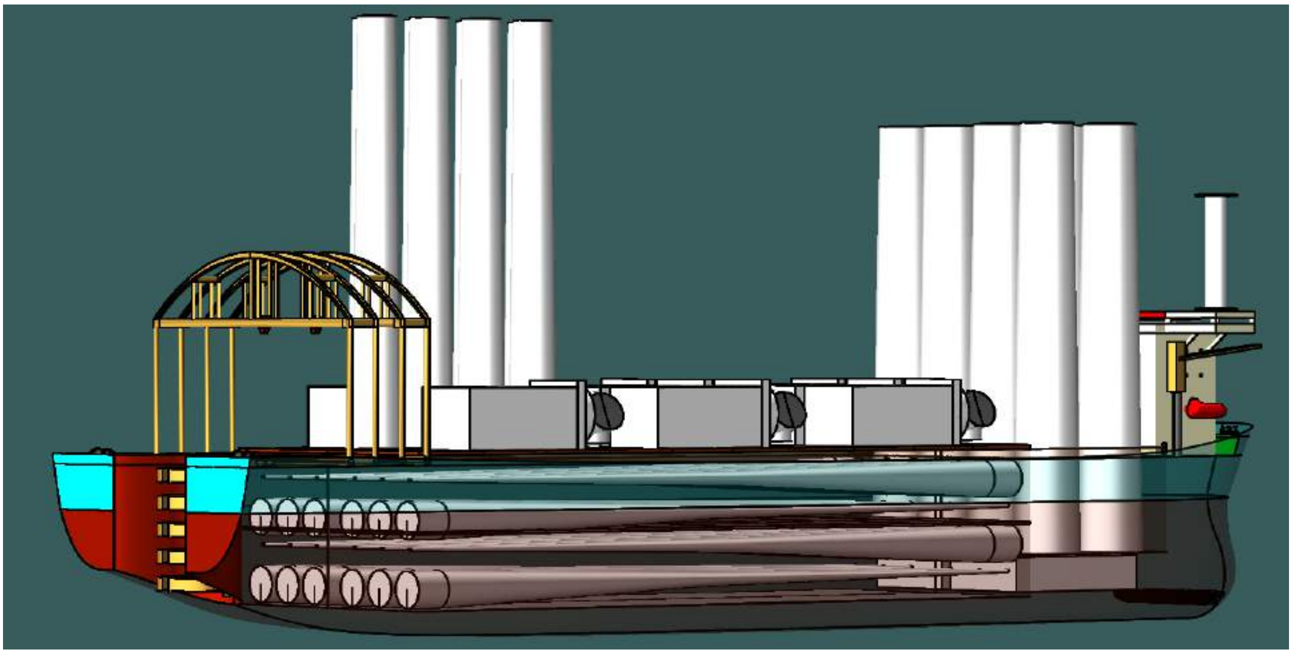


Figure 6-29 Perspective of Load out of 12MW Blades, Nacelle and Tower

So far maximum 6 sets of large wind turbines (7MW) were loaded and transported offshore by the most advanced fleet. The emergence of this designed vessel will help the industry for saving of the resources remarkably.

The Decom Tool vessel can load and transfer a considerable number of 12 MW transition pieces and monopiles also. The following figures show how many sets of monopile, and transition piece can be loaded on the Decom Tools vessel. The authors designed two different loading plans for transition pieces and monopiles which one of the lay out is more efficient since less voyage is needed to transport the wind farm components.

In the first loading plan, 11 number of transition piece[62] along with 11 numbers of monopile[63] can be transported, See Figure 6-30, Figure 6-31, and Figure 6-32.

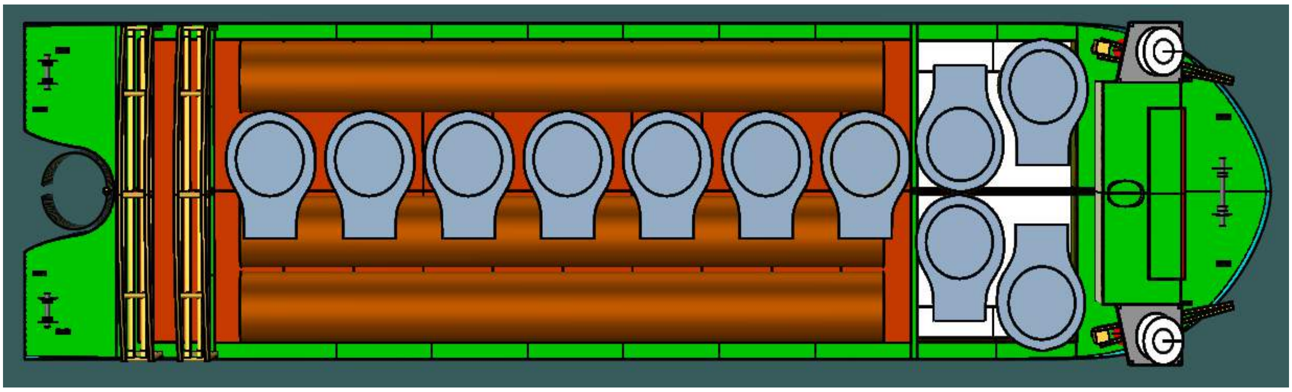


Figure 6-30 Top view of Load out of 12MW TP & Monopile (First Arrangement)

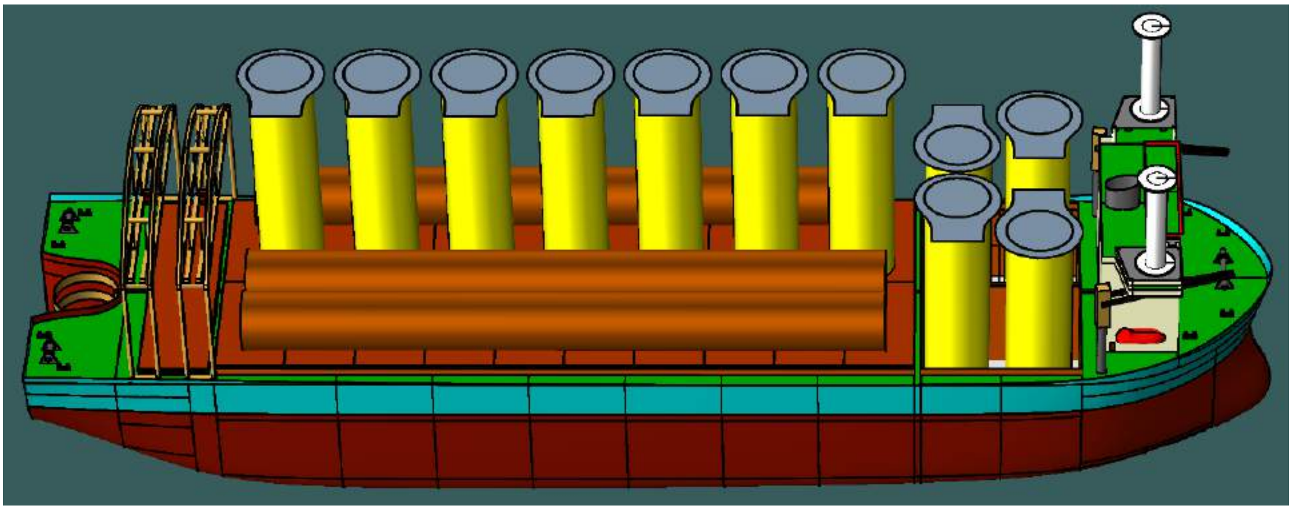


Figure 6-31 Top view of Load out of 12MW TP & Monopile (First Arrangement)

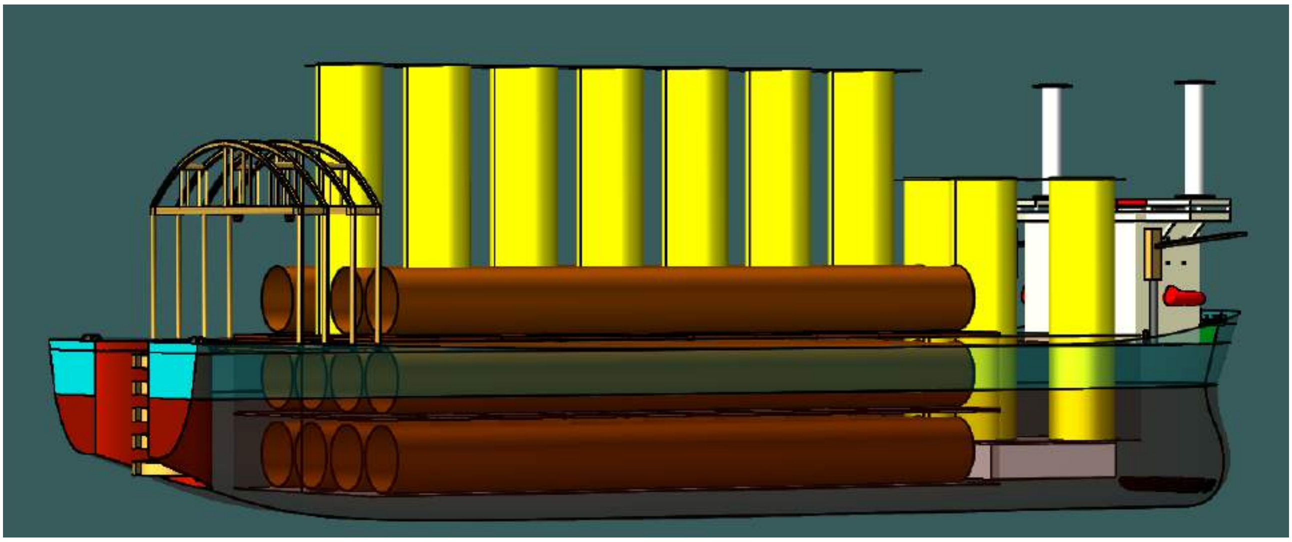


Figure 6-32 Perspective of Load out of 12MW TP & Monopile (First Arrangement)

[62] This transition pieces dimensioned for the 12 MW wind turbine. The transition piece has approximately height of 41 m and dimeter of 10.2 m.

[63] The monopile dimensioned based on the consultant of the GE company. The monopile of 12MW wind turbine in this research has diameter of 10 m and length of 100.

This cargo loading is suitable when the removal of TP and MP is planned to be conducted in same campaign.

The second load out arrangement of monopiles and transition pieces are shown in the Figure 6-33, Figure 6-34 and Figure 6-35.

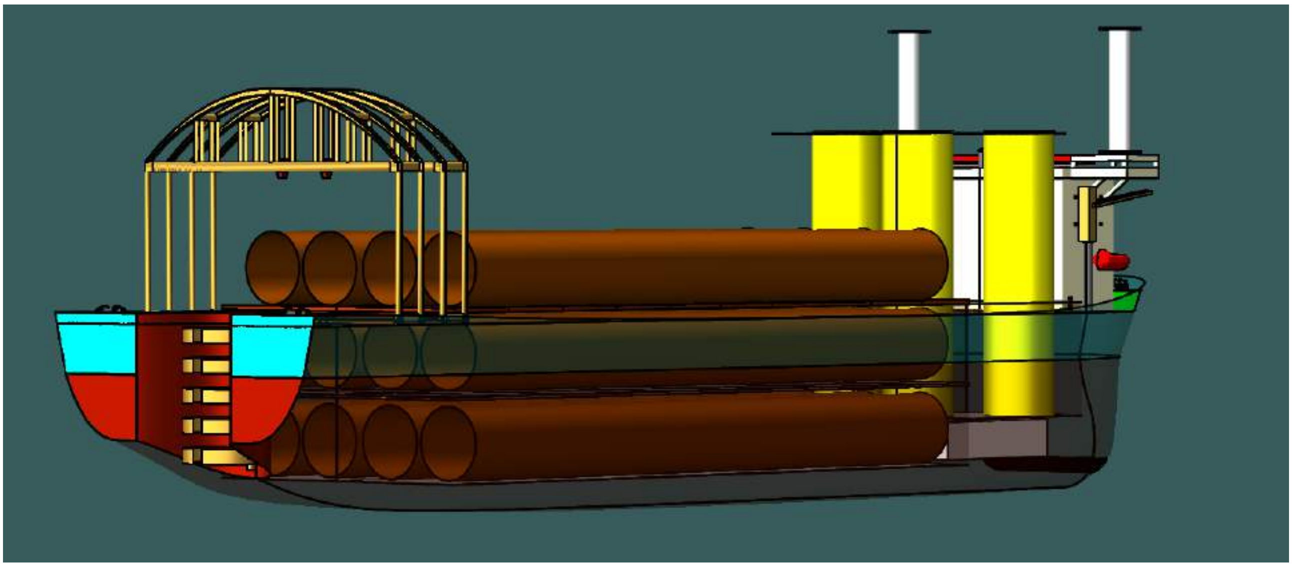


Figure 6-33 Perspective of Load out of TP and Monopile (Second Arrangement)

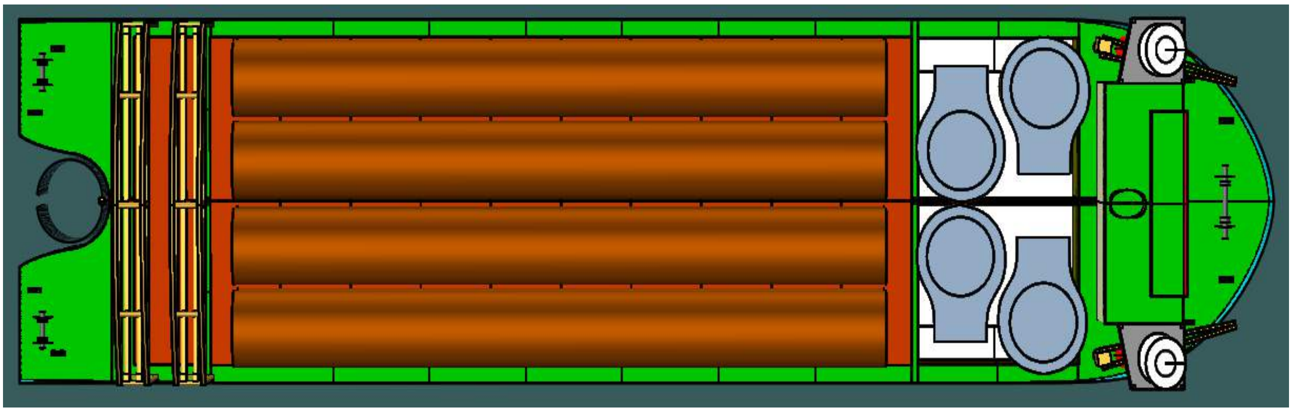


Figure 6-34 Top View of Load out of TP and Monopile (Second Arrangement)

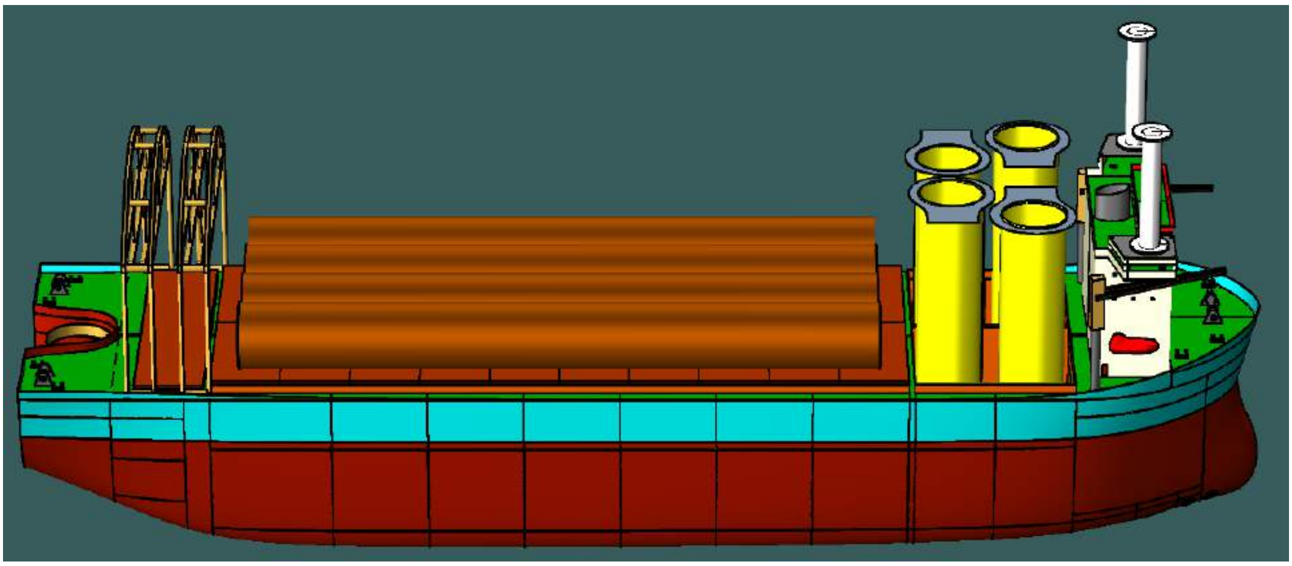


Figure 6-35 Side View of Load out of TP and Monopile (Second Arrangement)

This cargo arrangement is not so optimized in that just 4 sets of transition pieces plus 12 set of monopile can be loaded out and transported. It should be noted that by engineering of suitable seafastening, four more number of monopiles can be loaded on the top of the shown monopiles. In this case 16 sets of monopile plus 4 sets of transition pieces can be transported per trip. Transportation of more cargo per voyage lead to more efficient transportation. Thus, the first load out plans of transition piece and monopile seems more efficient.

6.11.2 5 MW Turbines Loading Arrangement

Based on the Table 2-1, the most installed wind turbine size across the EU is 5 MW wind turbine. Not only the cargo arrangement has been done for 12 MW wind turbine but also the cargo arrangement has been performed for 5 MW wind turbines too.

For the installation of 5MW wind turbine, so far on each voyage, maximum 6 sets of this wind turbine components (rotor, nacelle and tower) were transported by different vessels. However, in the installation of Wikinger offshore wind farm, the jack up installation vessel by the name of Brave Tern transported 3 full set of 5 MW wind turbine to the farm for the installation. The installation took place with star configuration (Fred Olsen Windcarrier 2017). Figure 6-36 shows the loading and arrangement of 5MW wind turbines of mentioned project (the rotors fully assembled onshore, star configuration). Prior to showing the cargo arrangement of 5 MW wind turbine on the Decom Tools vessel, we would like to show the dimension and weight of this turbine's component.

Table 6-4 shows the weight and size of major components of 5MW wind turbine.

Table 6-4 Weigh and Dimension of 5 MW Wind Turbine

Weight and Dimension of 5MW Wind Turbine	
Component Name	**Size**
Blade length (m)	66
Blade Diameter	4
Blade mass (t)	23.33
Max. chord (m)	5.0
Hub mass (t)	67.78
Nacelle mass (t)	240
Nacelle + Hub mass (t)	307.78
Nacelle dimensions (m) (L x W x H)	16 x 6.3 x 6.3
Nacelle with hub dimensions (m) (L x W x H)	21 x 6.3 x 6.3
Tower Mass (t)	347.46
Tower Height (m)	87.6
Tower top diameter (m)	3.87
Tower bottom diameter (m)	6

Figure 6-36 Transportation of 5MW Wind Turbine to Wikinger OWP (Fred Olsen Windcarrier 2017)

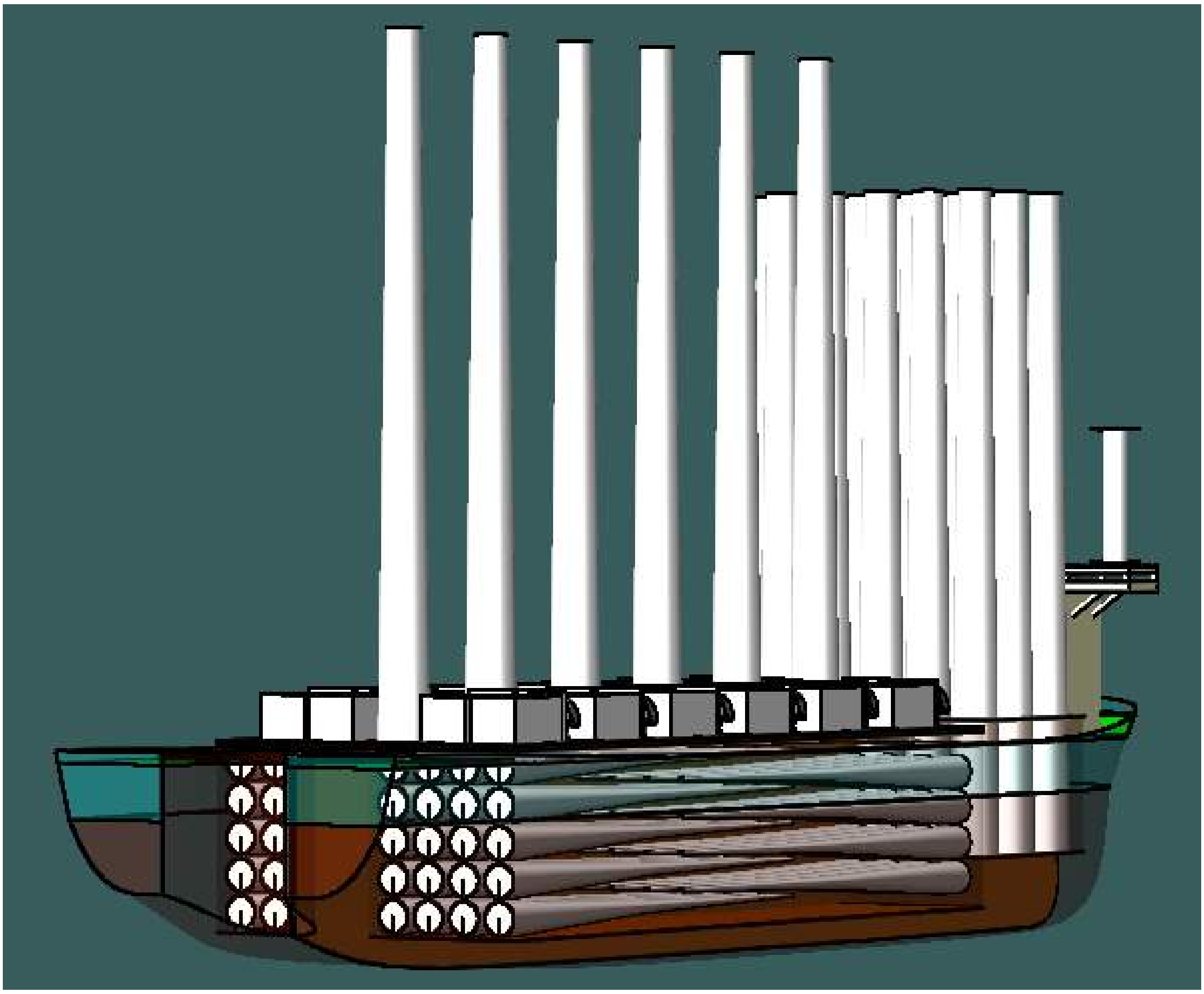


Figure 6-37 Perspective of Load out of 5MW Wind Turbine

Figure 6-38, Figure 6-37 and Figure 6-39 illustrates that the Decom Tools vessel can load and transport 24 full sets of 5 MW wind turbines.

As it shows, 24 set of 5 MW turbine can be loaded for each single voyage.

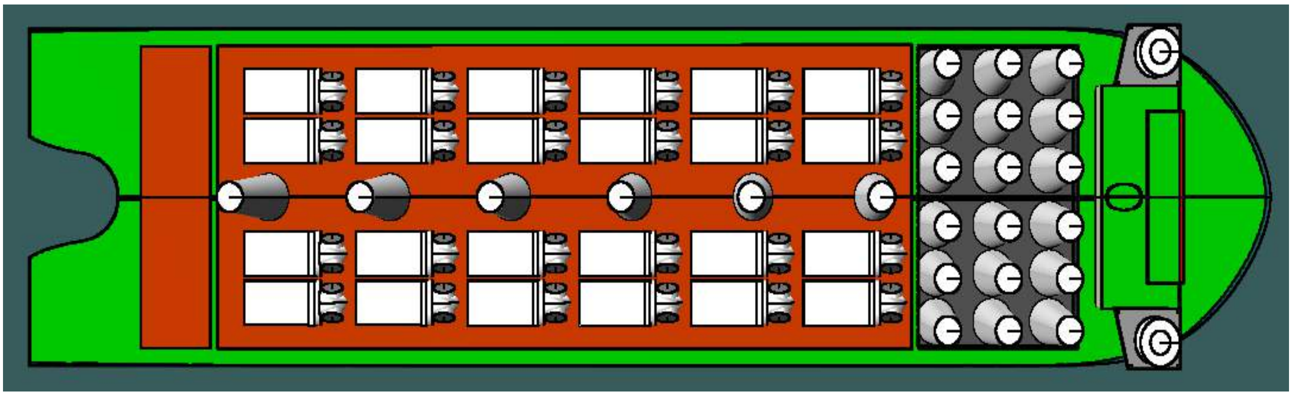


Figure 6-38 Top View of Load out of 5MW Wind Turbine

The highest number of sets of wind turbine that has been loaded and transported to the offshore wind farm was 8 sets of 3.6MW. As it stated before, mostly, in the overwhelming majority of the projects, the installation vessel transported the materials to the site (pendulum configuration).

It means that Decom Tools Vessel is at least 4 times more efficient than existing vessel in terms of transportation. The greater number of sets of wind turbines to be transported per cycle, the more efficient the transportation will be.

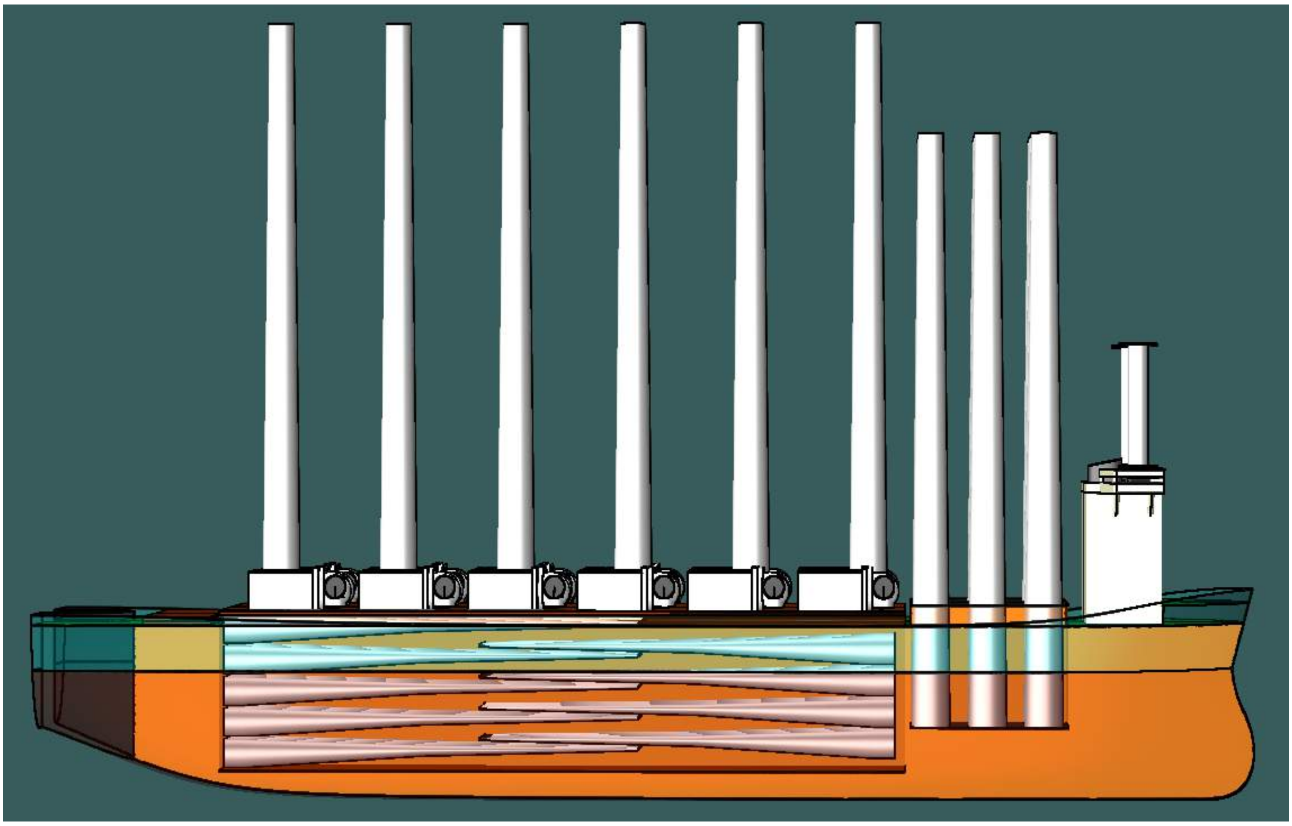


Figure 6-39 Side View of Load out of 5MW Wind Turbine

6.11.3 3.6 MW Turbines Load Out Arrangement

3.6MW wind turbine constitute approximately 20% of installed offshore wind turbine. This size is the third most installed wind turbine across the Europe. The maximum full set of 3.6 MW wind turbine that a vessel loaded and transported so far was 8 set.

Jack-up vessel Bold Tern transported and installed 80 Siemens 3.6 MW wind turbines at the Butendiek wind farm in the German North Sea. It seems the Bold Tern vessel transported and installed 7 full set of this wind turbine per cycle.

Figure 6-40 shows the installation of this wind farm with the Bold Tern jack up vessel.

The dimension and weight of this wind turbine are summarized in the Table 6-5.

Loading of 3.6 MW wind turbine components has been drawn. Figure 6-41, Figure 6-42, Figure 6-43 and Figure 6-44 shows the arrangement of this size of wind turbine onboard the Decom Tools vessel.

In all the loading configuration, it is assumed that dismantling of all components of wind turbines take place offshore. In other words, the wind turbines are dismantled to 5 different components excluding the transition pieces and foundations.

Table 6-5 Weight and Dimension of 3.6MW Wind Turbine

Weight and Dimension of 3.6 MW Wind Turbine	
Component Name	**Size**
Blade length (m)	58.5
Blade Diameter	3.5
Blade mass (t)	17.74
Max. chord (m)	4
Hub mass (t)	25
Nacelle mass (t)	125
Nacelle + Hub mass (t)	150
Nacelle dimensions (m) (L x W x H)	12.5 x 5 x 5.5
Nacelle with hub dimensions (m) (L x W x H)	17 x 5 x 5.5
Tower Mass (t)	210
Tower Height (m)	90
Tower top diameter (m)	3.2
Tower bottom diameter (m)	5

Figure 6-40 Installation of Butendiek Offshore Wind Farm

Decom Tools vessel is able to load and transport 33 full sets of 3.6 MW wind turbine.

The following figures (Figure 6-41, Figure 6-42, Figure 6-43, and Figure 6-44) shows how the loading of this size of wind turbine take place onboard Decom Tools Vessel.

It means transportation by Decom Tools vessel is 4.125 times more efficient than transportation by the jack up vessel.

It should be noted that 3 more nacelles and towers can be loaded on the vessel, since blades are bulky objects, this does not allow to transport more complete set of wind turbine.

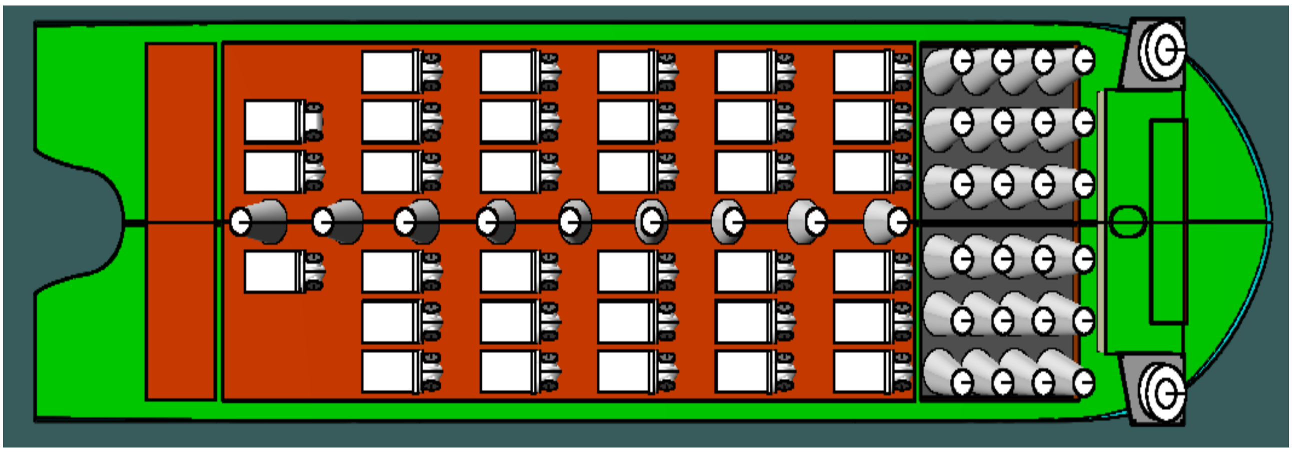


Figure 6-41 Top View of Load out of 3.6 MW Wind Turbine

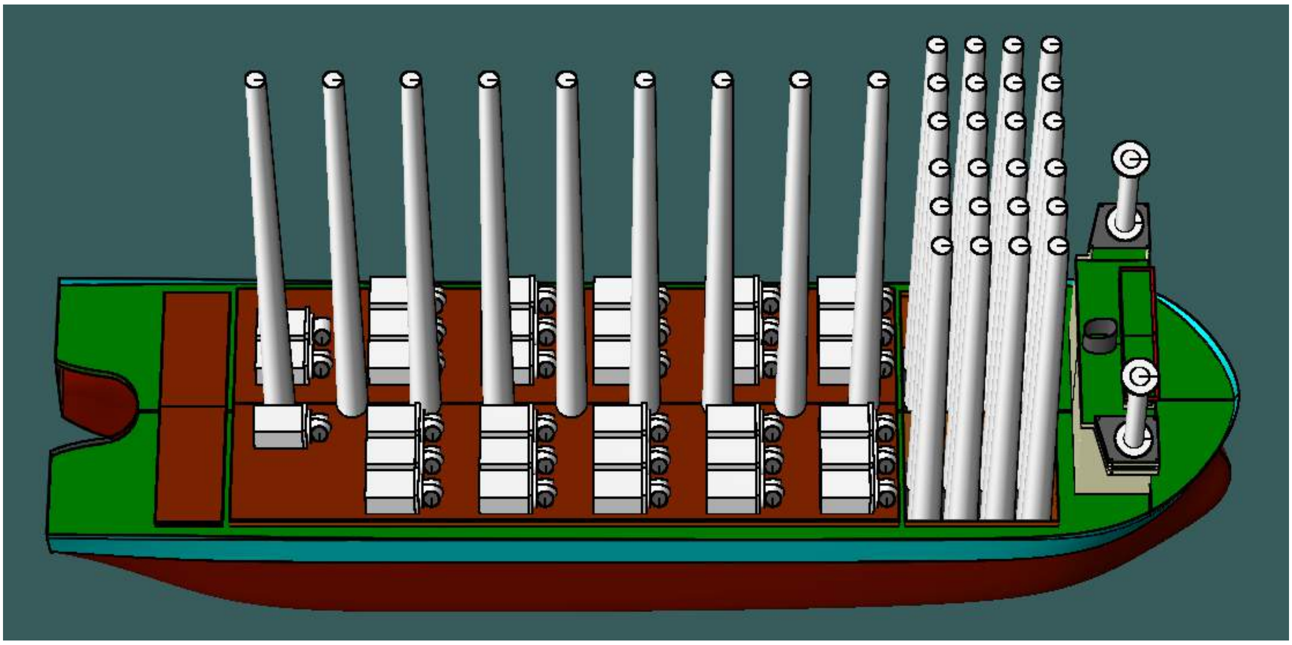


Figure 6-42 Top View of Load out of 3.6 MW Wind Turbine

As it shows in the figures, the towers consist of one segment the same as Figure 6-40. It seems that in transportation of 3.6 MW wind turbine, the tower is made of one segment. Not only the tower of the 3.6 MW is constructed on one segment, but also, the towers of 7 MW are constructed from one segment. The number of segments heavily depend on the boom length of the vessel as well as SWL of the crane. Therefore, it depends which vessel is negotiated to be used for the installation or decommissioning. But it is evident, lower number of segments, need less offshore lifting, less seafastening which lead to less offshore operations. On the other hand, handling and lifting of large components is more difficult and riskier.

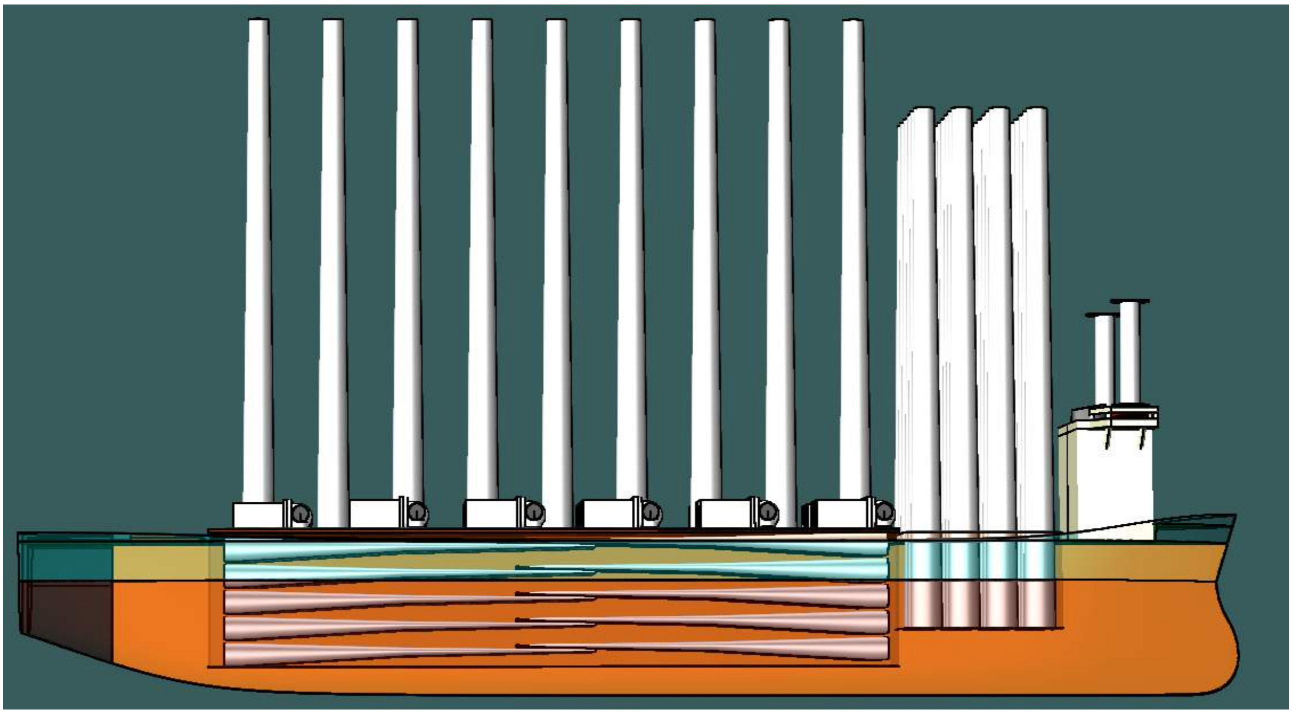


Figure 6-43 Side View of Load out of 3.6 MW Wind Turbine

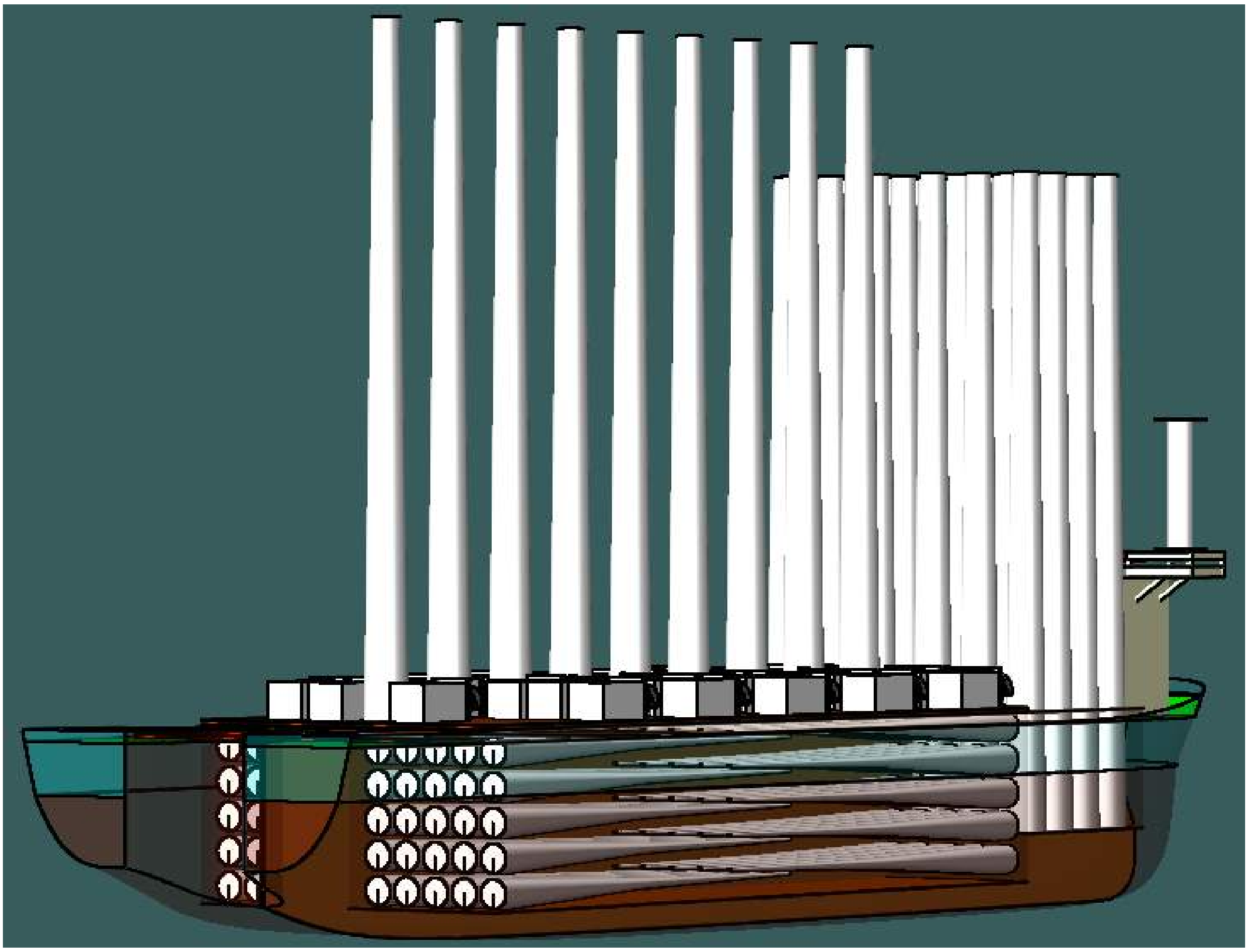


Figure 6-44 Perspective view of Load out of 3.6MW Wind Turbine

6.12 Second Method of Cargo Loading Arrangement (Component Wise)

The second method of cargo arrangement crucially and mainly depends on the port infrastructure and accessibility to the waste management company as well as nacelle manufacturer. The distance and access to the shore infrastructures namely recycling and disassembly companies in the port or in vicinity of the port totally change the business model and logistic method which will impact the overall cost of project and environmental impact. To put it simply, some ports are in proximity of recycling companies which can handle and recycle the composite material such as blade. The other port is in vicinity of the nacelle assembly company like Cuxhaven port which can do the function test of nacelle components as well as disassembly of nacelle. Ultimately, some ports the same as Greena Havn port has metal shredding and recycling facilities inside the port which is a great candidate for the transportation of tower, monopile and transition piece. It can be discussed that there is not any port that can have capabilities to manage all types of materials including cable, blade, nacelle, offshore high voltage substation and structure. This means if all the materials of one offshore wind farm transported to one port, after conduction of the primary process like cutting and disassembly of the main part, they need to be transported again to another ports or base for shredding and recycling. This time, transportation should be done either via high seas, inland waters or shore transportation system namely truck or train. So, in this case the cost of transportation will be higher and also the emission resulting from transportation damage the environment. Therefore, it is highly recommended to decide for each wind park based on the location and access of the ports to the recycling and nacelle manufacturer companies.

Based on our finding which shows in the following figures, even more items can be transported per voyage by the same vessel which lead to higher efficiency. Transportation of more cargo per voyage contributed to less cost, less fuel consumption, and less CO_2 emission.

As an illustration, The Decom Tools Vessel can carry out 16 set of 12MW GE X-Heliade blade, and 24 set of nacelles of same wind turbine.

The following table shows the difference of cargo loading:

Table 6-6 Comparison of Various Loading Plan

Comparison of Cargo Loading Arrangement for 12 MW Wind Turbine					
Loading Plan	**1. Component Wise (Segregation)**				**2. Complete Set (Mixed)**
Components	**Blade**	**Nacelle**	**Tower**	**TP**	**Blade + Nacelle + Tower**
Loading Per Cycle	16 sets (48)	26 No.	24 No.	20 No.	8 set
Efficiency	200%	325%	300%	250%	Base Scenario

Figure 6-45, Figure 6-46 and Figure 6-47 shows load out of 12MW transition piece by Decom Tools vessel. As the above figures show, 20 number of 12 MW transition piece with diameter of 10.2m and height of 41meter can be loaded on the Decom Tools Vessel.

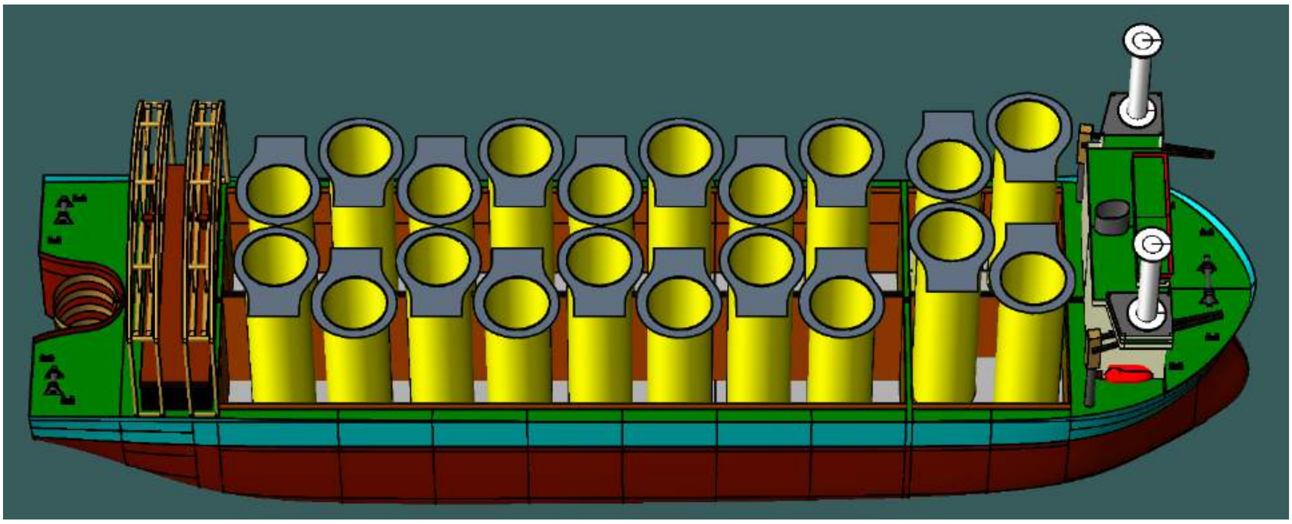


Figure 6-45 Top View of Load of 12MW TP with Decom Tools Vessel

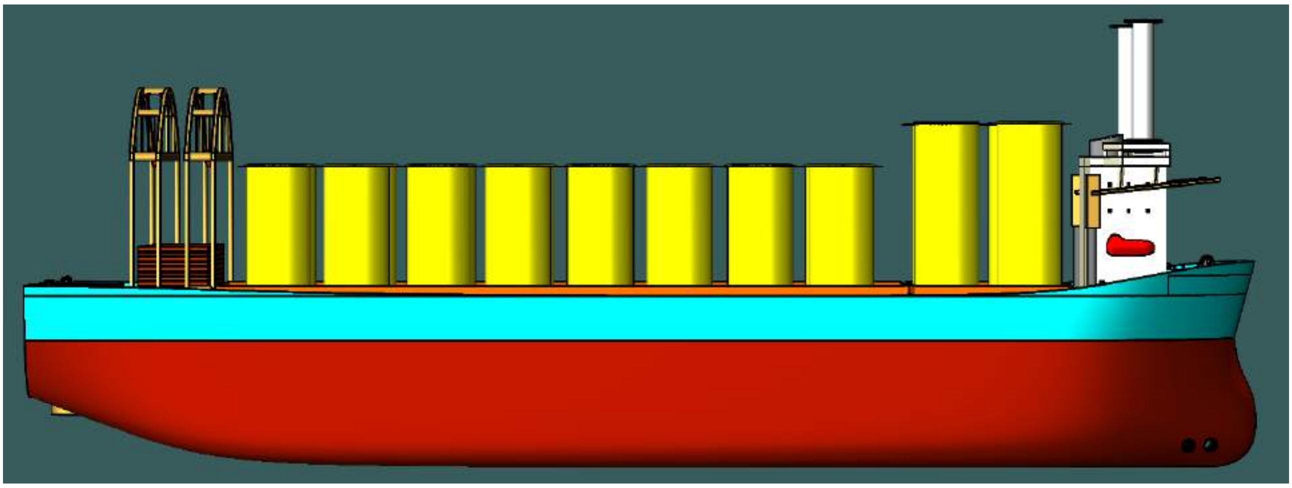


Figure 6-46 Side View of Load of 12MW TP with Decom Tools Vessel

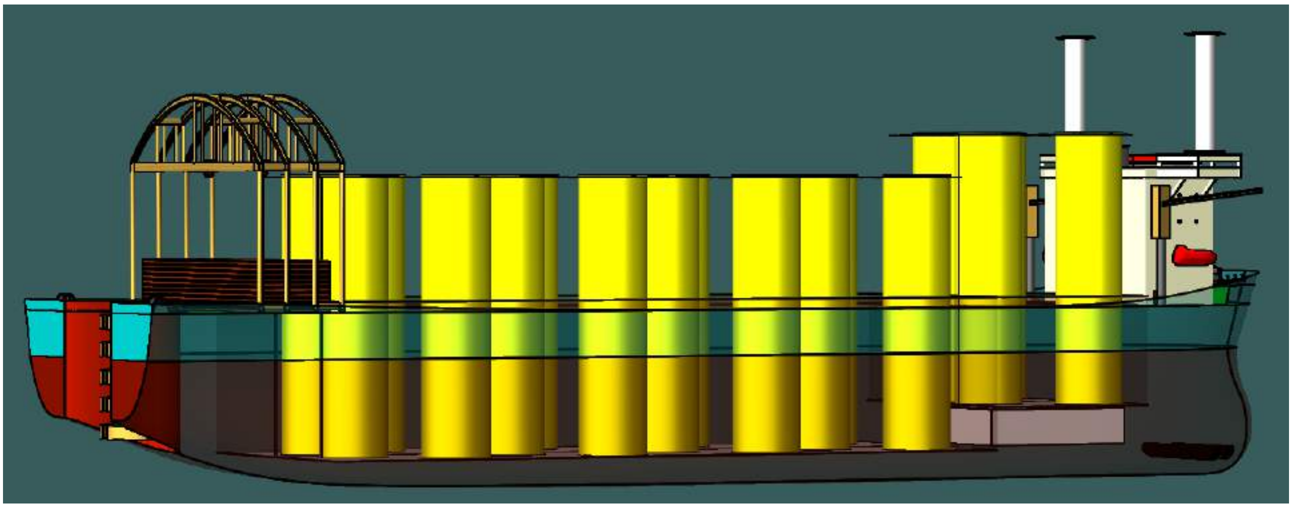


Figure 6-47 Perspective View of Load of 12MW TP with Decom Tools Vessel

Furthermore, Figure 6-48 shows that 48 number of 107-meter blade with root diameter of 5.5 m and weight of 55 tones can be loaded on the Decom Tools Vessel.

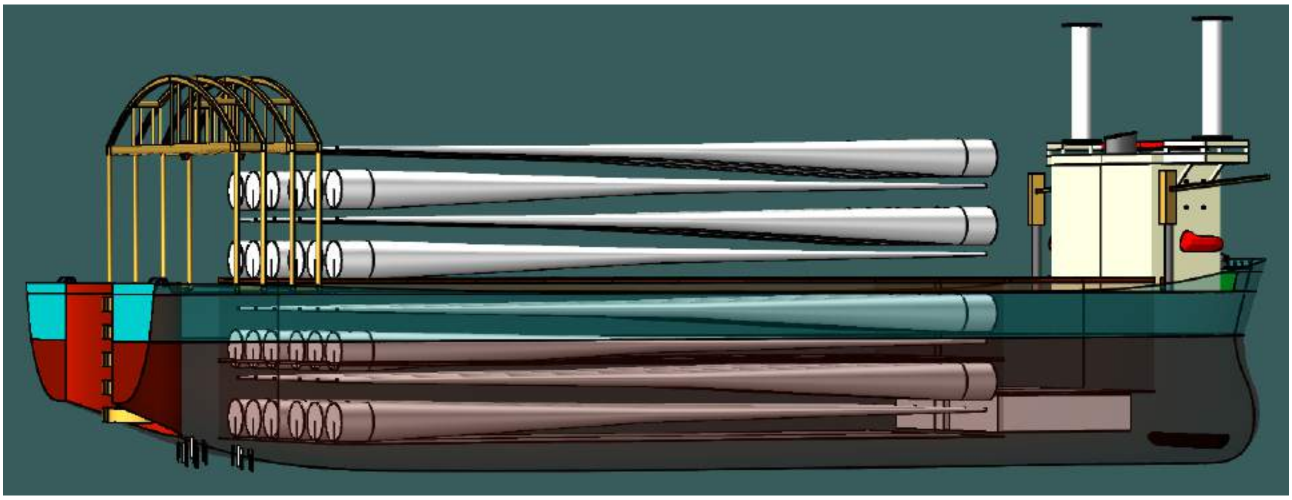


Figure 6-48 Perspective View of Load of 12MW Blade with Decom Tools Vessel

Figure 6-49 and Figure 6-50 show that 24 number of 12MW tower with overall length of 129.1 meter (each tower made of two segments) and weight of 880 tones are loaded onboard the Decom Tools vessel.

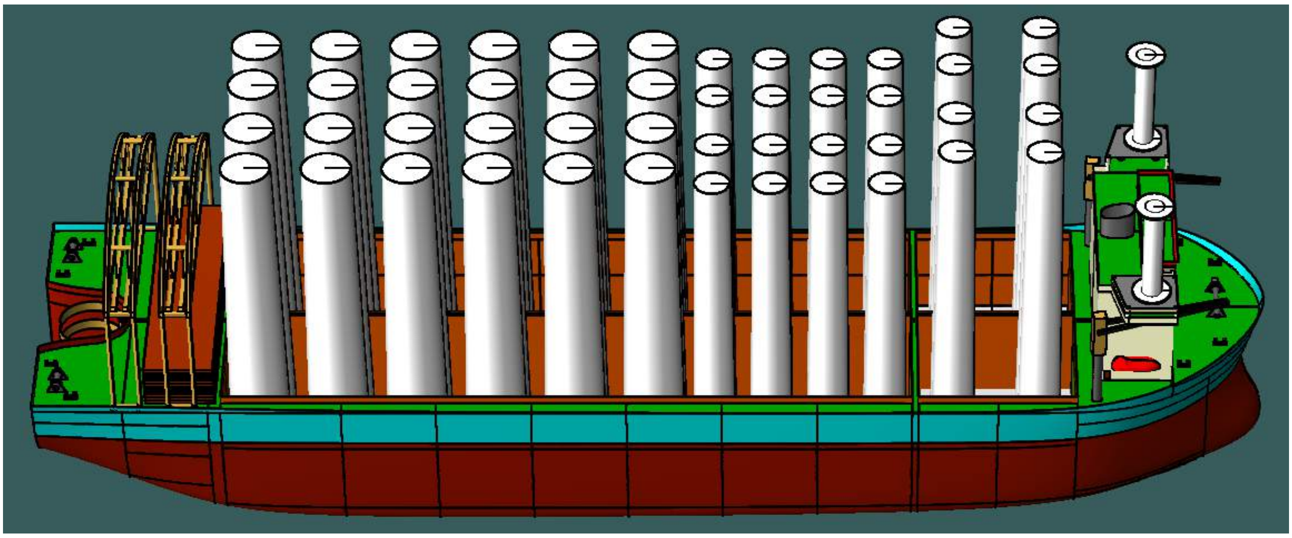


Figure 6-49 Top View of Load of 12MW Tower with Decom Tools Vessel

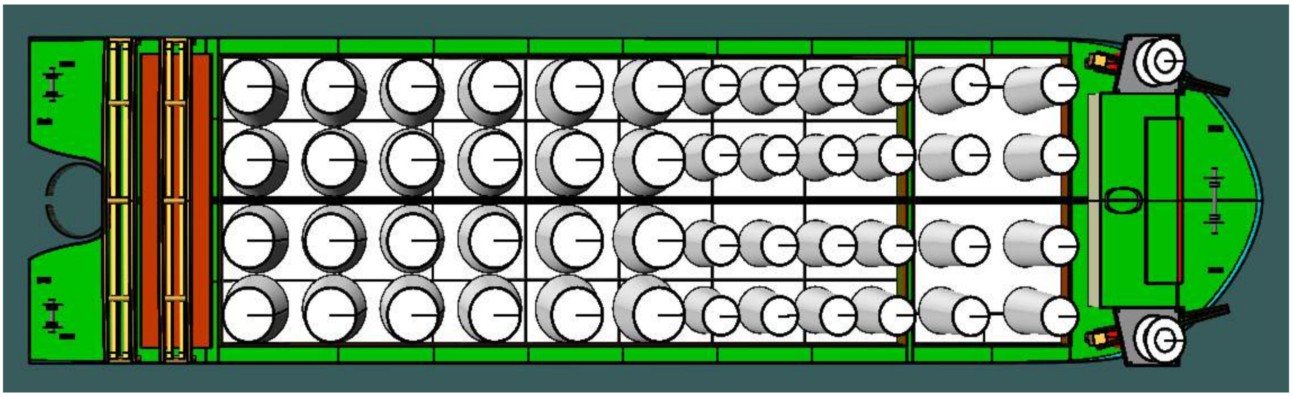


Figure 6-50 Top View of Load of 12MW Tower with Decom Tools Vessel

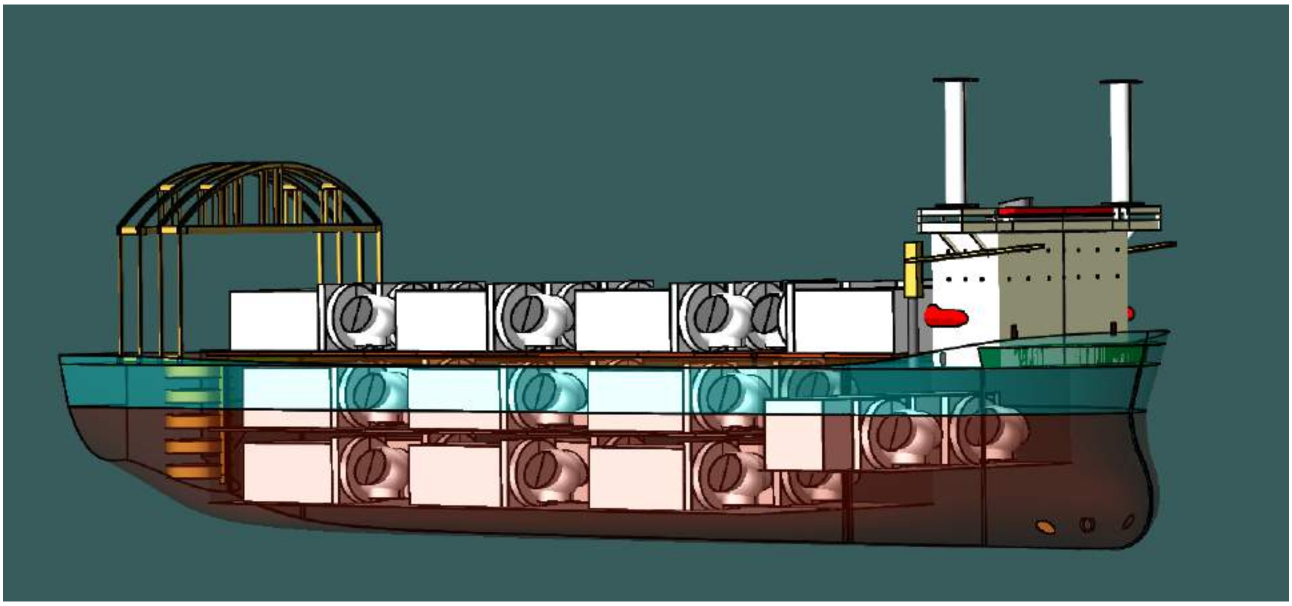


Figure 6-51 Perspective View of Load of 12MW Nacelle with Decom Tools Vessel

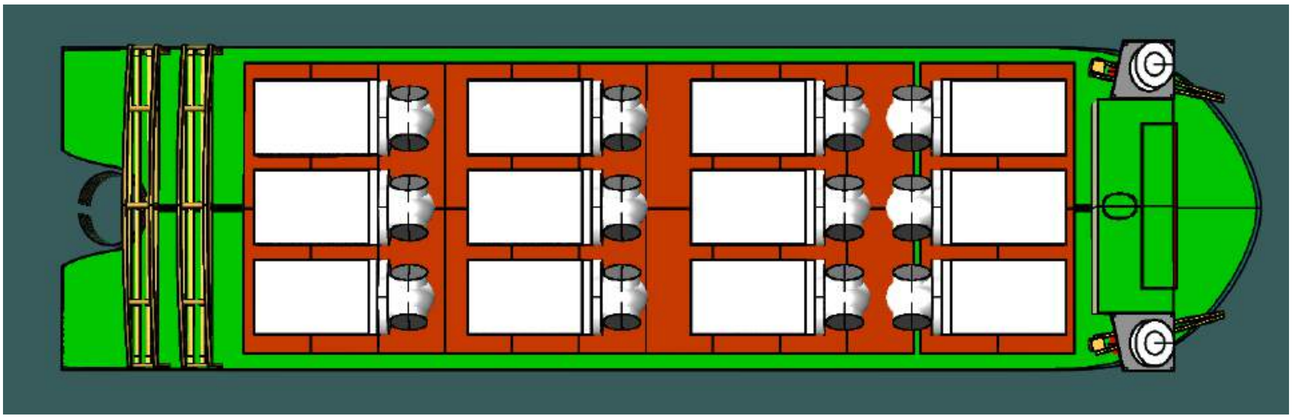


Figure 6-52 Top View of Load of 12MW Nacelle with Decom Tools Vessel

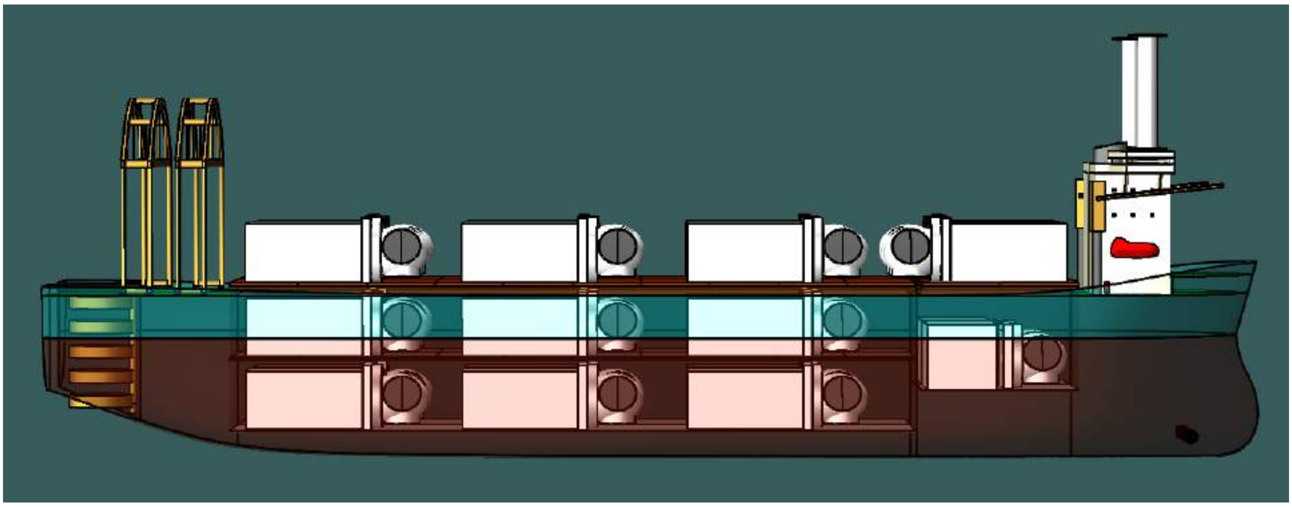


Figure 6-53 Side View of Load of 12MW Nacelle with Decom Tools Vessel

Lastly, Figure 6-51, Figure 6-52 and Figure 6-53 show that 26 number of 12 MW nacelle plus hub with the overall weight of 675 tones and dimension of 29.5 x 11 x 10.5 (L x W x H) can be loaded onboard the Decom Tools vessel.

6 number of nacelles are placed on the top of tank deck (hold number 2), 6 on the tween deck, 12 on the top deck and 2 inside the hold number 1.

6.13 Efficiency of Components Wise Load Out Versus Full Set Load Out

In order to assess which cargo arrangement is more efficient for decommissioning of a wind farm, we have to assume a wind park with specific number of wind turbine.

We assume there is a wind park which has 80 numbers of 12 MW wind turbine that is located 59 km from shore. Then the efficiency of transportation for different cargo loading arrangement can be interpreted as following.

Table 6-6 shows in the segregation loading arrangement (component wise loading plan) greater number of components can be loaded and transported per cycle. However, Table 6-7 shows that for the transportation of all components of the given wind farm, a greater number of voyages is needed by the segregation method. It means that transportation with segregation cargo loading arrangement method will be effective just in case the recycling companies for blade, metal-based materials as well as disassembly company are distributed in vicinity of different ports.

Table 6-7 Comparison of efficiency of Transportation of the given OWF

Comparison of Efficiency of Transportation of the Given Offshore Wind Farm				
Loading Plan	**1. Component Wise (Segregation)**			**2. Complete Set (Mixed)**
Components	**Blade**	**Nacelle**	**Tower**	**Blade + Nacelle + Tower**
Loading Per Cycle	16 set	26 set	24 Set	8 set
Number of Sailing	5 times	3.07 times	3 times	N/A
Overall Number of Sailing	**12 Times (27% Less efficient)**			**10 Times**

In a nutshell, the segregation loading arrangement of component can be efficient in terms of cost, fuel consumption as well as emission just in case the further transportation either onshore or high seas can be avoided. It means, it can be efficient, if the further onshore, inland or high seas transportation can be avoided. However, even, in this case, the calculation has to be done in order to see which modes of transportation (offshore or onshore) is more productive in terms of cost and emission.

6.14 Decom Tools Vessel Seafastening

Seafastening is one of the most significant structures of the projects which is used to secure the components in order to have safe transportation. The importance of seafastening is often undervalued which is a critical stage for the installation/ decommissioning operations (Goalen, Why sea fastening is critical to safe and efficient offshore wind installation 2020).

However, it should be noted that the reusable and adjustable seafastening for the blades have been designed for the Decom Tools vessel.

Prior to explaining the seafastening of the Decom Tools vessel, the existing seafastening in the industry along with pros and cons of each type need to be explained. There are two methods of seafastening of cargos as following.

6.14.1 Conventional Seafastening

The first method of seafastening is the conventional method which have been using in oil and gas industry often as well as sometimes in the wind industry. In this method, mostly the seafastening are welded to the vessel deck from one side and on the other side are welded/secured to the components. In this method, seafastening are designed based on the geometry, weight and centre of gravity (COG) of the components. For offloading the material, they need to be cut, or released if they are secured with wire. Figure 6-54 illustrate the conventional seafastening for the monopile and transition pieces. Figure 6-55 shows how the monopile are secured on the saddle.

Figure 6-54 Conventional Seafastening of TP and Monopile

In addition, Figure 6-56 shows the structure of the sea fastening in the hold of Jumbo vessel for securing the transition pieces. The problem with this method is that seafastening is designed only for the specific cargo according to the weight, COG and geometry of the components. If the new cargo needs to be transported, seafastening shall be cut from the vessel, and new seafastening should be designed for the new cargos. In this case not only the project incurs with huge amount of cost for engineering and construction of new seafastening but also will face with massive amount of unusable materials as well as labour wage for welding and cutting which will damage the environment and resources. Noticing the increase in the size of wind turbine which lead to heftier components, the challenge of seafastening becomes more formidable. Consequently, the conventional seafastening is not any more efficient and cost-effective for the wind industry.

Figure 6-55 Conventional Seafastening of TP and Monopile


Figure 6-56 Seafastening of TP inside the vessel holds (Jumbo Maritime 2010)

6.14.2 Adjustable, Reusable and Automatic Seafastening

Engineering and implementation of proper seafastening enables the safe and efficient transportation of project materials, minimizing the number of trips required to transport the decommissioned components (Goalen, Why sea fastening is critical to safe and efficient offshore wind installation 2020). Not only proper seafastenig can reduce the number of voyage and increase the safety of transportation, but also can reduce the duration of the project substantially. The time that vessel should be in the port for the welding of seafastening or cutting the seafastening can be reduced by using the adjustable, reusable and automatic seafastening which lead to decrease in the charter time of the vessel too. The less charter time means less cost, less fuel consumption and ultimately less CO_2 emission.

New generation of wind turbines just are not bigger and heftier, but also the geometry of them is undergone alteration. Therefore, these types of cargos are different with other cargos which makes securing of them a challenge. In general, the blades need to be transported in racks, the monopiles in cradles or on grillages, and the towers on grillages (Goalen, Why sea fastening is critical to safe and efficient offshore wind installation 2020).

Nowadays, adjustable, reusable, and automatic seafastening for the tower, transition pieces and nacelle has been utilized for installation of OWP. For example, a company by the name of Conbit according to the Figure 6-57 designed a system by the name of Vickas which allows for the safe seafastening of monopiles with a large variety of diameters and up to 1350 tones. Vickas can be used over and over again on different foundation-installation projects (Conbit n.d.).

Figure 6-57 Reusable and Adjustable Seafastening for Monopile Designed by Conbits

Source: (Conbit n.d.)

6.15 Blade Seafastening of Decom Tools Vessel

Not only for monopile, but also for nacelle, transition piece and tower the reusable seafastening has been designed by different companies. The omission to design a reusable seafastening for securing blades in the wind industry is evident. Figure 6-58 and Figure 6-59 illustrates the current seafastening methods which are used to secure the blade for safe transportation.

As you can see in the following photos, the seafastening is designed to secure one size of wind turbine blades. Therefore, for the smaller or bigger blade, new structures should be designed and constructed. This cause wasting huge number of resources including engineering, purchase of the material, construction and finally recycling them.

To fill this gap of the industry, the conceptual design of a seafastening for 12 MW GE X-Heliade wind turbine carried out. The designed structure is adjustable and reusable. It can secure all sizes of produced blades smaller than 12 MW, including 12 MW. The structure is primarily designed to secure the 12 MW blade in 10 points across the length of the blade.

Considering that the length of 12MW blade is about 107 meters, it means that the blade will be secured every 11 meters approximately.

Figure 6-58 Lifting Rack of Blades

However, in the original loading and seafastening which has been done by the blade manufacture (Figure 6-60), the blade is secured from two points. It means that for the safe loading of blades having two racks is enough.

The reason to design 10 racks for securing the blade is as following:

I. These racks can cover the length of all generations and types of blades with different length. However, the racks in the Decom Tools vessel are designed to be mounted on the skid (rail) in order to be adjusted in the longitudinal direction.

II. The main reason is to cut the blade from various points while the vessel is under sailing. The benefits of cutting the blades inside the Decom Tools vessel are explained in the next section. Therefore, 10 racks are designed in order to secure the blade after cutting.

Figure 6-59 Current Structure for Seafastening the Blade (Akavi n.d.)

Figure 6-60 Seafastening of 12 MW Blade for GE X-Heliade

Figure 6-61 shows how the seafastening of Decom Tools vessel look like.

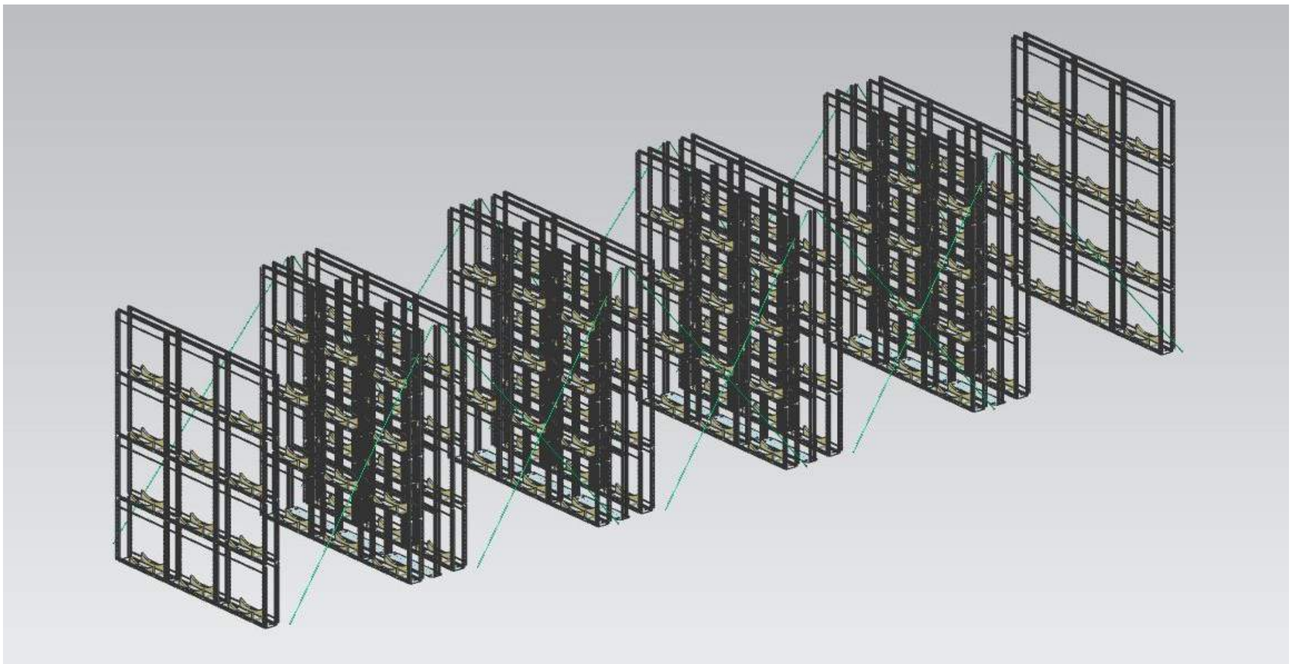


Figure 6-61 Blade's Seafastening of the Decom Tools Vessel

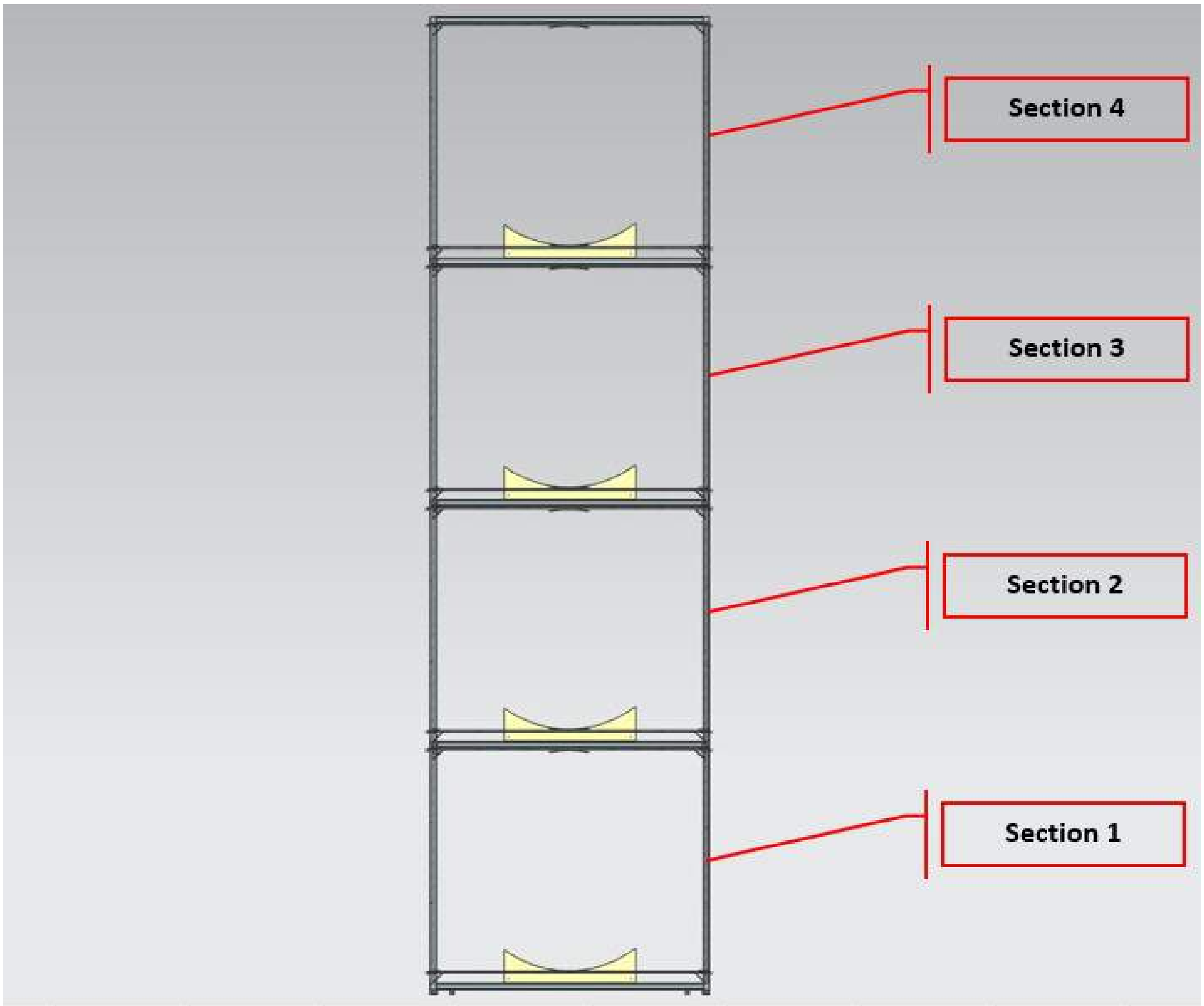


Figure 6-62 One rack for the Seafastening 4 blades (12 MW)

In this design, one rack is made of 4 sections which are mounted on top of each other. In each section, one blade with diameter of 5.5 meter can be secured. Then sections are secured on top of each other by using the twist lock. This type of lock is used in all the containers for securing them on top of each other. It means that the technology and the method is reliable and safe.

Figure 6-63 Twist Lock & Bridge Fitting Clamp

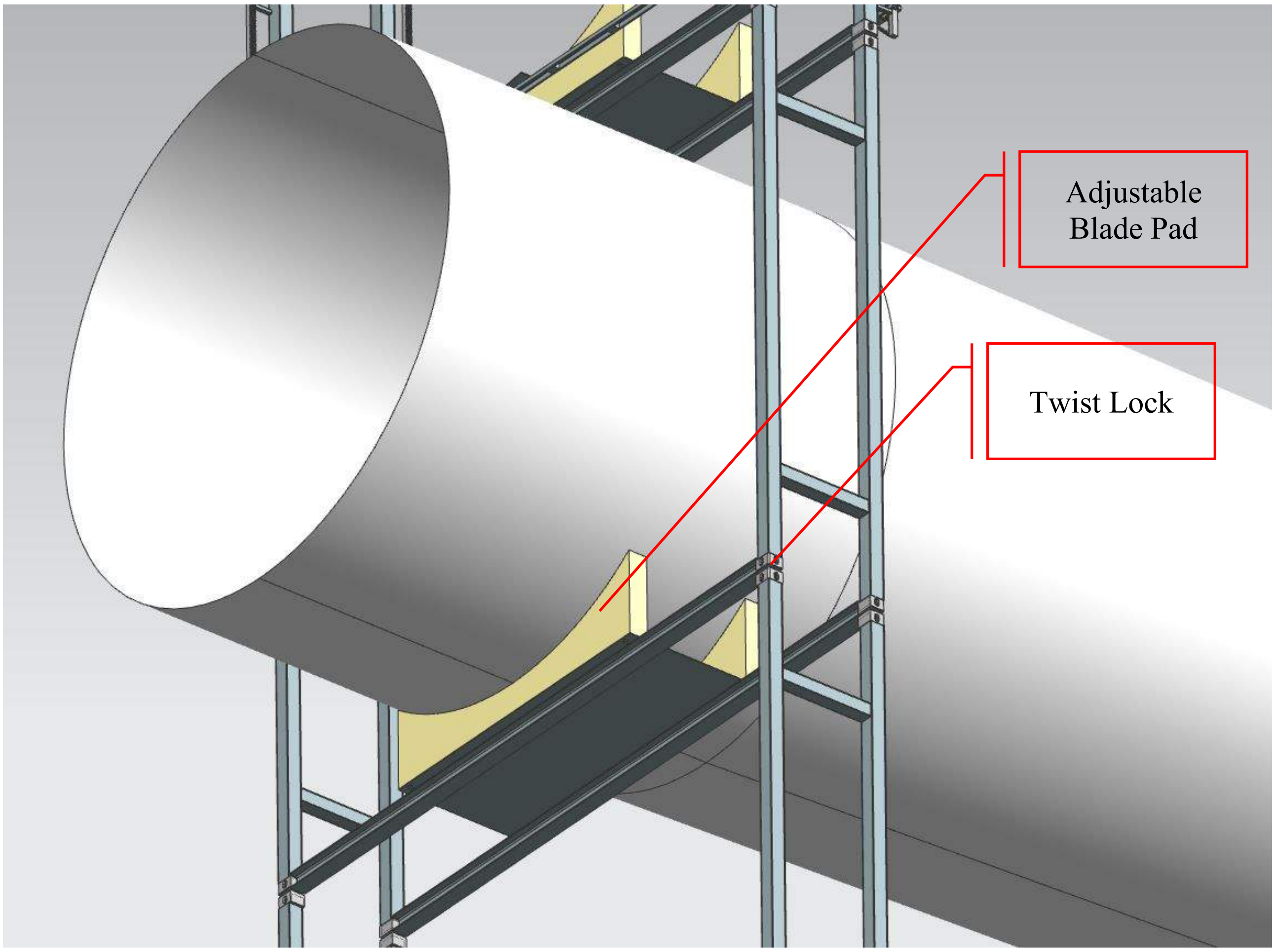


Figure 6-64 Blade Pad and Twist Lock

Figure 6-64 shows how one blade rest on the blade pad and how the sections can be locked on top of each other. In this design, the only component which need to be adjusted for different size of blade is the blade pad. This pad is designed for the 12 MW GE X-Heliad blade.

In case, the smaller size of the blade needs to be secured inside the rack, just the pad should be changed.

In the following figure, the mechanism how the sections are secured on top of each other by using the twist locks are shown. Figure 6-65 shows how the twist lock and bridge fitting clamp secure the large size containers.

Bridge fitting clamp is another tool that can be used to lock the sections either on the horizonal or vertical direction. As it showed before, in each section of hold number 2, 3 racks of blade can be installed adjacent to each other. These three racks need to be secured by means of bridge fitting clamp. In the next figures, it shows how the racks can be secured on the horizontal and vertical direction.

Figure 6-65 Application of Twist lock in securing containers

Figure 6-67 and Figure 6-68 shows how the racks are connected to each other. The whole racks can be lifted and placed inside the hold number 2 of the Decom Tools vessel. they can be lifted as a single rack or all racks together.

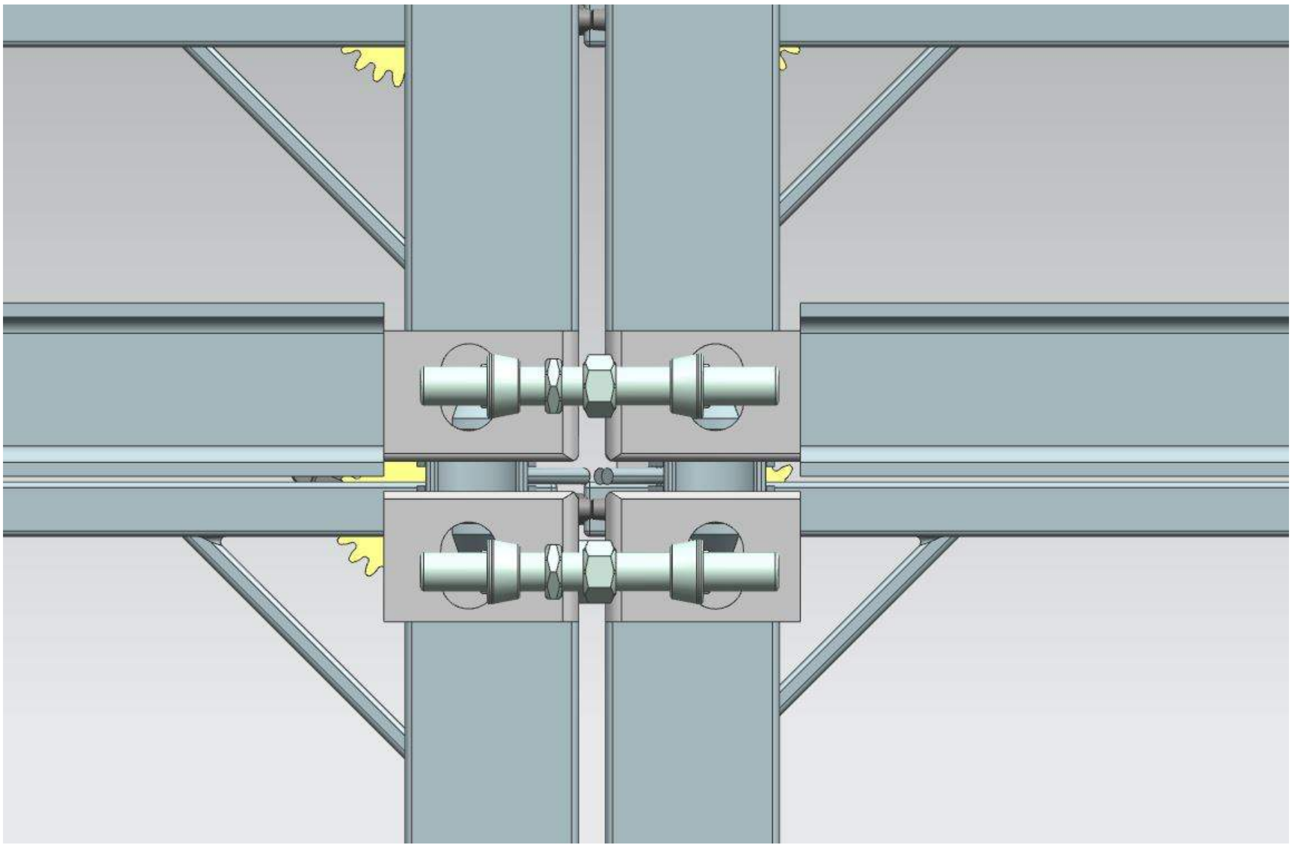


Figure 6-66 Connection of Blades Rack

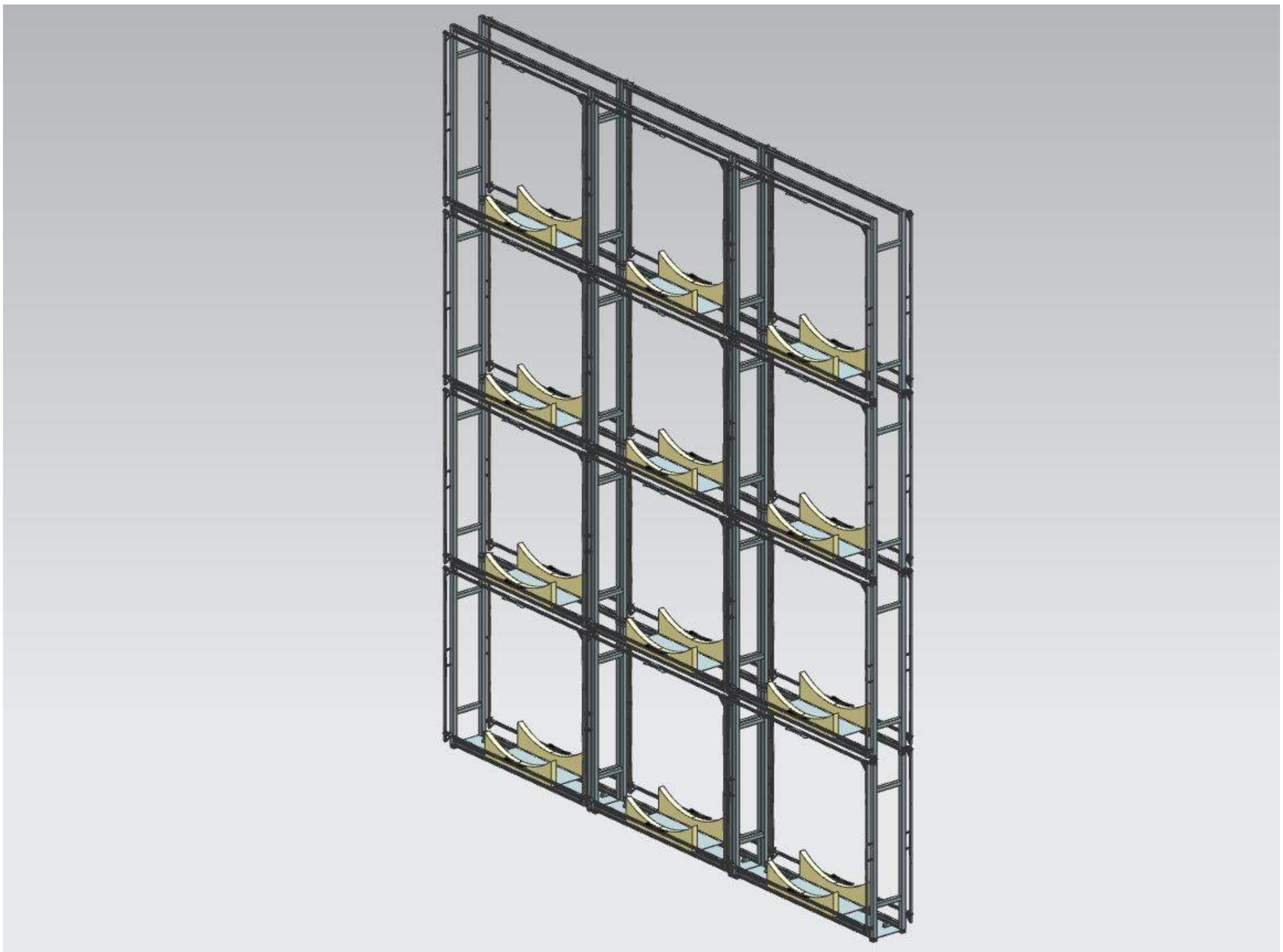


Figure 6-67 Perspective View of 3 racks of Blade

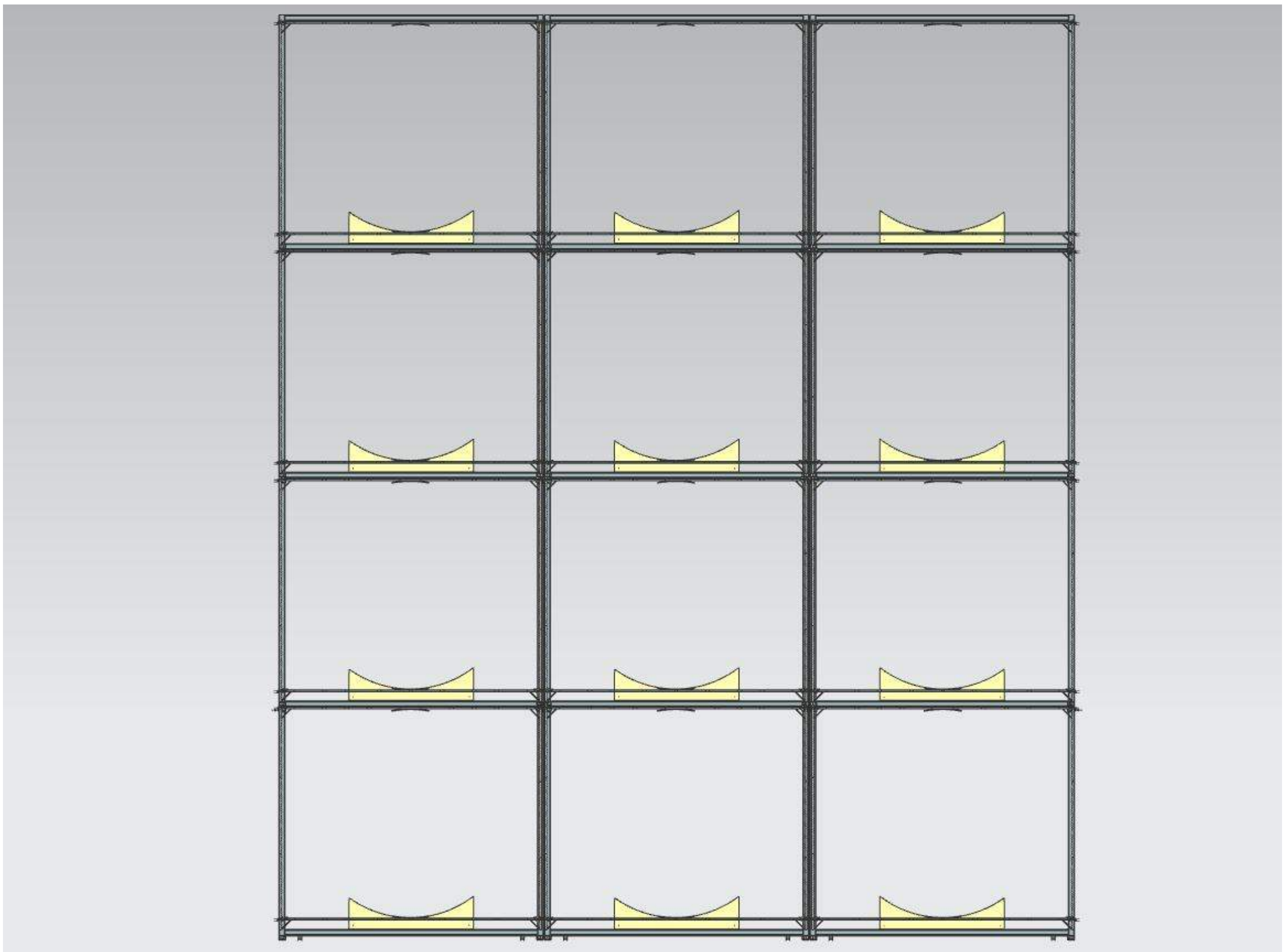


Figure 6-68 Front View of 3 Connected Racks

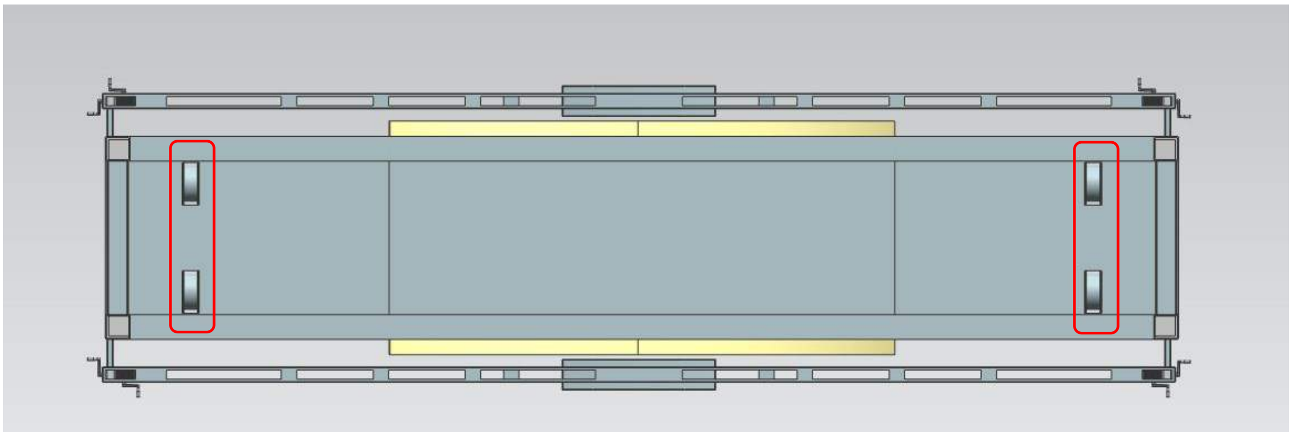


Figure 6-69 Bottom View of the Rack

As it stated earlier, the racks are installed on the rail in order to be adjusted longitudinally inside the hold number 2. Figure 6-69 shows the wheel that makes the rack adjustable for various length of blades.

Figure 6-70 shows the adjustable clamp which is designed for the securing of the blade inside the rack. This clamp can be adjusted with a manual lever or with motorized one. In this figure the manual seafastening is shown. The clamp is moving up and down with the pinion and rack system. This clamp is reusable and adjustable. It means in case one blade need to be secured with diameter of 5.5 meter or less, the clamp can secure it safely inside the section of rack. The above method of securing the blade is so easy, quick and safe. The problem is that this tool can secure just one number of blades inside each section of the rack. To solve this problem, another set of movable and adjustable pad eyes are designed to move inside the rail to secure the blades with wire.

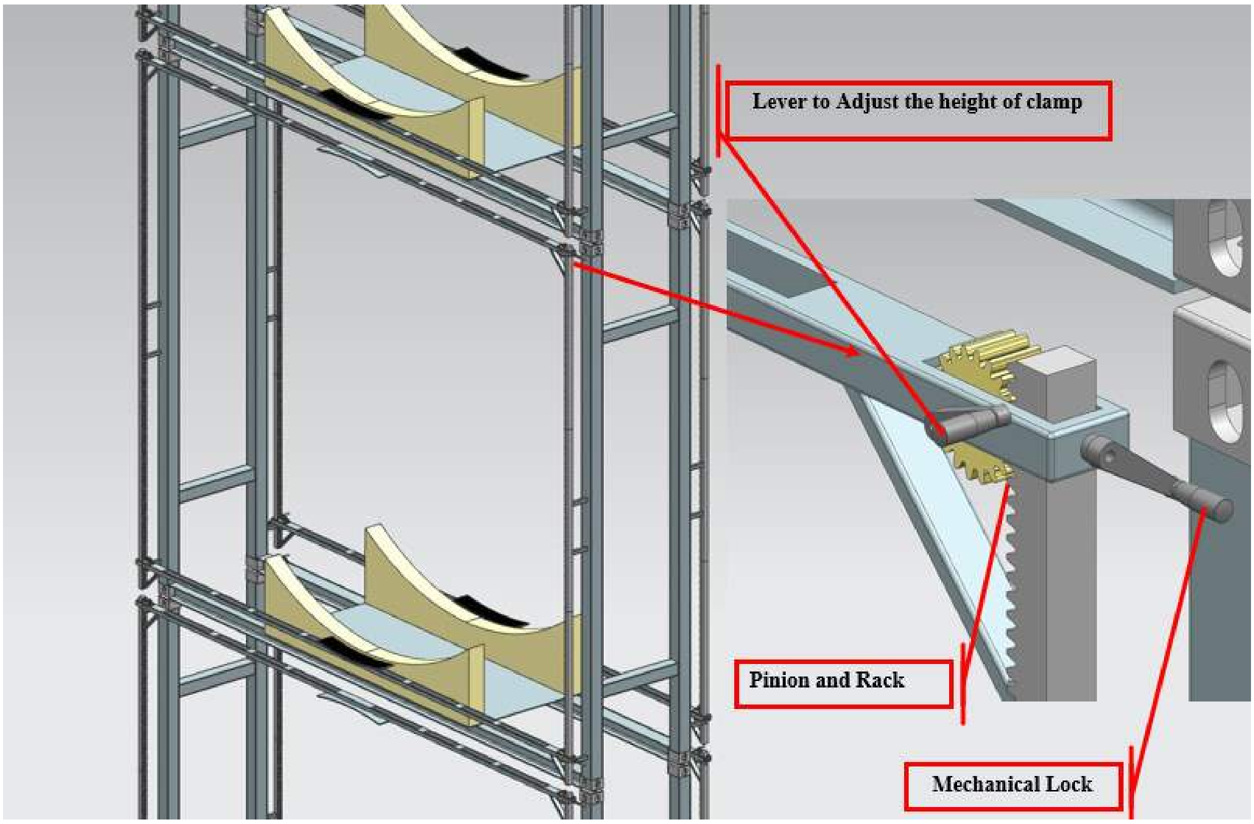


Figure 6-70 Blade Securing System

6.16 Blades Cutting Mechanism

To reduce the cost of onshore transportation as well as preventing damage to the environment, and personnel authors designed an economic and environmentally friendly strategy which is cutting the blades while the vessel is under sailing from offshore wind farm to the port or decommissioning yard. This strategy has many advantages as following:

1. Cutting the blades with any technology result in creation of the dust and small pieces of materials which will spread in the environment and consequently harm the environment and personnel. In case of cutting the blades inside the Decom Tools vessel holds, the dust resulted from cutting will be accumulated in the holds which will be collected by industrial vacuum cleaner to prevent damaging to the environment and personnel. Figure 6-71 and Figure 6-72 show that during manufacturing the blades all the involved personnel in the factory worn special face mask and personal protective equipment (PPE) which shows how detrimental the blades materials are for the human being and environment. In other words, cutting and shredding the blades which are mostly made of fiberglass and resin should be

carried out in enclosed space to avoid spreading of the materials. Besides, the operators and technicians should take precautionary measures to keep themselves safe.

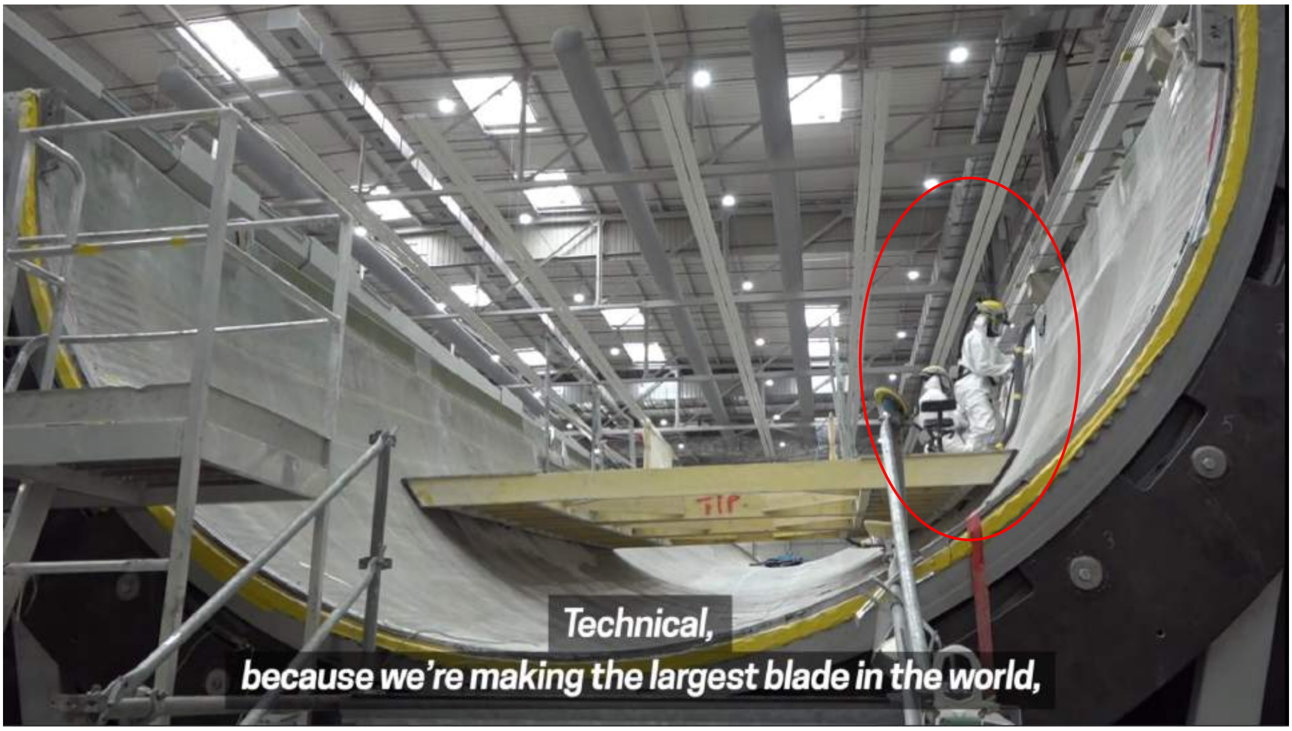


Figure 6-71 Manufacturing of 12 MW Blade (all staffs with Special Face Mask and PPE)

Figure 6-72 Manufacturing of 12 MW Blade (all staffs with Special Face Mask and PPE)

2. If the blades are not cut into the small pieces, for offloading the blades from Decom Tools vessel or any other vessel to the port, at least two cranes are needed to lift the blades from the vessel to quayside. In addition, for further transportation at least two SPMTs or trucks are needed to transport the blades to the desired location for further processing. Demanding two SPMTs or truck for transportation and 2 cranes for safe offloading means incurring double cost to the project as well as double emission. Moreover, the handling and lifting the big and heavier objects are more difficult and has higher risk to the personnel.

3. The ship is under sailing and consuming fuel, so any operation to ease the onshore waste management or recycling during sailing will lead to saving cost and mitigation of CO_2. A meeting with one Italian company regarding this system has been held and they said that cutting the blade into the size of 10 meter which make it possible to transport it with normal truck reduce the cost of onshore transportation more than 10 times. Since no cost calculation has been done, therefore, the authors cannot proof the cost reduction exactly.

6.16.1 Operation of Cutting Machine and Seafastening

Figure 6-74 shows schematically how the blades can be secured inside the holds and how the cutting of them take place. It should be noted that the cutting technology is diamond wire cutter since the cutting does not emit any emission and is fully electrical.

According to Figure 6-73, the details of cutting tool are elaborated as following:

1. The force that are applied to the blade during cutting can cause the blade cutting tool unstable. Therefore, on the top of the cutting tool pad eyes are devised to connect the top of blade cutting tools to the bottom of hold. The green lines in the Figure 6-74 and other figures shows how cutting tools are secured.

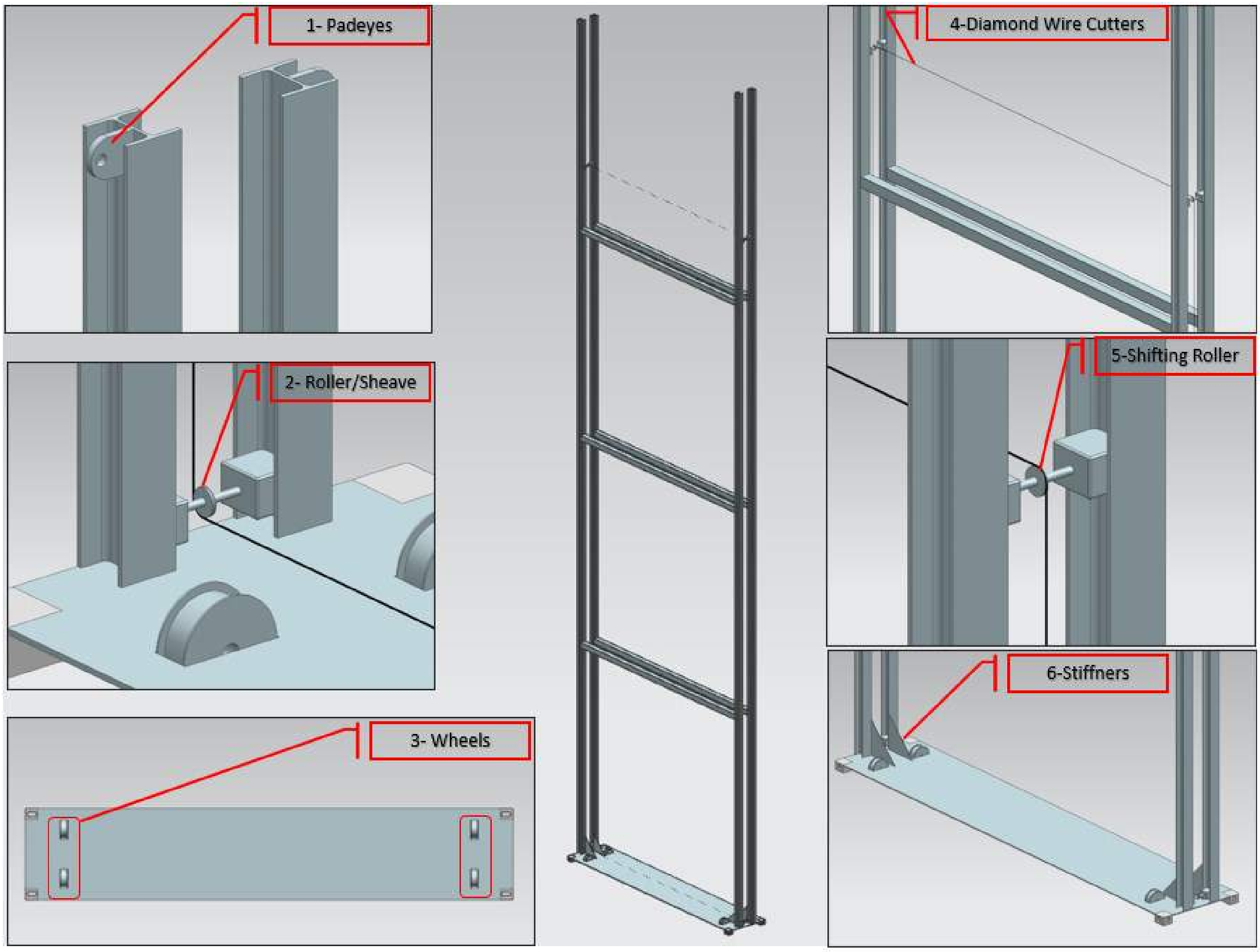


Figure 6-73 Details of Blade Cutting Tool

2. The roller/sheave causes the wire to move inside a loop.
3. More importantly, the wire cutter can also be skidded longitudinally since it will be mounted on skid. It means that operator can shift the cutting tools and cut the blades from any location. The aim of authors is to cut the blade to the length of maximum 13meters in order to be easily offloaded and transported onshore.
4. The diamond wire cutter which cut the blades.
5. The shifting roller which leads the diamond wire cutter to move up and down.
6. To make the structure more rigid and stable, the stiffeners are designed at the base frame of the cutting tools.

The finite element analysis has been carried out for the structure of the seafastening, yet for the cutting tools no analysis has been done since the information regarding the hardness of the blade is not available.

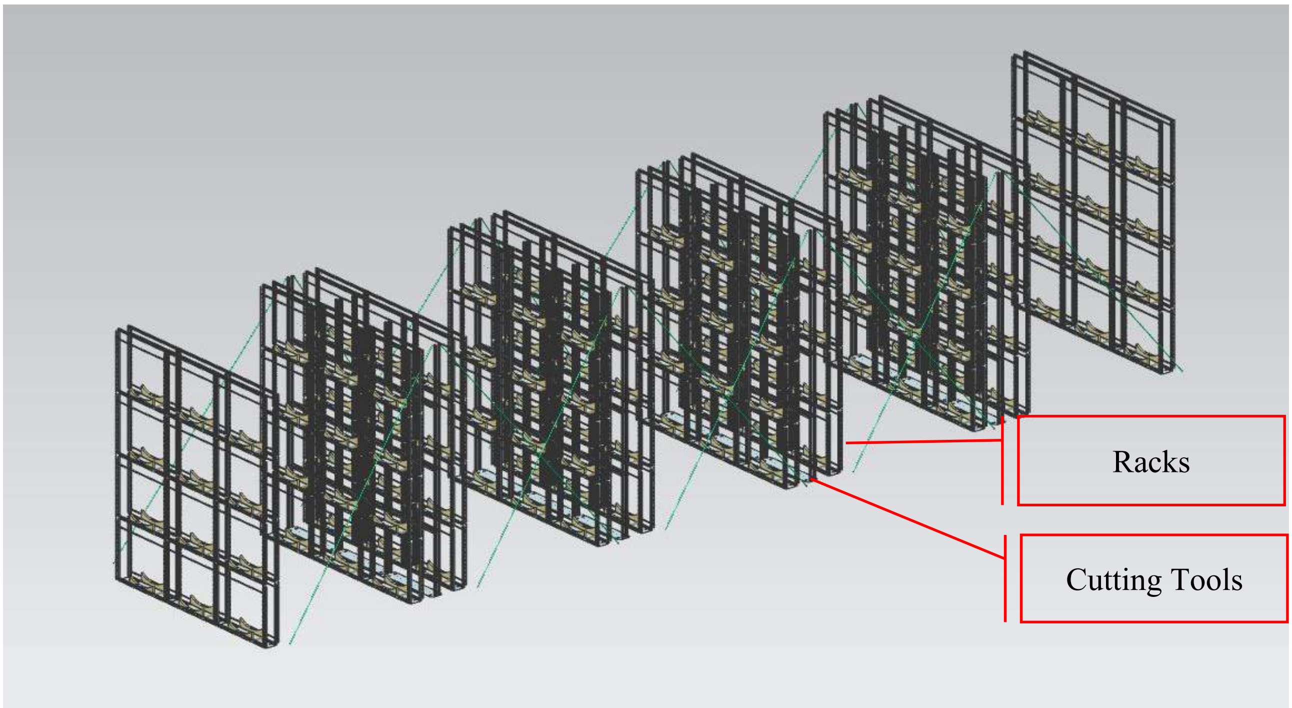


Figure 6-74 Blades Rack and Cutting tools

6.16.1.1 12 MW Blade Loading Arrangement

The FE analysis and calculation for the structure of racks for three different sizes of blades namely for 12 MW, 5MW and 3.6 MW blade are carried out. The detail of design and calculation can be found in another document[64]. Figure 6-75 shows how 12 MW blades can be loaded inside the designed racks. Figure 6-75 shows two different sets of cutting tools. The first sets are fixed which are placed between the racks.

[64] The seafastening and blade cutting tools have been designed as a bachelor student under supervision of Dr Marcus and Hamed Askari, but the document is in German language.

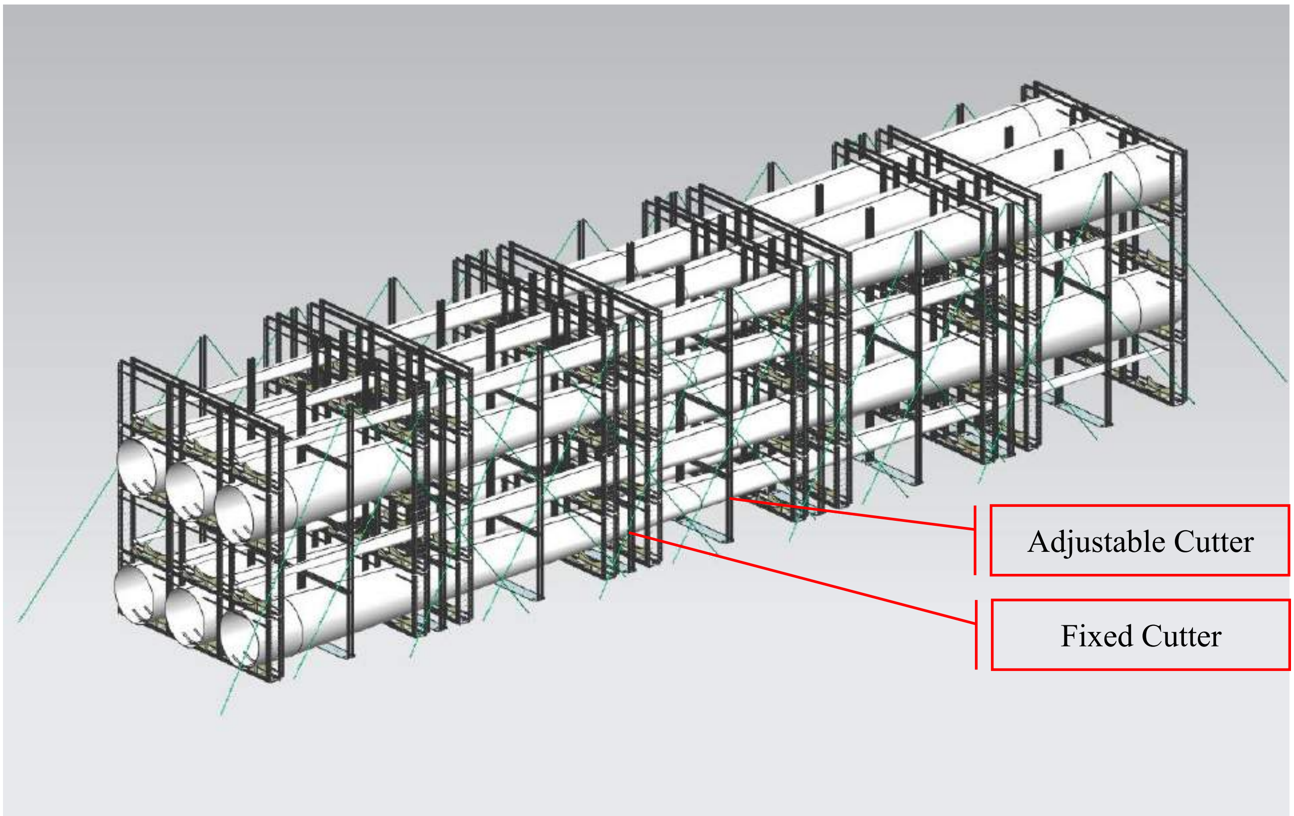


Figure 6-75 12 MW blades inside the racks (Ready for cutting)

These sets of cutters are arranged to cut the 12 MW blade every 26 meter. Adjustable cutters are in the middle of two sets of racks. These are installed on the rails and can cut the blades into the small pieces. It is proposed to cut the blades into the length of 13 meters since the maximum length of a cargo that a normal truck can transport is 13 meters. However, if time allow, the cutting can be done into smaller sections too. Furthermore, for securing one number of blades inside the rack, clamp with pinion and racks are designed to hold the blades firmly. This clamp is suitable in case one blades planned to be loaded inside each section of the rack. The following figure shows the clamp and how it can work.

6.16.1.2 5 MW Blade Loading Arrangement

Figure 6-76 shows 24 numbers of the 5 MW blades can be loaded inside the racks as following. With this arrangement, in both sections of second holds, 48 numbers of blades can be loaded which means 16 full set of 5MW turbine. However, this loading configuration is not optimum loading arrangement.

Figure 6-76 shows 2 significant problems. The first problem is that due to length of 5MW blades, half of the racks and cutting tools are useless. The avoid this problem, the racks and cutting tools are installed on the rails. Therefore, after adjusting the racks and cutting tools, the location of cutting tools and racks with respect to the blade will be the same as Figure 6-77.

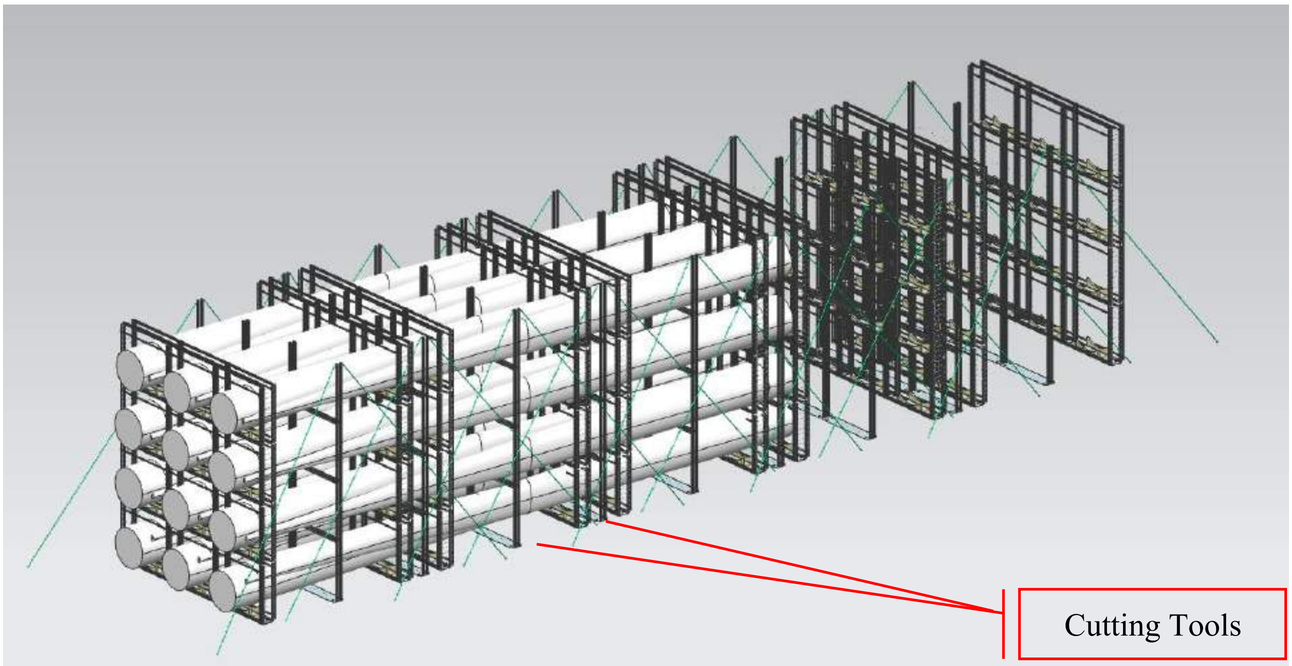


Figure 6-76 5MW blades inside the racks

Then in this case the blade can be cut to the section of 7.33 meter with using 9 number of adjustable and fix cutter.

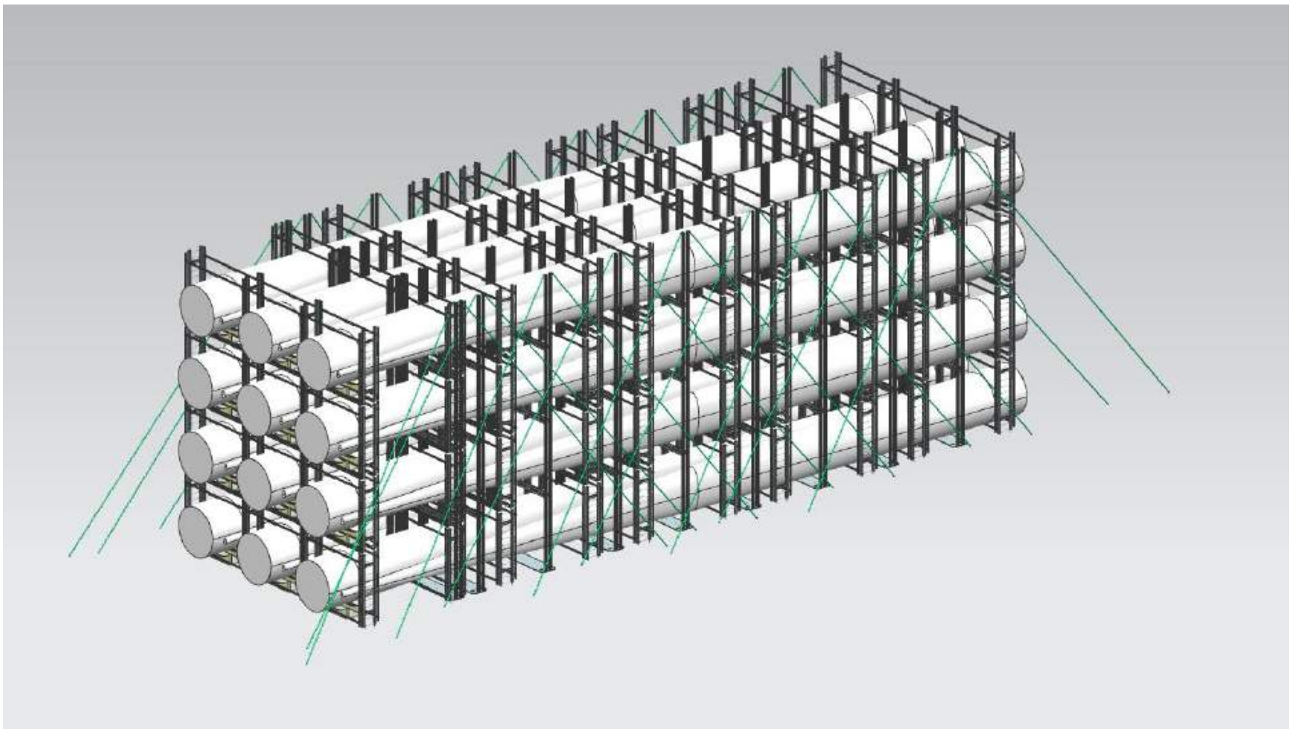


Figure 6-77 Racks and Cutting Tools are Adjusted for 5 MW blades

The problem with the above figure is that just 48 numbers of 5MW blades can be loaded inside the second hold with this arrangement. To increase the efficiency of the transportation, another cargo loading arrangement for 5 MW blades has been adopted the same as Figure 6-79.

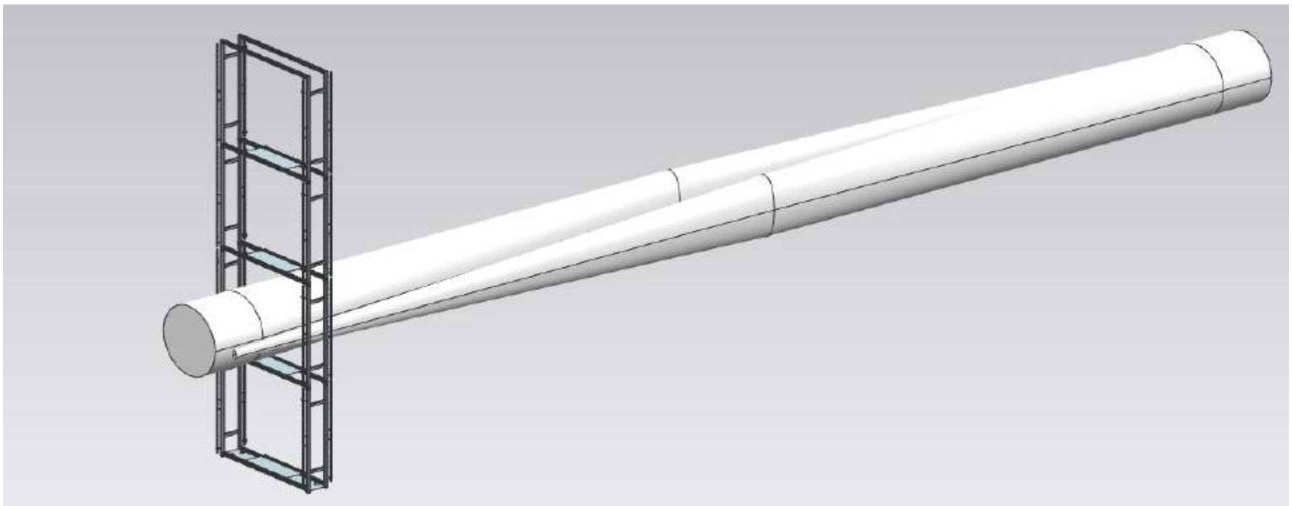


Figure 6-78 Securing 2 numbers of 5MW blades inside the racks

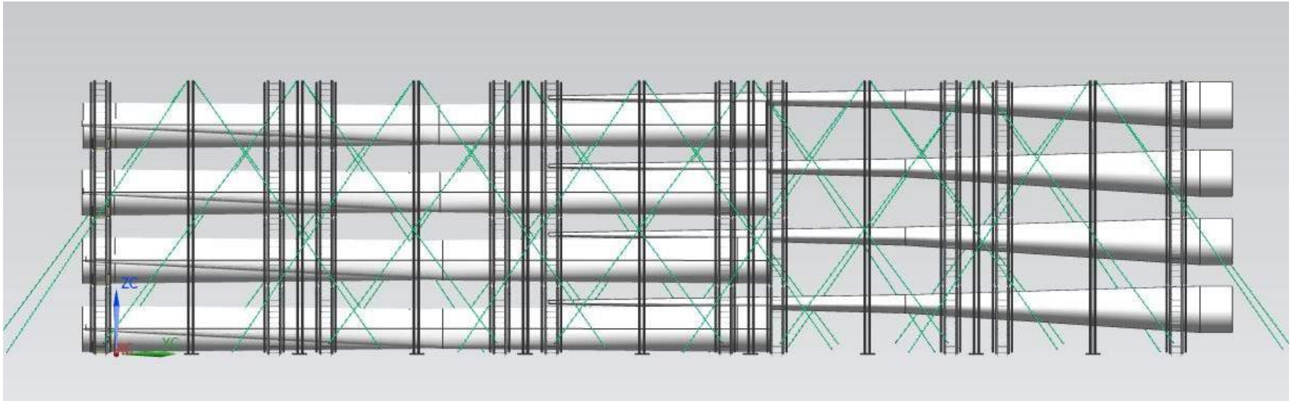


Figure 6-79 Optimum Load out of 5MW Blades

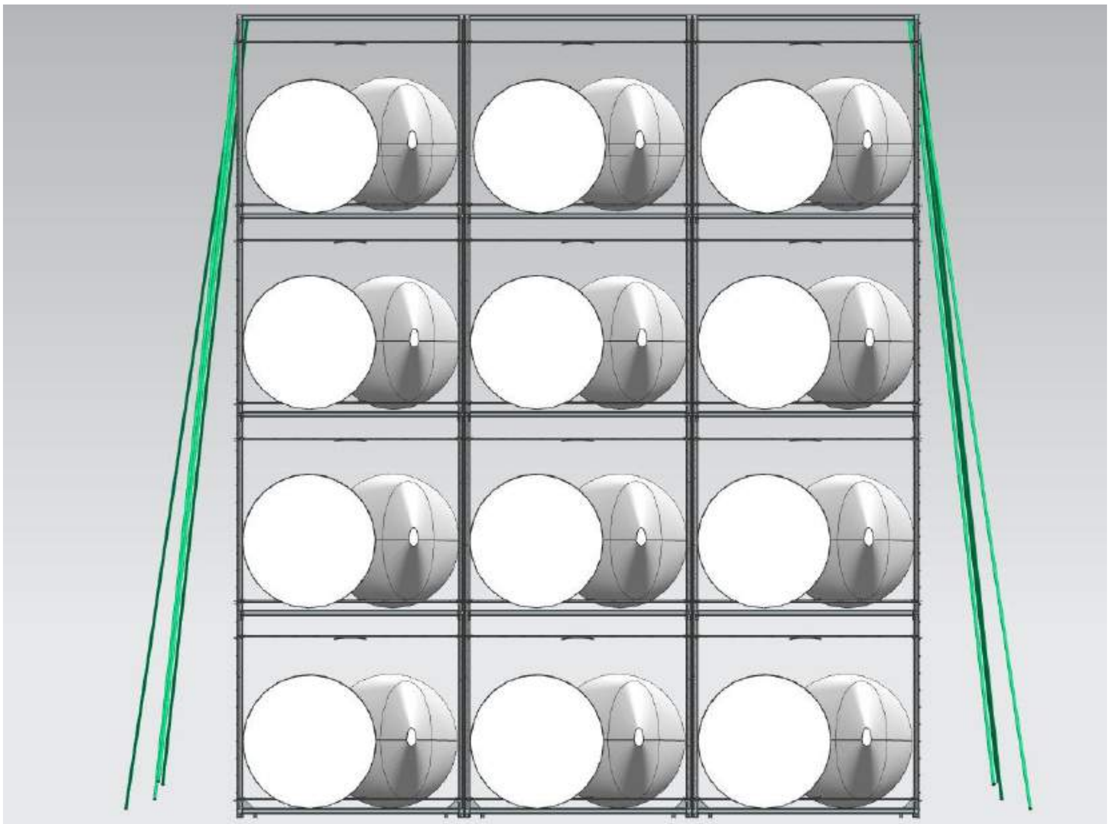


Figure 6-80 Front View of Loading 5MW blades inside the racks

Figure 6-79 shows by adopting this cargo loading arrangement, 36 numbers of blades can be loaded inside each section of hold which means in overall, 72 numbers of 5MW blades can be loaded in hold number 2. Again, the 5MW blades can be cut to the length of 13 meter.

6.16.1.3 3.6 MW Blade Loading Arrangement

Figure 6-81 shows the load out of 3.6 MW blades inside the racks. If the racks and cutting tools are not adjustable, this problem will be happened.

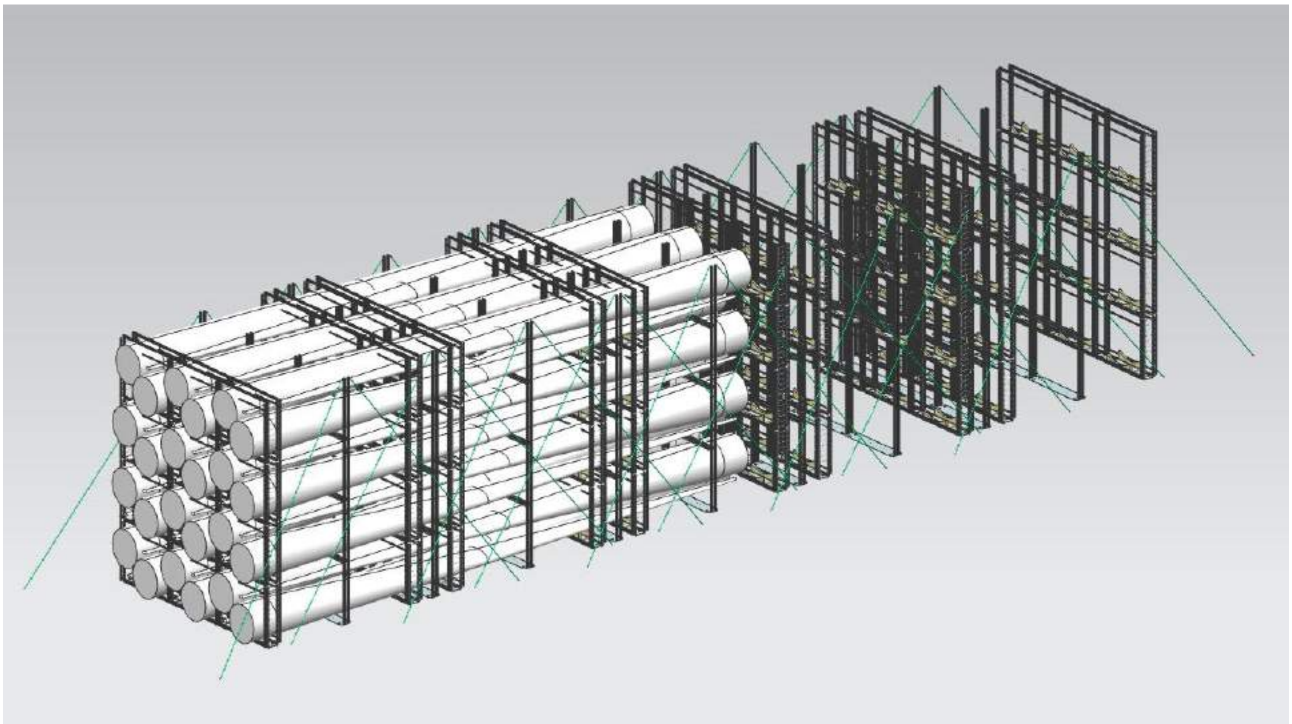


Figure 6-81 3.6 MW blades inside the racks (Perspective View)

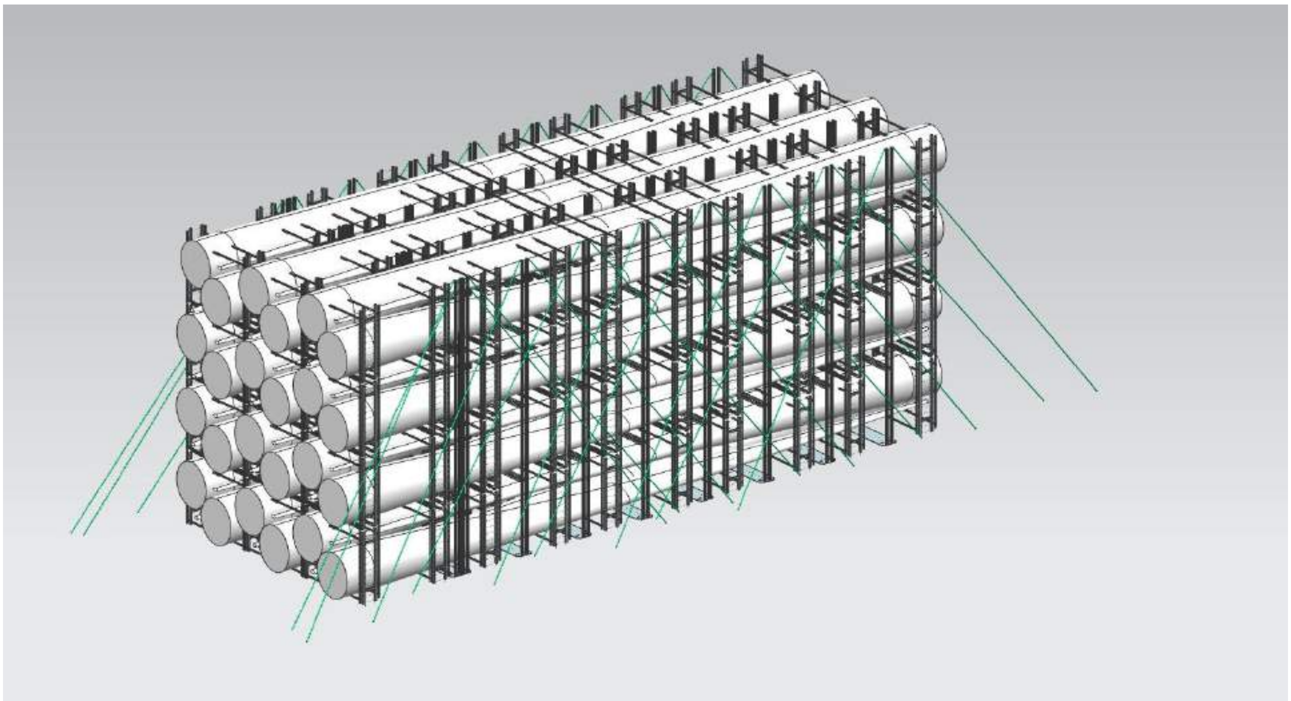


Figure 6-82 Optimum Arrangement of Rack and Cutting Tools for 3.6 MW blades

The problem of Figure 6-81 is that in this situation, 4 numbers of cutting tool cannot work and they will be useless onboard the vessel. To solve this problem, the racks and cutting tools are tailored to the size of the blades by adjusting their distance on the rail. In this case, the 3.6 MW blades can be cut into the length of 6.5 meter

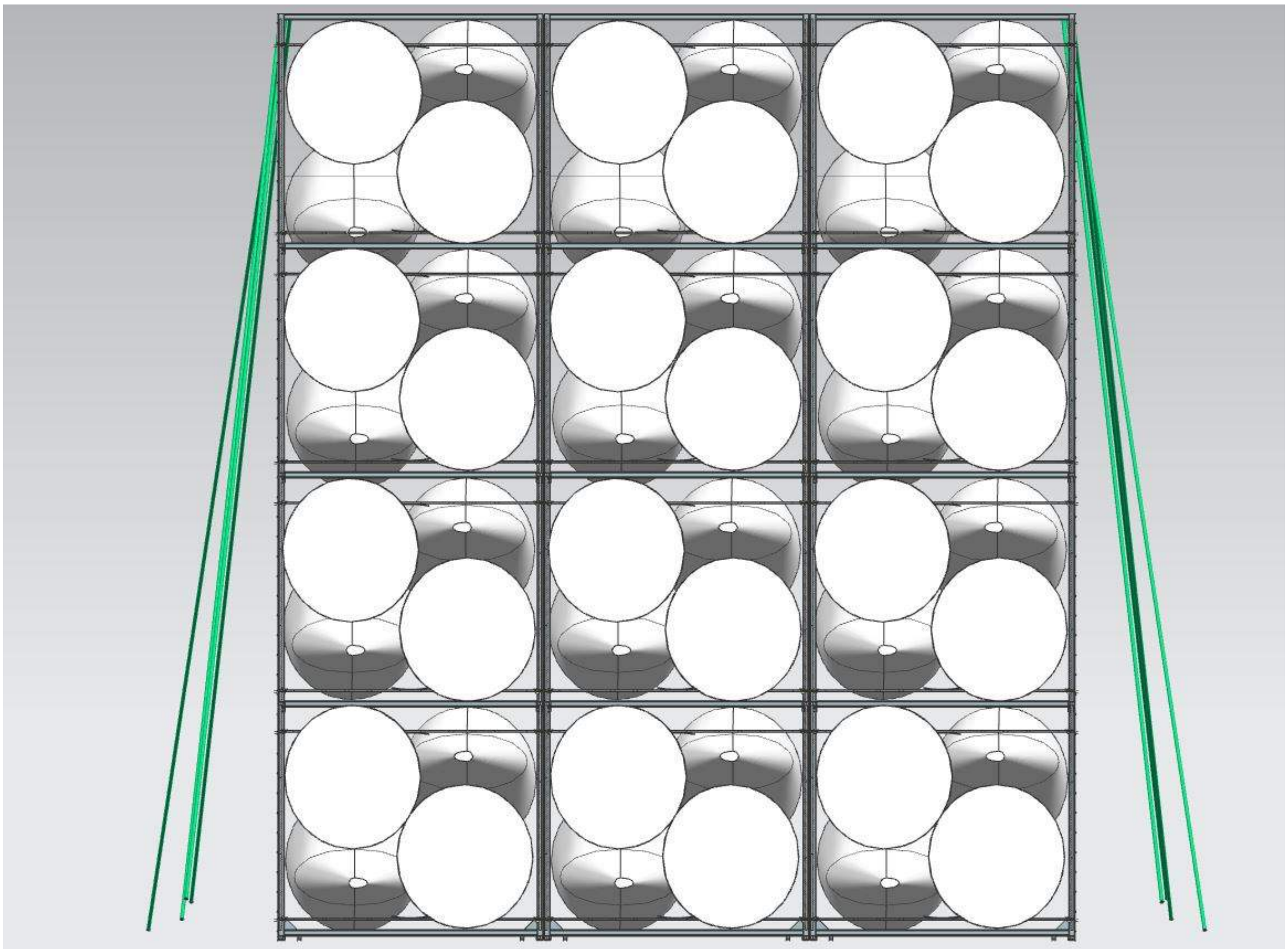


Figure 6-83 3.6 MW blades inside the racks (front View)

Figure 6-83 shows that inside each section of the rack, 4 numbers of blades can be loaded. It means in general 96 numbers of 3.6 MW blade can be loaded inside the second hold, if this rack is used for safe transportation.

Figure 6-85 shows that a couple of padeyes are designed in the structure in order secure the blades. These sets of padeyes are used for lashing and securing the blades inside the section of each rack. In Figure 6-85, the yellow line is presenting a wire which is secured the blades by rigging to the padeyes.

Therefore, if it is planned to load one number of blades each section of the rack, the clamp can be used to secure the blade, otherwise the blades can be secured by means of padeyes and slings.

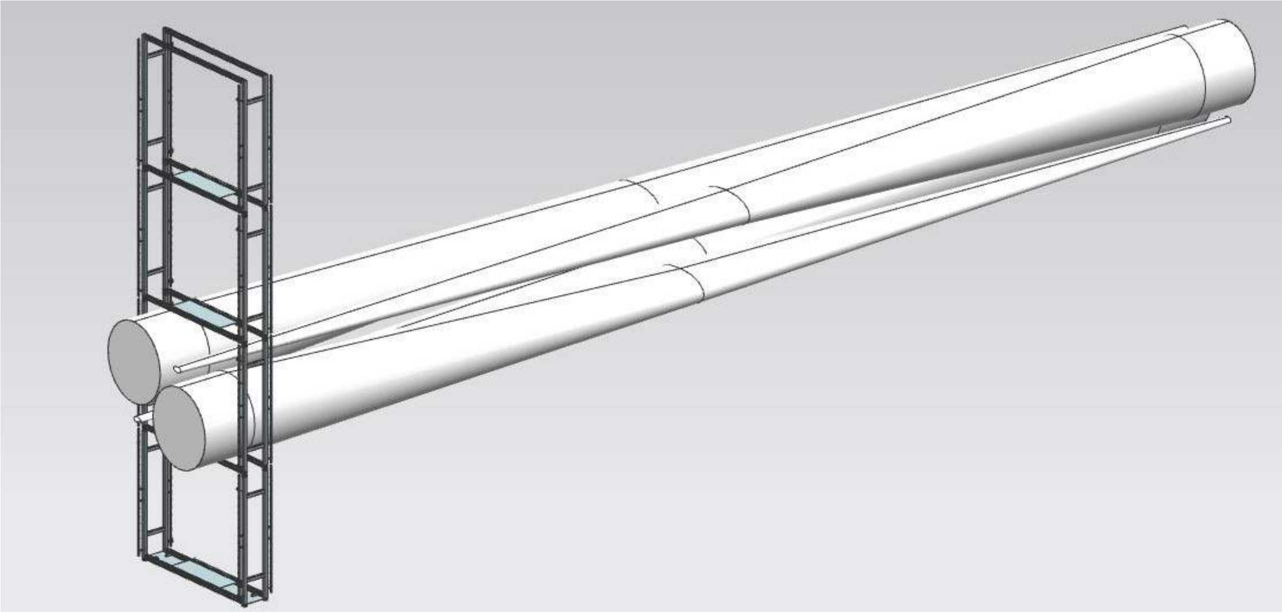


Figure 6-84 Securing 4 numbers of 3.6 MW blades inside the racks

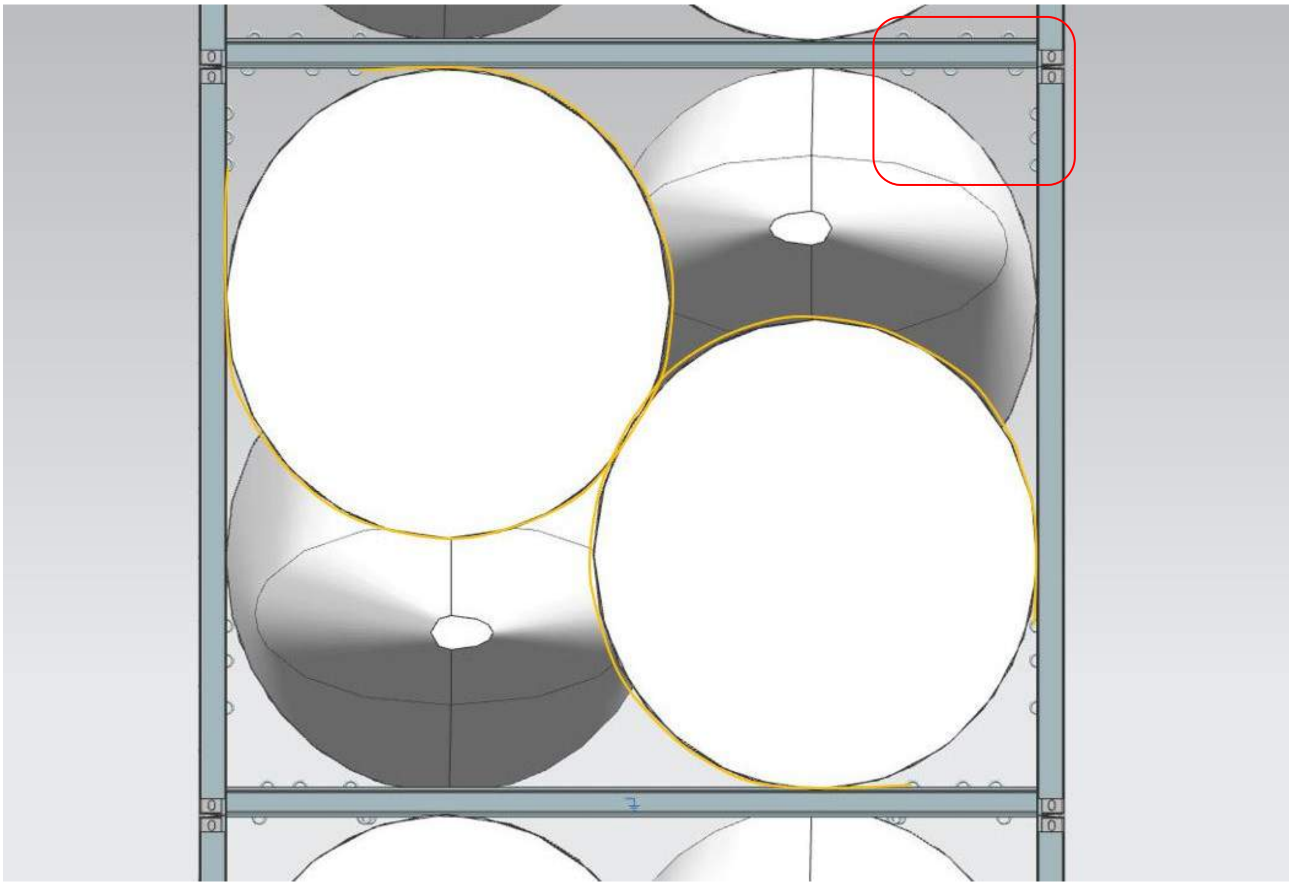


Figure 6-85 Method of Securing Small Size Blades

6.16.1.4 Blade Cutting Control Room

To operate the cutting tools and cutting operation, an operator is needed to run the cutting tools and monitor the cutting operations. In addition, in case of losing items he has to take necessary and precautionary measures. According to given explanation under section 6.16 the operator should be protected from harms of cutting process. Hence, a room for technician is considered in the aft of the vessel, adjacent to the holds. The room is totally isolated from holds when the door is closed. The technician can control and operate the cutting machines. So, just one technician is needed to do both operations for both sections of hold number two.

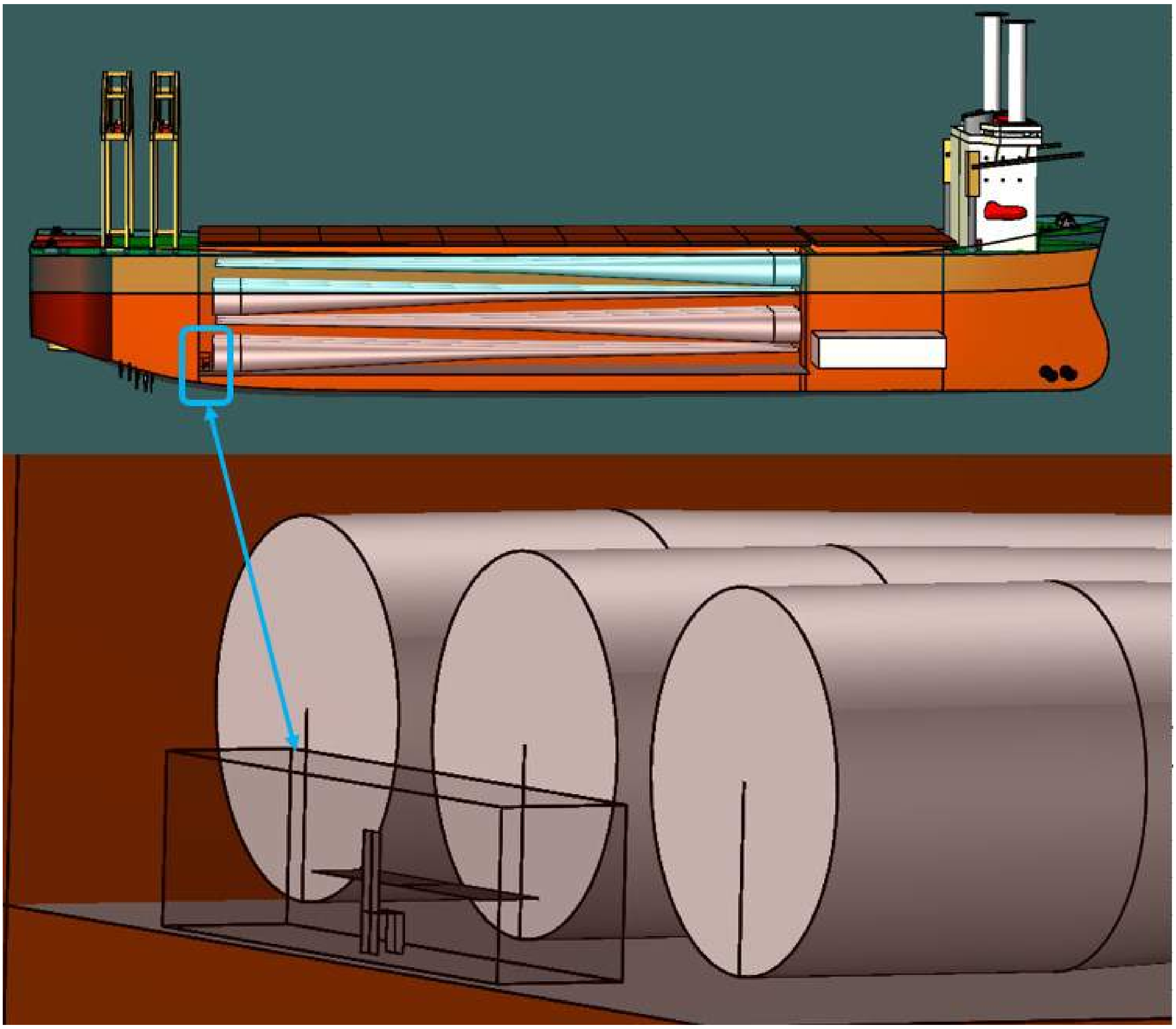


Figure 6-86 The Portable Cabin for Operator for Cutting

6.17 Transition Piece Removal

Normally during the installation of offshore wind parks, after completion of installation of monopiles, a specific vessel with special machineries and tools/materials[65] along with relevant experts are mobilized for installation of transition pieces. The installation of transition pieces onto the monopile is taken place by means of either grouting or flanges[66]. However, vast majority of transition pieces are installed to the monopile by composite (grout) connection.

[65] Tools such as lifting gear for lifting the TP, grouting equipment and pumps, and material such as cement.
[66] In case of flange connection, the disassembly can take place with unbolting the bolts which is so easier and highly likely quicker and cheaper.

Figure 6-87 shows how transition piece is connected to the monopile. In most of the wind parks in the North Sea region, the tip of monopile is about 5-6 meter above sea level the same as below figure. Then the Transition Piece (TP) is stabbed onto the monopile. Most of section that the monopile and transition pieces are overlapped are filled with special grout (the annulus between MP & TP). Figure 6-87 shows the joint between the monopile and TP.

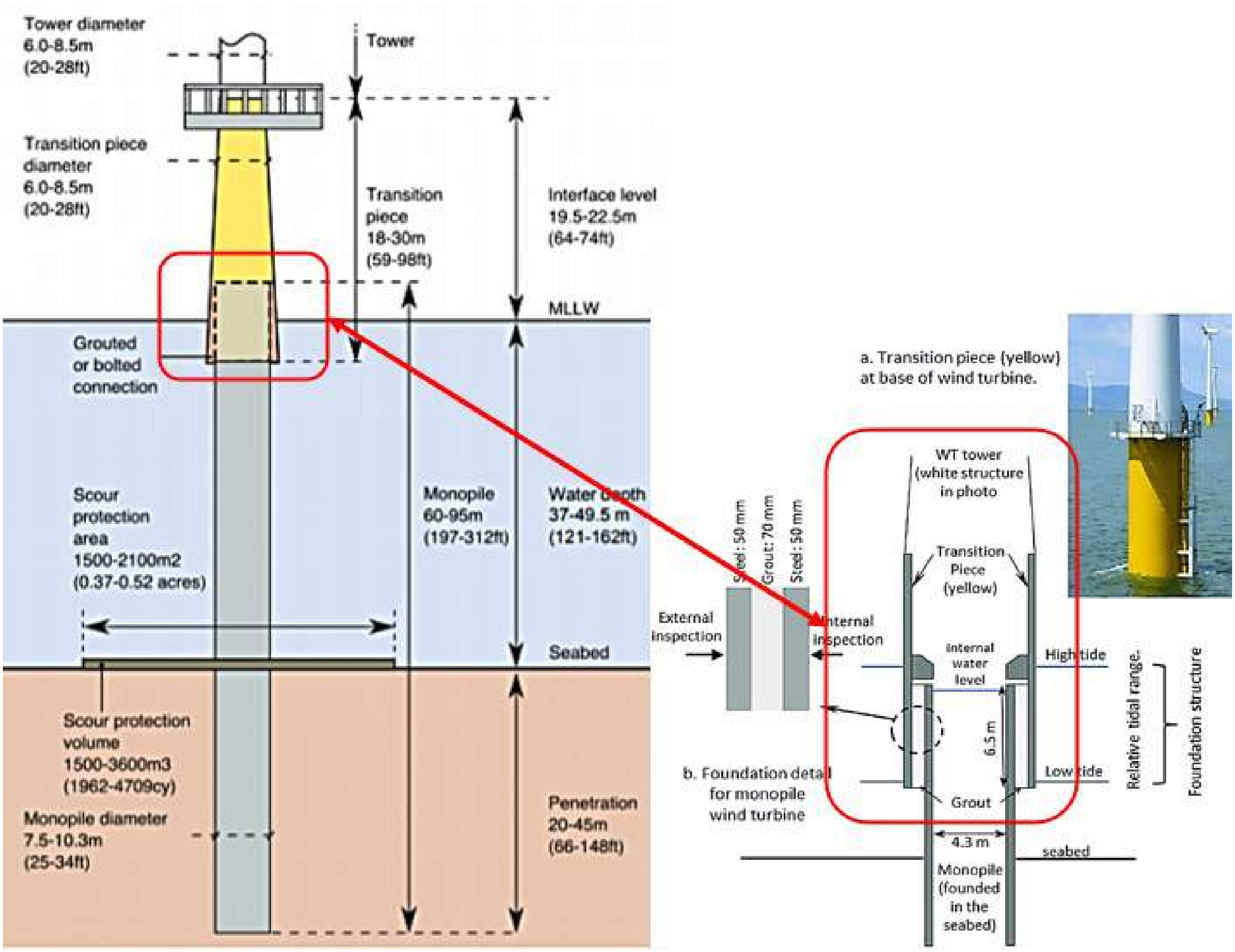


Figure 6-87 Detail of Installation of TP & MP

Source: (EPSILON ASSOCIATES, INC. 2020) & (Wilkinson, et al. 2018)

6.17.1 Cutting the Transition Piece

There are three different methods for removal of TP as following:

I. To unbolts the flanges between the MP and TP. This can be occurred if the connection has been done by flanges and bolts which low number of WTs have this connection.

II. To remove the TP by use of vibratory hammer. Also, it is impossible in many cases. Secondary and tertiary structures are welded to the TP which shift the COG. Furthermore, there is not access on top of many TPs for the clamp of vibratory hammer (the top is flange which vibratory hammer cannot grip it). The following figure shows the design of different TPs. The only generic method is to cut the top of the TP including the access platform in order to provide the access to rig the vibratory hammer for removal.

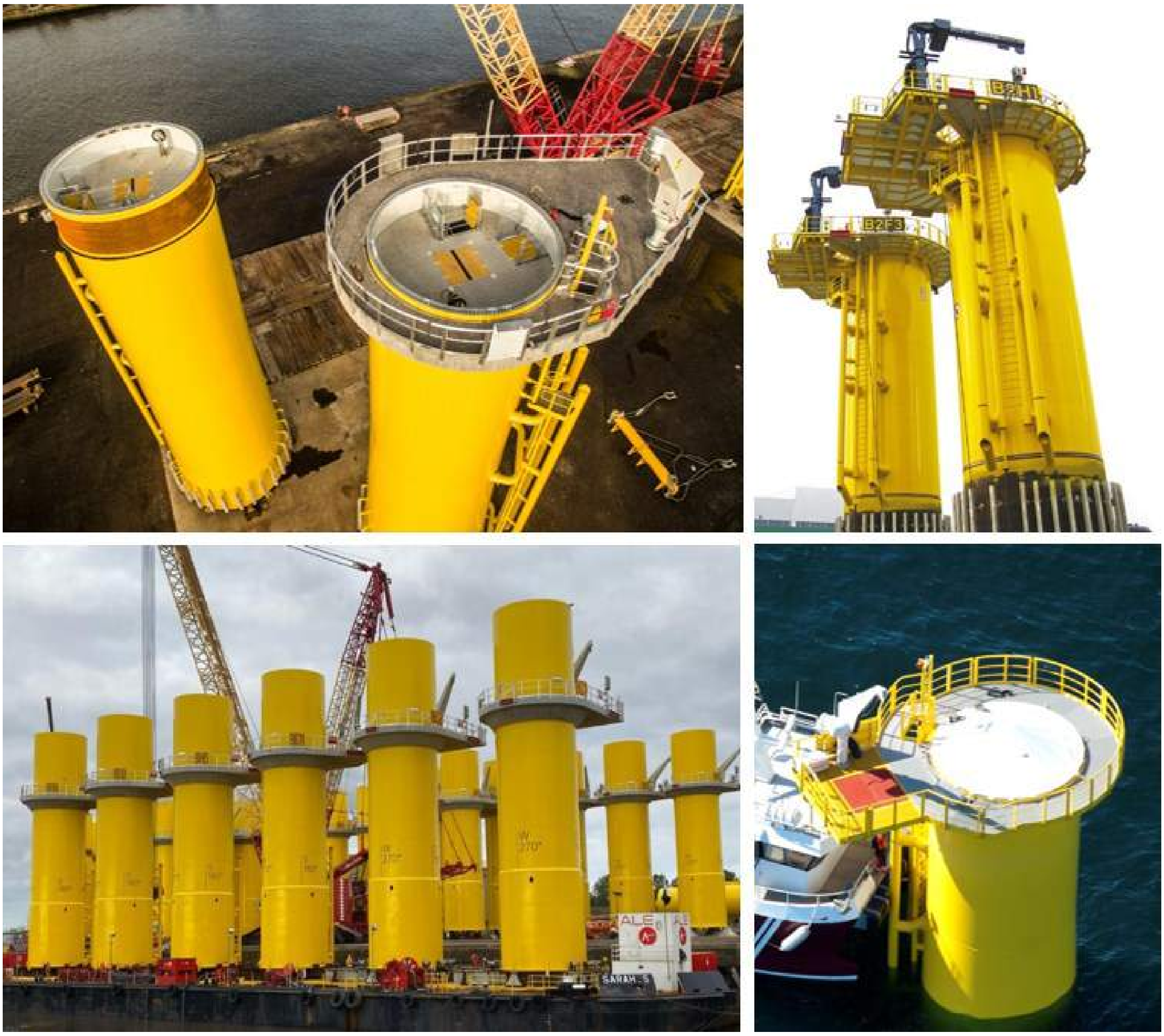


Figure 6-88 Different Design of Transition Pieces

III. The last method is cutting the transition piece. TP should be cut from a location, if it is not installed via bolts and flange to the monopile. The question of where to cut the TP is so challenging in the sense that the required tools for cutting can be changed, the cost of operation vary and more importantly the vessel that need to lift it can be changed. There are two locations that the TP can be cut. Cutting at each location have its own merits and demerits as following:

6.17.1.1 Cutting the Transition Piece above the Tip of Monopile

Cutting above the monopile has following advantages and disadvantages:

- ☑ There not any grout in this section, so most of types of metal cutting tool can cut this section including diamond wire saw, the oxy fuel cutting techniques, abrasive water jet etc.
- ☑ Cutting above the monopile tip means cutting above the sea level. Therefore, cutting at this level avoid using diver for installation of cutting tools. The day rate of divers/diving equipment is so high, and the risk of diving operation is so serious and significant. In addition, the diving operation is complex.
- ☑ Cutting above sea level provides the opportunity to use Oxy fuel cutting techniques which is so quick, reliable, common and cheap.
- ☑ The weight of cut section is light which result in mobilization of crane with short lifting capacity. The mobilization of such vessel results in less cost and CO_2 emission.
- ☑ Access will be provided to remove/cut the rest of the TP and monopile.
- ☒ The remaining part of TP need to be removed. It means in another attempt tools and equipment are needed to remove the rest of the TP.

6.17.1.2 Cutting the Transition Piece in one Piece

Cutting transition piece in one piece means that subsea cutting shall take place since the bottom section of TP is inside the water. Also, there are a couple of pros and cons with this cutting area as following:

- ☑ The entire removal of TP can be done in one campaign.
- ☒ For such a cutting, subsea cutting tool is required which can be diamond wire cutter, torch cutting, abrasive water jet (shear cutting is so effective, but so far there is not any shear cutter for large diameter of piles)
- ☒ The divers are needed either to install the cutting tools or to do the cutting manually (except if abrasive water jet is planned to be used).
- ☒ The cost of subsea cutting is so high since it need diver, special tools ROV and submarine certified hook of crane and rigging items (except if abrasive water jet is planned to be used).
- ☒ The subsea operations are so risky and complex.
- ☒ After cutting the TP inside the sea, the access to remove the monopiles is difficult since it is inside water. Therefore, again diver or ROV need to be mobilized.

6.17.2 Procedure of Transition Piece Removal Reverse to the Installation

There is a couple of technical problems for removal of TP, if removal of entire TP takes place reverse to the installation. To remove the TP entirely, the cutting of monopile should be performed below the TP. There are some issues and technical problem here as following:

- ☒ In this case, the subsea cutting tool and diving team/equipment is needed to cut the TP and monopile.
- ☒ In addition, crane with larger lifting capacity is required since the weight of cut piece is the weight of transition piece plus some part of monopile plus the grout between annuluses. This means more cost because of greater crane which lead to more CO_2 emission.
- ☒ There will be difficult access to remove the rest of monopile.
- ☒ For removing the monopile, after removal of TP, either diving team or ROV is needed.
- ☒ The crane for removal of TP or removal of MP, need to be certified for seawaters operations since the hook and slings shall go to the seawater.

An analysis has been performed in order to calculate the duration, time and fuel consumption of TP removal operation, if reverse installation take place. In this analysis, it is considered that the same vessel should be used with same logistic configuration for the removal of TP. To verify the algorithm and compare the different methods of removal, we select the Hornsea I offshore wind park as a case study. The analysis has been carried out for removal of TP of 91 numbers of wind turbine of this wind farm (this wind farm has 174 number of 7 MW WT).

The diameter of TP in this project is 6.21 meter since top of monopile is conical (the diameter of MP at top is less than bottom diameter which is 8.1m (SAL 2018).

Construction of transition pieces of Hornsea 1 project have been executed in various locations (Power World Analysis n.d.). Also, the transportation to wind park took place with different logistic configuration and different types of vessels. Innovation jack up vessel and Sea Installer jack up vessel are involved in the installation of the transition. The authors did not find complete information about transportation and installation of all TPs of this wind farm.

SAL's MV Svenja transports the foundations from fabrication yards in Rostock (Germany) as well as Aalborg (Denmark) to the feeder port in Tees (United Kingdom). Direct transhipments of the TP from cargo vessel to the jack up vessels by the names of Innovation and Sea Installer has been conducted.

Figure 6-89 and Figure 6-90 shows that the cargo vessel transported the TP from fabrication yard and loaded them on the jack up vessel for further shipment and installation.

Based on available information, the Sea Installer jack up vessel has been transported and installed 6 numbers of TP per cycle. The following figure show how the transportation and loading on the jack up vessel has been carried out. In this case, the installation of TPs has been done in pendulum configuration.

Therefore, in the reverse installation, it is considered that the same vessel (sea Installer) is planned to work with same logistic configuration and same number of TP should be transported per cycle.

Figure 6-89 Transportation of TP with Svenja to be Loaded to A2SEA

Figure 6-90 TP Loaded from Svenja to the Sea Installer

6.17.3 Time-Cost Analysis of Transition Piece Removal Reverse to the Installation

If the decommissioning operation reverse to the installation take place, calculation with same vessel and logistic configuration need to be analyzed. The vessel by the name of Sea Installer has been installed TPs of this wind farm. In each cycle it transported 6 number of TPs with diameter of 6.21 meter and approximate weight of 340 tones (SAL 2018). In this analysis it is supposed the

TP planned to be cut by abrasive water jet[67]. Cutting the TP/MP with diameter of 6.21m and thickness of 78mm takes 53 hours approximately. However, due to uncertainty regarding the thickness of TP In this calculation it is considered that cutting take place 30 hours for each TP. Then the calculation will be as following:

In this case the result will be found in the following table.

Table 6-8 Time & Cost Analysis of Removal of 91 Numbers of TPs of Hornsea 1 Reverse of Installation

Results of Pendulum Configuration in Removal of TP with DP2 Jack Up Vessel			**Hornsea 1**
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Positioning	55.73	22.8%	$ 11,145,814.81
Figures of In-Field Transit	1.89	0.8%	$ 378,347.73
Figures of Sailing	12.00	4.9%	$ 2,399,808.02
Figures of Offshore Construction	117.54	48.0%	$ 23,508,333.33
Figures of Offloading	5.69	2.3%	$ 1,137,500.00
Figures of Unplanned Activities	52.07	21.3%	$ 10,413,847.05
Grand Total	**244.92**	**100.0%**	**$ 48,983,650.95**

According to Table 6-8, which is result of calculation, 6 modes of operation for jack up vessel during removal of transition piece have been defined. The elaboration of above table is as following:

I. **Positioning:** The position is the time that vessel has to jack down the legs, carry out soft pin of the legs, pre-load the tanks until legs reaching final penetration. Also, it consists of deballasting of the pre-load tanks. The time for each set of TPs is considered 12 hours approximately based on the specification of the jack up vessel and some estimation about the soil condition. Therefore, the overall time for positioning of the jack up vessel for 91 number of TP is about 55.73 days.

II. **In-field Transit:** This is the time that vessel need to sail from one turbine to another one. It depends on the distance of wind turbine and the number of them. The speed during in-field sailing is considered 1 knot. The duration of this mode of operation is 1.89 days in total.

III. **Sailing:** Sailing is the time that the vessel has to sail between port and OWP. Since this jack up barge carried out 6 set of TP per voyage, it has to sail 16 times to port to bring the TP to

[67] The cutting process for a monopile with a diameter of 3.5 m and a wall thickness of 78 mm can take up to 30 hours and more (Hinzmann, Stein and Gattermann 2018).

OWP for installation. Sailing with 60% of the maximum speed (mean 7.2 knots) of this vessel which is 12 knots take 12 days approximately.

IV. **Offshore Construction:** offshore construction is the time of installation of cutting tool and cutting the transition piece. The time for installation of subsea cutting tool as well as the time of cutting of TP with diameter of 6.21 meter, lifting and loading the TP on the deck is considered 30 hours. In general, the duration of this operation is 117.54 days.

V. **Offloading Operation:** The time that the vessel in the port transfers the TPs from the vessel to the quayside is considered as offloading operation. It is considered that lifting each piece of TP and placing on the quayside takes 1.5 hours which in general it constitutes 5.69 days.

VI. **Unplanned activities:** unplanned activities are the time of the bad weather which vessel cannot work. It is considered as 25% of operation time of the vessel. In addition, waiting on client and mechanical break-down which is considered 2% of the operational time of the vessel. Based on this assumption, the unplanned activities constitute 52.07 days. However, it depends heavily on the season and sea state.

This above are the result of TP removal reverse to the installation. However, the TP removal reverse to the installation is not a wise process and operation since the duration and cost of this operation is extremely enormous.

Conclusion: The TP removal with above-mentioned procedure for 91 numbers of monopile take about **244.92** days and cost about **48,983,650.95** $ considering 200 000$ as the daily charter rate of jack up vessel.

6.17.4 Procedure of Transition Piece Removal with Decom Tools Vessel

Even with the defined scenario to remove the TP with Decom Tools vessel, the removal and transportation of transition piece shall take place in a separate campaign. It means that after removal of rotor, nacelle and tower, cutting and transportation of transition piece shall take place with Decom Tools. This is our suggestion for removal and transportation of transition piece with Decom Tools Vessel.

Figure 6-91 shows that after installation of monopile, the installation of TPs is executed in Arkona wind park. However, it is normal sequence in installation of offshore wind parks.

Figure 6-92 shows installation of TP of Anholt wind farm. As it shows the monopile is about 5-6 meter above sea level.

According to the design of the Decom Tools vessel, in order to cut and load the TPs, the TP should be positioned in the stern of the vessel. The height of gantry crane is designed to go underneath of the transition piece for cutting and lifting purpose. However, due to freeboard of the Decom Tools vessel, just the top 9.5 meters of the transition pieces can be cut. Normally in the first 9.5 there is not any overlap between the monopile and the transition piece. Due to lack of composite joint between transition piece and monopile, the oxy fuel cutting tools can be used to cut this section.

Figure 6-91 Installation of Arkona Transition Pieces

Source: (Offshore Energy 2018)

Figure 6-92 Anholt TP Installation (Orsted 2019)

The sequences of cutting and loading the transition pieces with Decom Tools vessel are as following:

1) The grippers of the Decom Tools vessel should be opened fully.
2) The transition pieces should be positioned in the stern of the Decom Tools vessel.

3) In order to minimize the emission, we suggest holding the TP by the grippers. So, after holding the TP with gripper, there is no need to maintain the position of Decom Tools vessel by DP. In this case, from aft it is positioned by gripper. Positioning of the vessel from forward can be maintained either by anchors or by bow thrusters. However, in the load calculation and fuel consumption, it is considered that positioning is maintained by grippers and the bow thrusters (please refer to the Table 5-30 and Table 5-36).
4) The cutting tools should be installed at the level of the weather deck.
5) The large hoist of gantry cranes should be placed on top of the TP.
6) The crane hoist should be rigged to the TP. Depending on the weight of TP, either one or both of gantry cranes can be rigged to the TP. In this drawing both cranes are connected in tandem configuration. The TP of Hornsea1 wind park has diameter of 6.21 meter and has weight of 340 tones.
7) The cutting of TP should take place.
8) The TP should be lifted and lowered into the holds.
9) The vessel can switch to DP.
10) The grippers can be opened.
11) The vessel can sail to the next location.

The following figures illustrate the above-mentioned sequences of TPs removal.

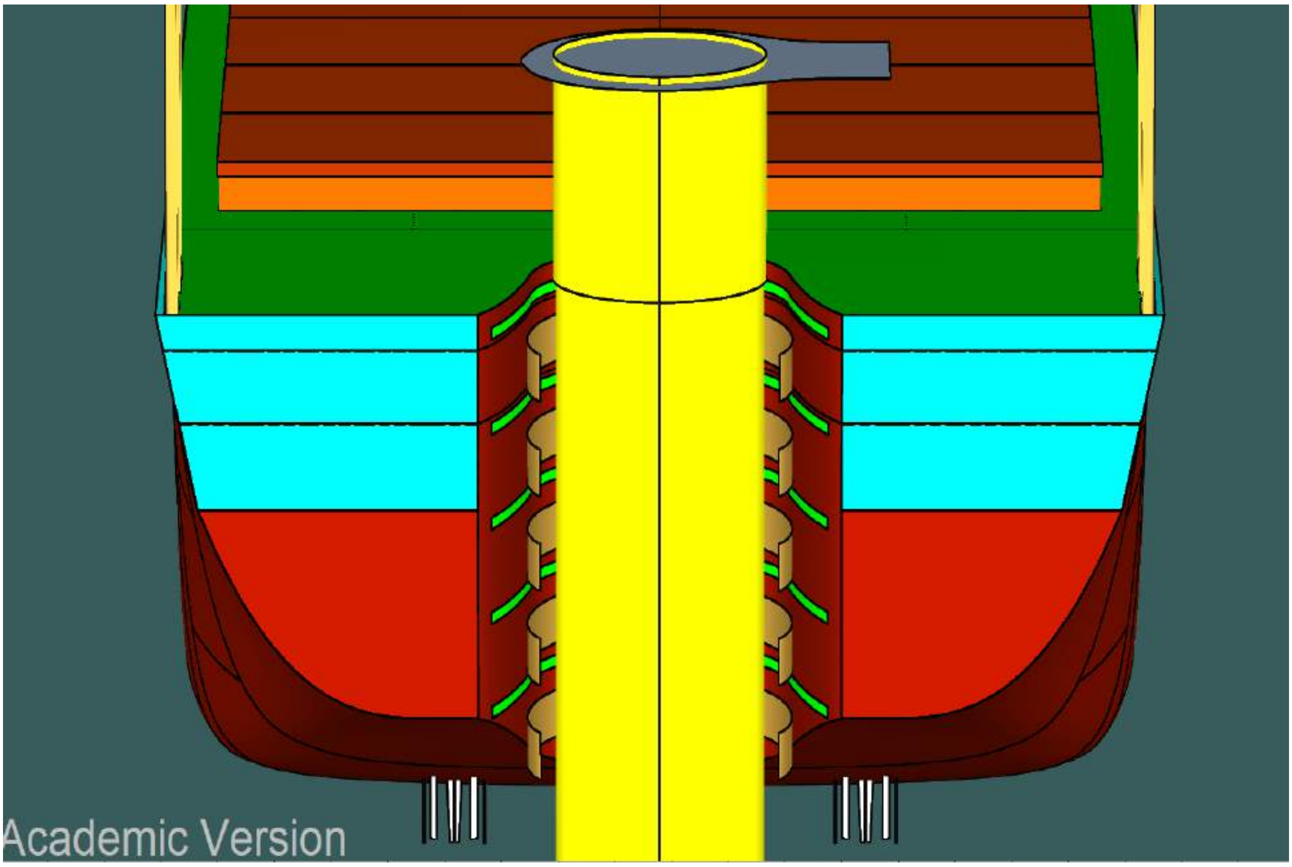


Figure 6-93 Grippers are Open to hold the TP

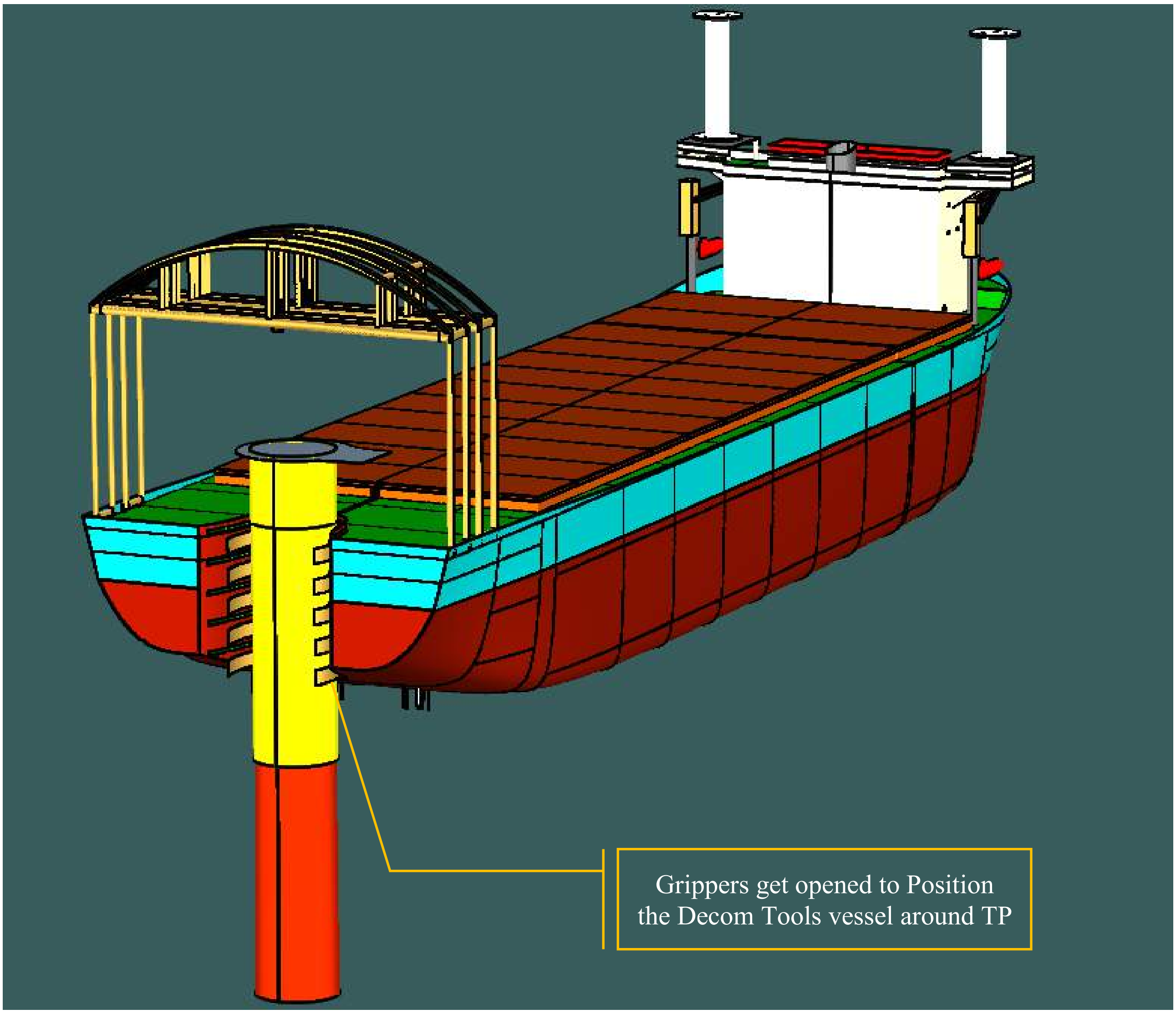


Figure 6-94 Positioning the TP Inside the Grippers

After holding the transition piece by grippers and fixing the position of the vessel, the cutting tools shall be installed around the TP. To increase the safety of operation, after cutting 50% of the TP or even earlier, the gantry crane(s) can be connected to the TP (the SWL of each of the gantry cranes is 750 tons since the weight of TP normally is less than 500 tons). After conduction of cutting, the TP can be lifted and placed on the desired location.

For installation of cutting tools around MP/TP mobile platform is designed to be placed behind the TP/MP. Figure 6-95 shows the mentioned platform. This platform has the width of 60 cm and can be installed with gantry crane. not only can it be used for cutting operation but also it can be used for removal of marine growth too.

The following figure shows the mobile access platform from different view. It is mounted on a skid. So, it can skid longitudinally according to the diameter of transition pieces or monopiles. It has very simple structure and can be installed easily.

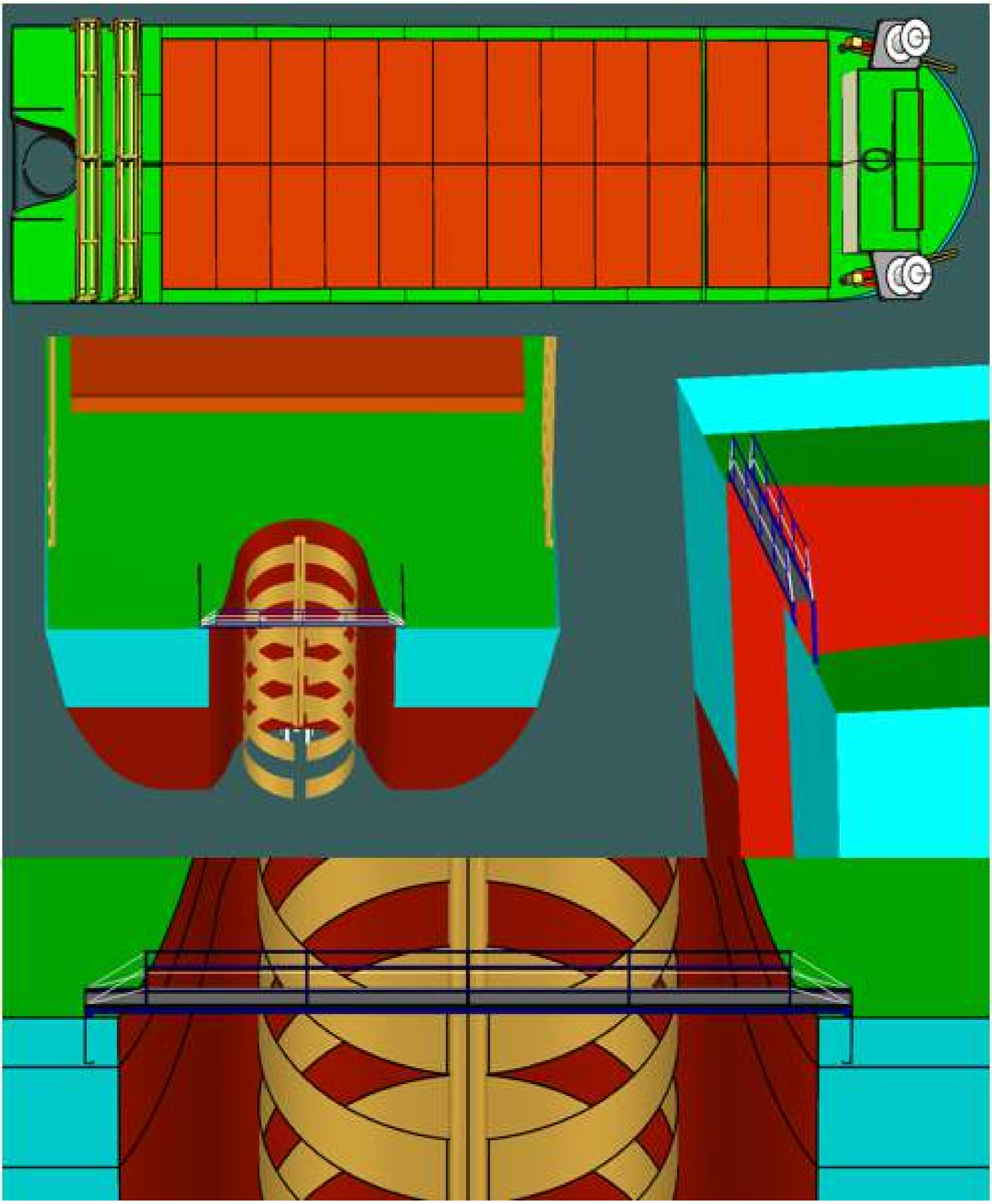


Figure 6-95 Mobile Access Platform for Cutting MP/TP

Cutting transition pieces can be done even without having this structure.to ease the installation of cutting tools and increase the safety of the cutting operation, this structure has been designed.

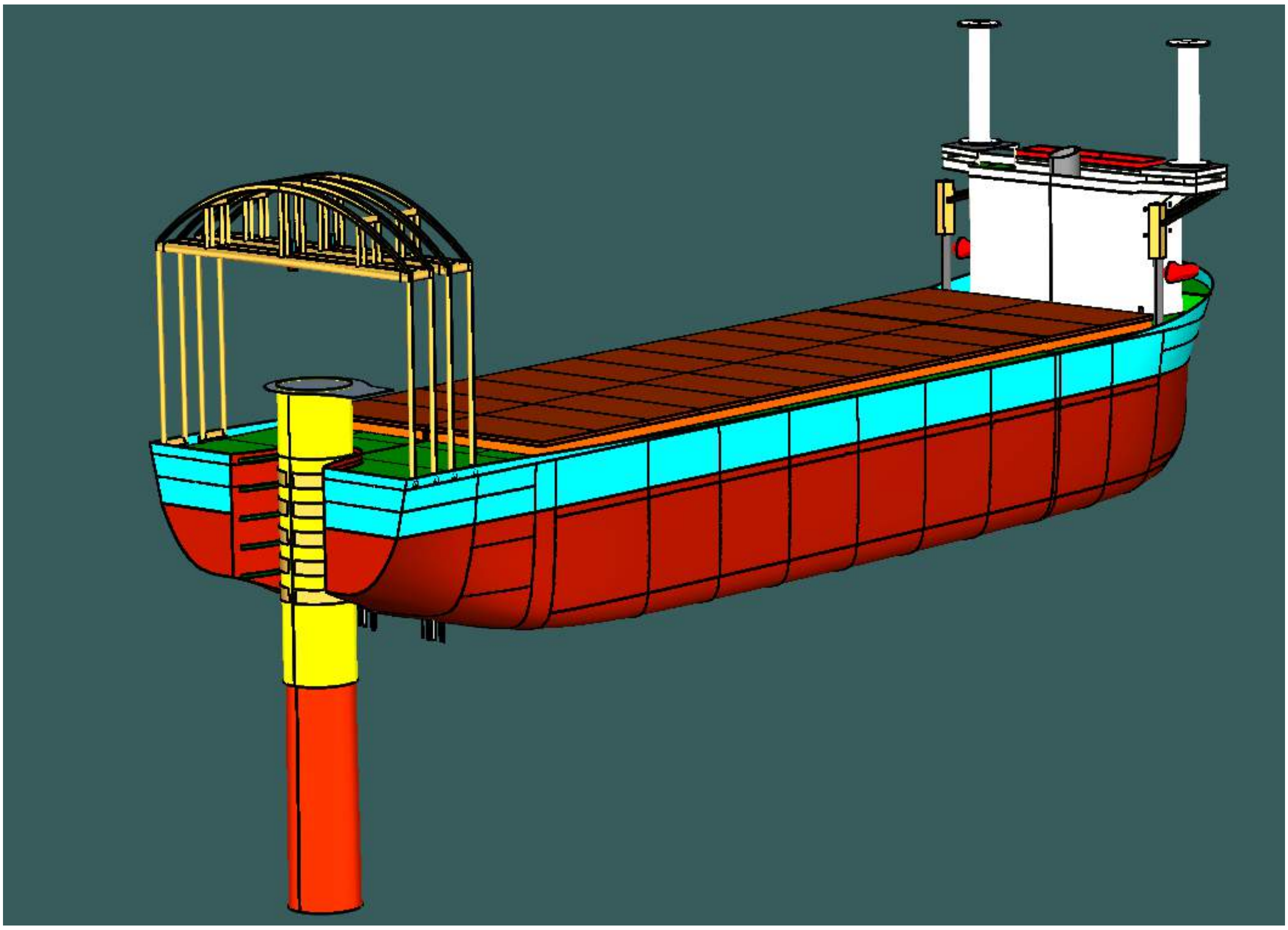


Figure 6-96 Grippers Hold the TP

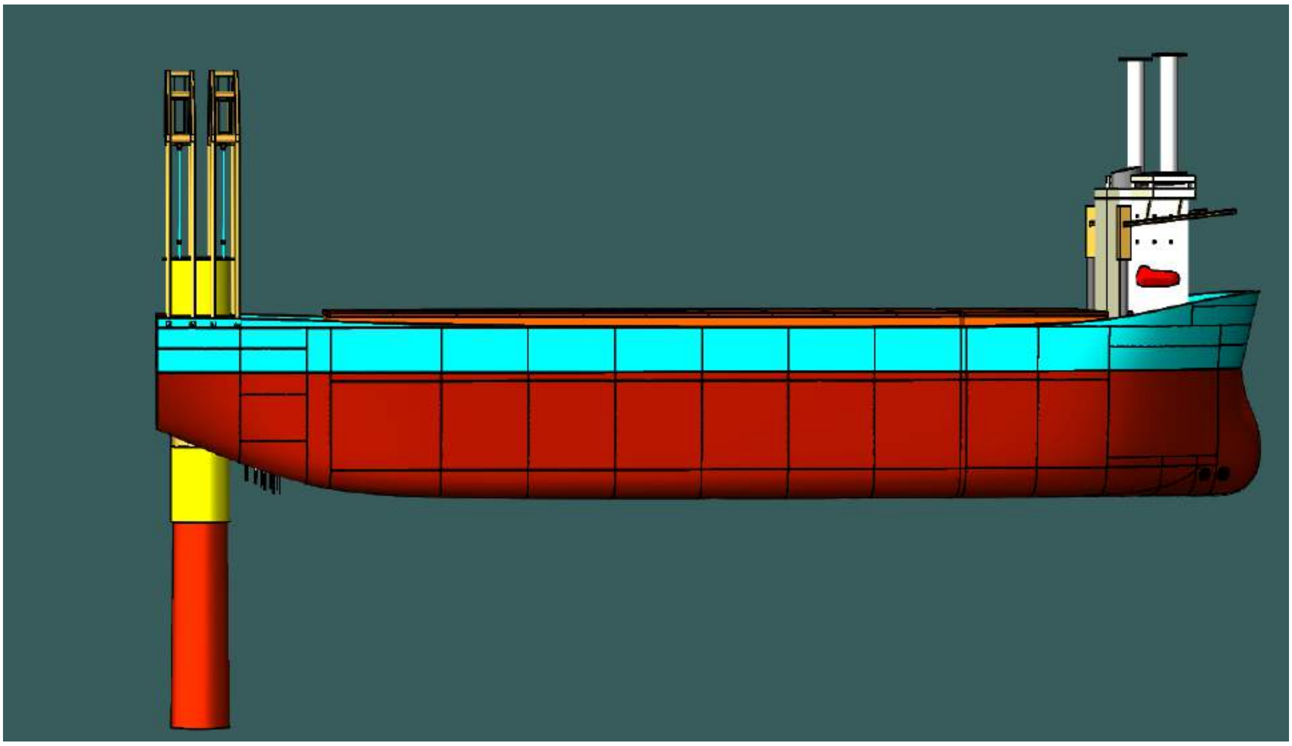


Figure 6-97 Transition Piece are rigged to both gantry cranes (Side view)

In this stage, after positioning of the Decom Tools vessel, holding the TPs by grippers and rigging of the TPs with gantry cranes, the cutting can be performed.

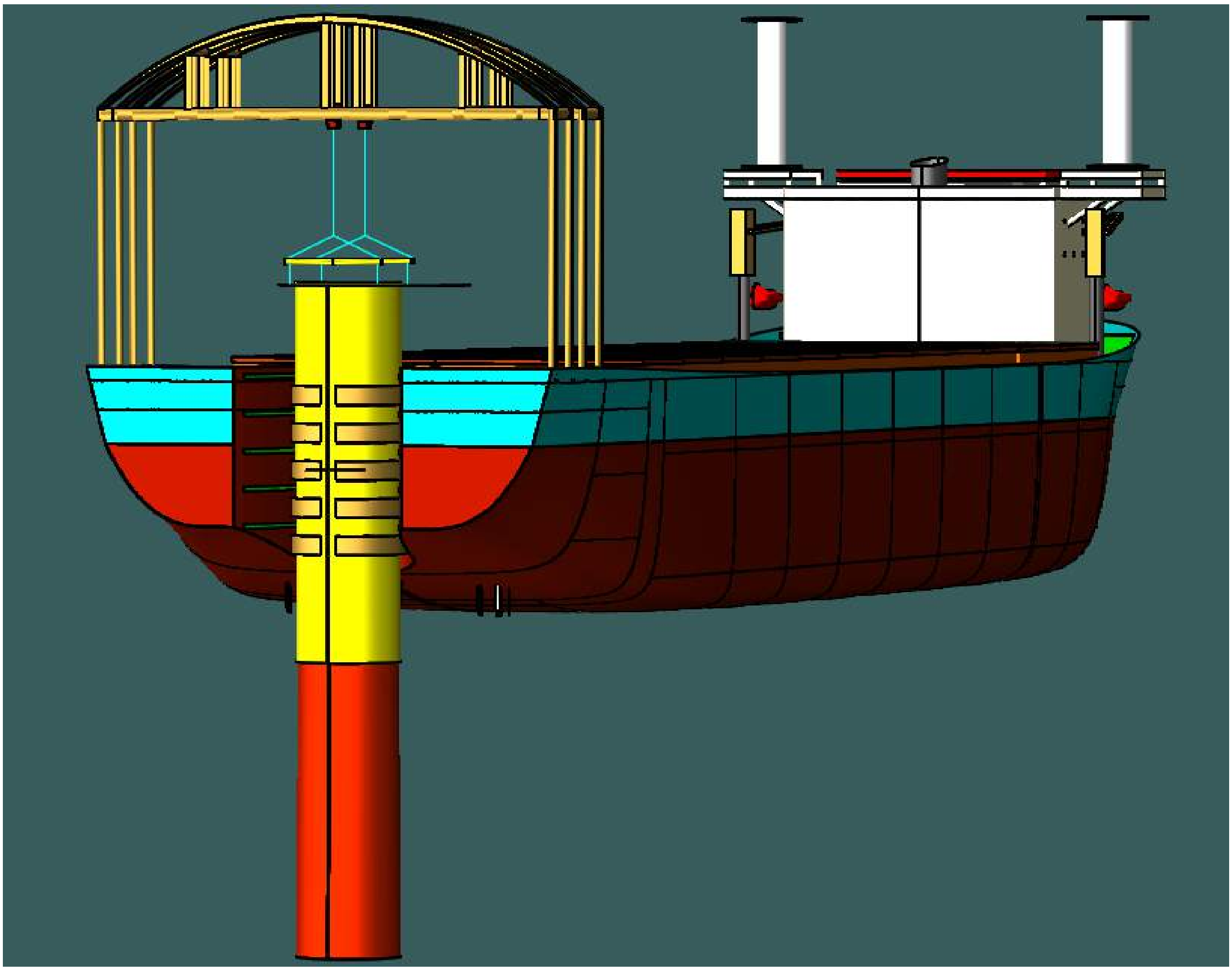


Figure 6-98 Transition Piece are positioned inside the grippers (perspective view)

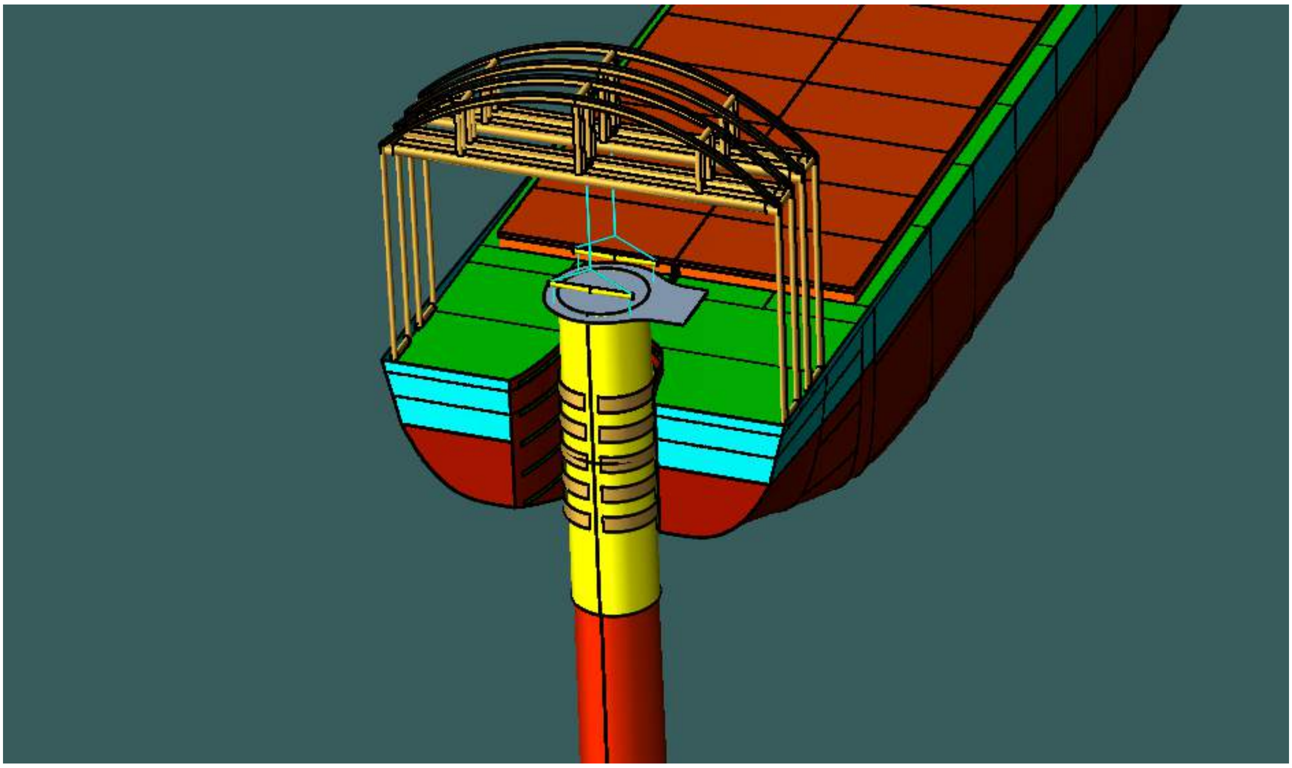


Figure 6-99 The Transition piece is hold by the Grippers & connected with slings to the Gantry Cranes

The following figure shows lifting the cut section of TP after executing of cutting tools. As it illustrates, the top 9.5 meter can be cut by the oxy fuel cutting tool. Cutting from this section avoid using of the subsea cutting tool.

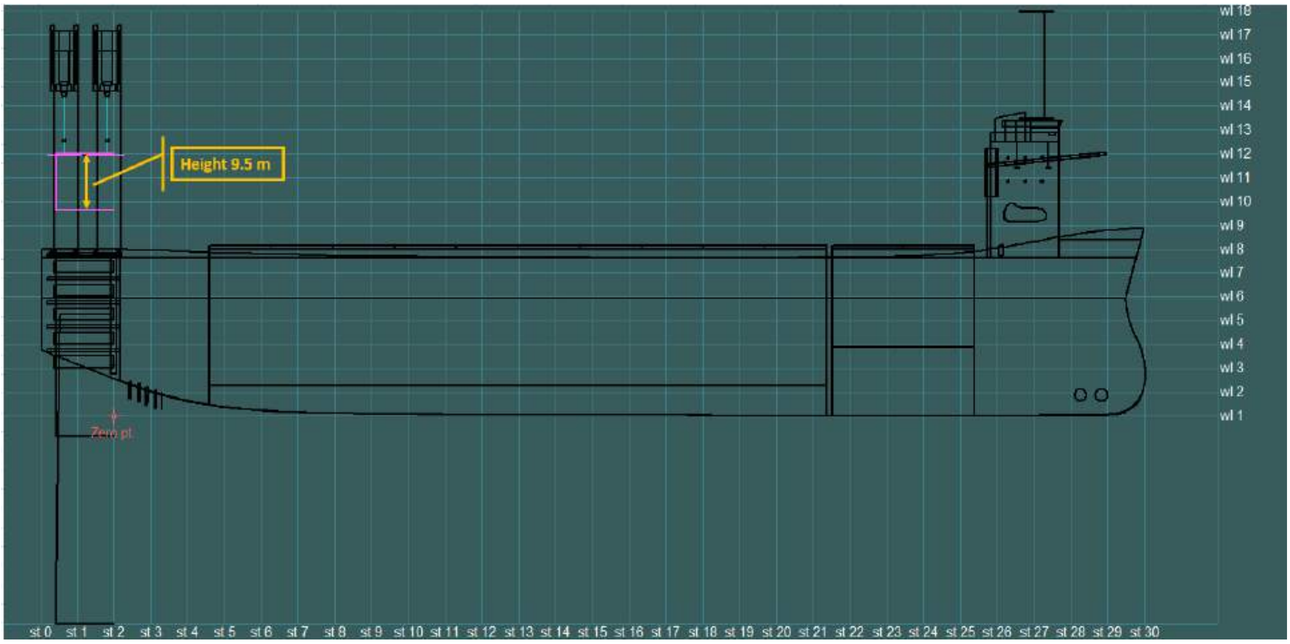


Figure 6-100 The Height of Cut section of TP

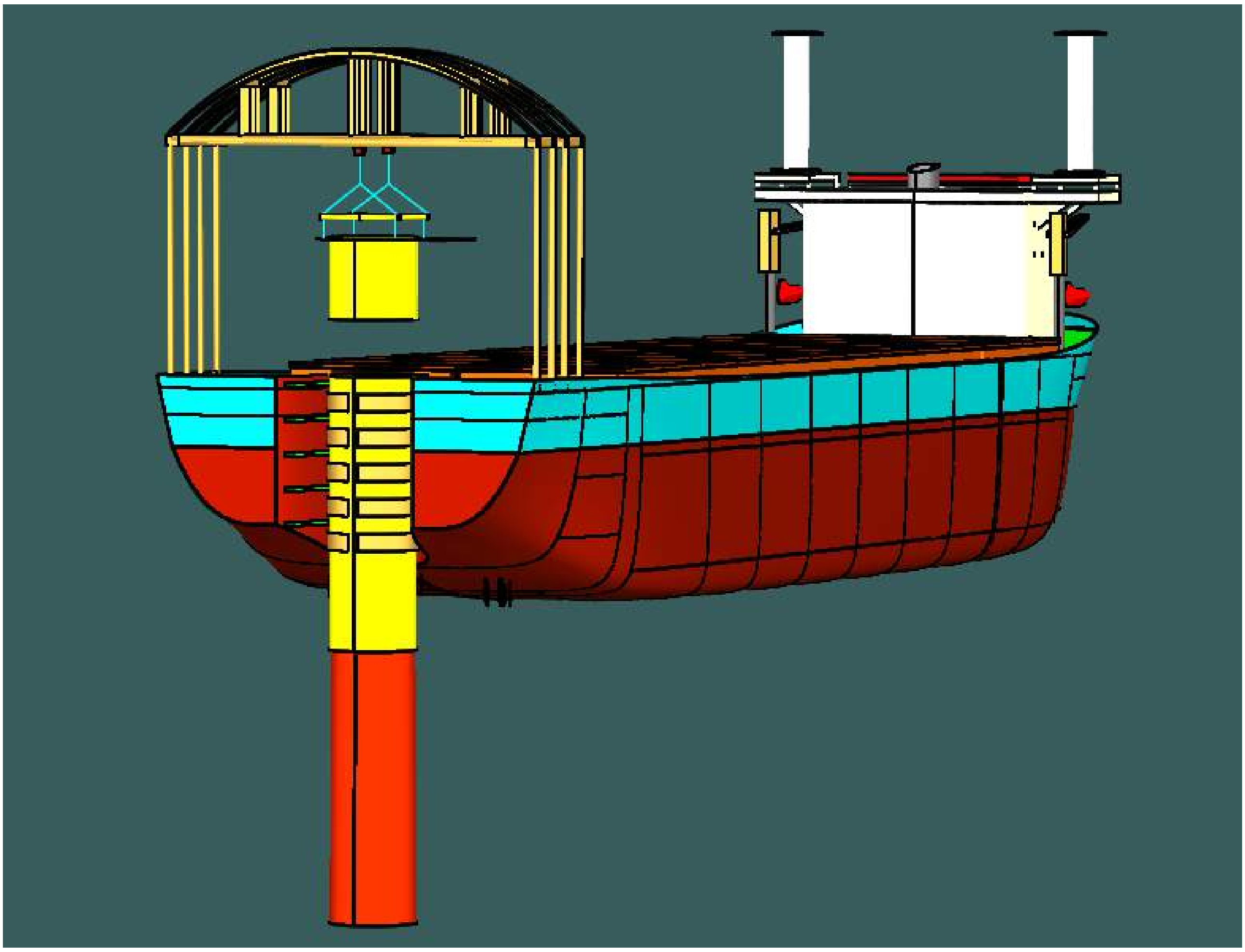


Figure 6-101 The top section of TP is cut

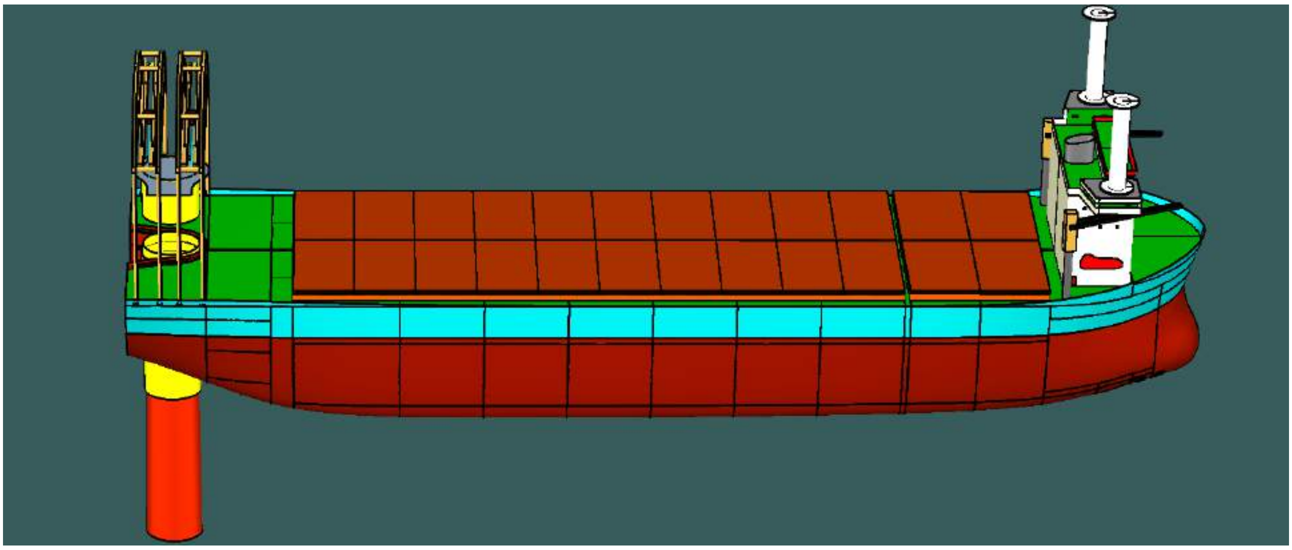


Figure 6-102 Lifting the Cut section of TP

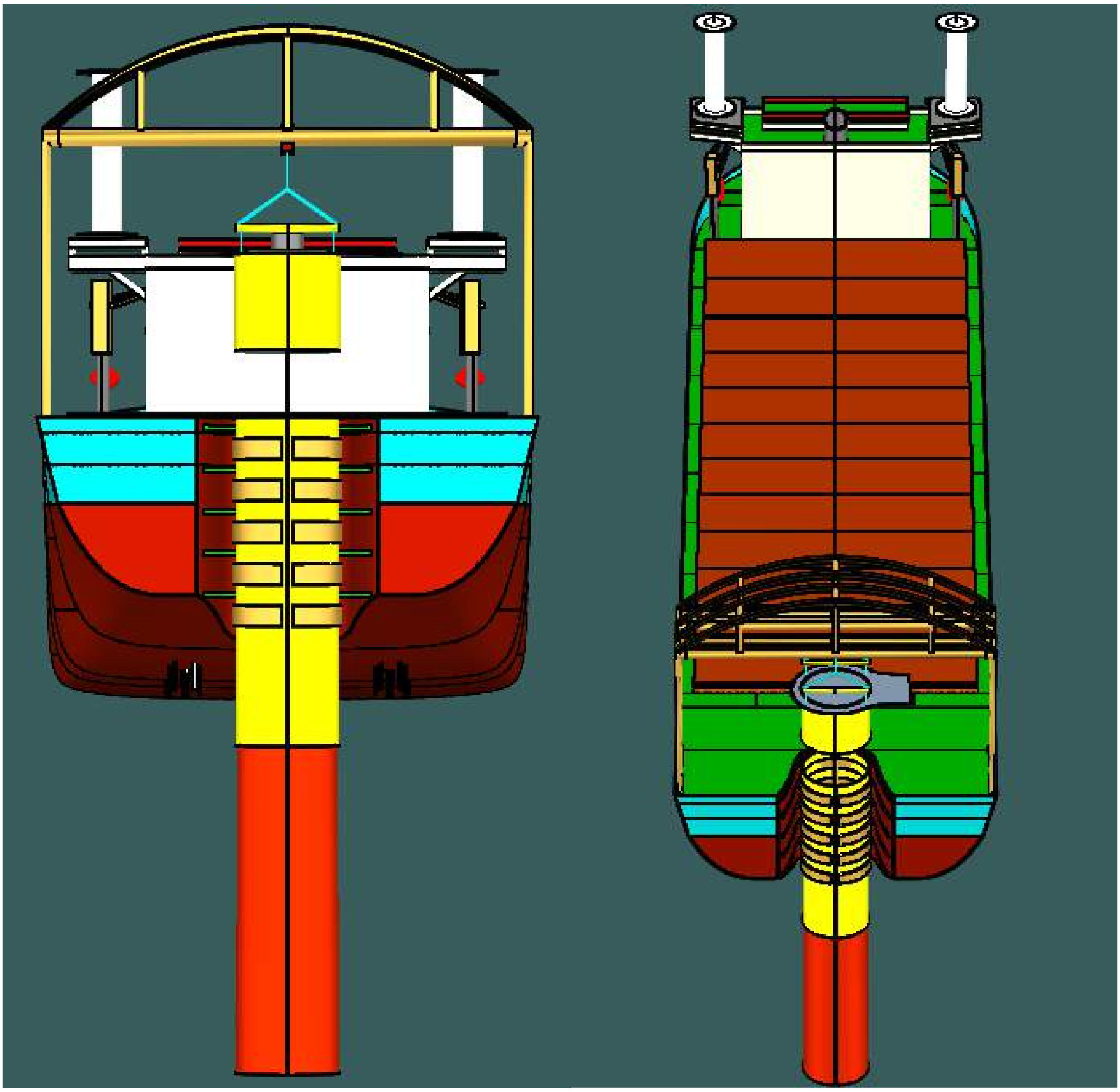


Figure 6-103 Back and Birds Eye View of Lifting the Cut Section of TP

According to above figures, in order to reduce the fuel consumption of the vessel and mitigate the emission, the vessel can switch off the DP system and maintain the position by using the grippers and forward anchors or bow thrusters.

In addition, the lifting of transition piece can be performed by using a sling, shackles and spreader bar as well as transition piece lifting tools. It depends on the engineering of the transition piece and method of lifting. We propose the lifting gears since this operation can be undertaken by any riggers and without special tools. The following figure shows how lifting of TP can be done.

Figure 6-104 Lifting the TP by lifting gears and Spreader bar

Source: (Cranemarket24 2017)

Figure 6-105 Lifting the TP by Hydraulic TP lifting Tool (IHC n.d.)

Figure 6-106 shows that in lifting of the TPs in the port, both method of hydraulic lifting tool and manual rigging have been used. Each of mentioned equipment has some merits and demerits which describing them is out of scope of this research.

Figure 6-106 Lifting the TP with Hydraulic lifting Tool and Spreader Bar
Source: (SAL 2018)

Figure 6-107 demonstrates how lifting and loading the TP in the holds can take place with gantry cranes. As it stated earlier, the weight of 12 MW TP is not revealed yet. So, due to lack of data, it is devised to lift and place the top section of TP with two gantry cranes. But most probably the weight of TP after cutting is less than 500 tons. Therefore, in order to save energy, it is recommended to use one of the gantry cranes for this operation.

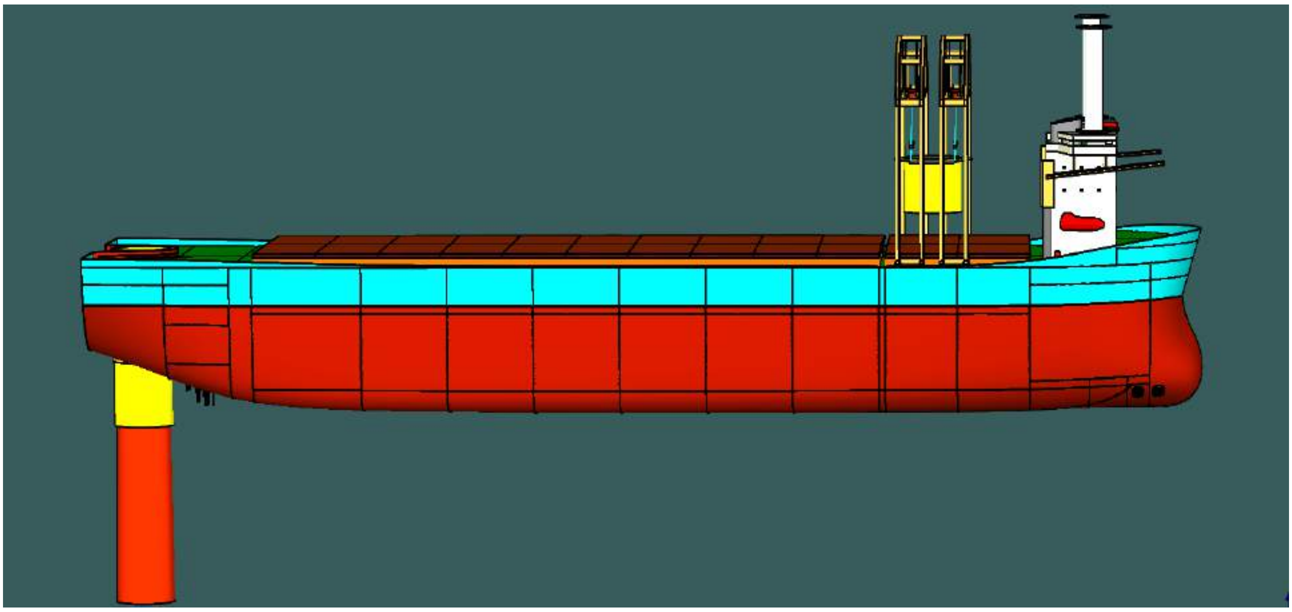


Figure 6-107 Loading of cut section of TPs (Side View)

Regardless of lifting methods, referring to the following figures, 56 number of transition pieces with diameter of 10.20 meter can be loaded inside the holds and on the hatch cover. This dimension of TP is designed for 12MW wind turbine which has not been used in any offshore wind parks yet. It should be noted that the height of TP here is 9.5 meter after cutting. Also, in order to load more TP in the hold number 2, the tween deck has been used.

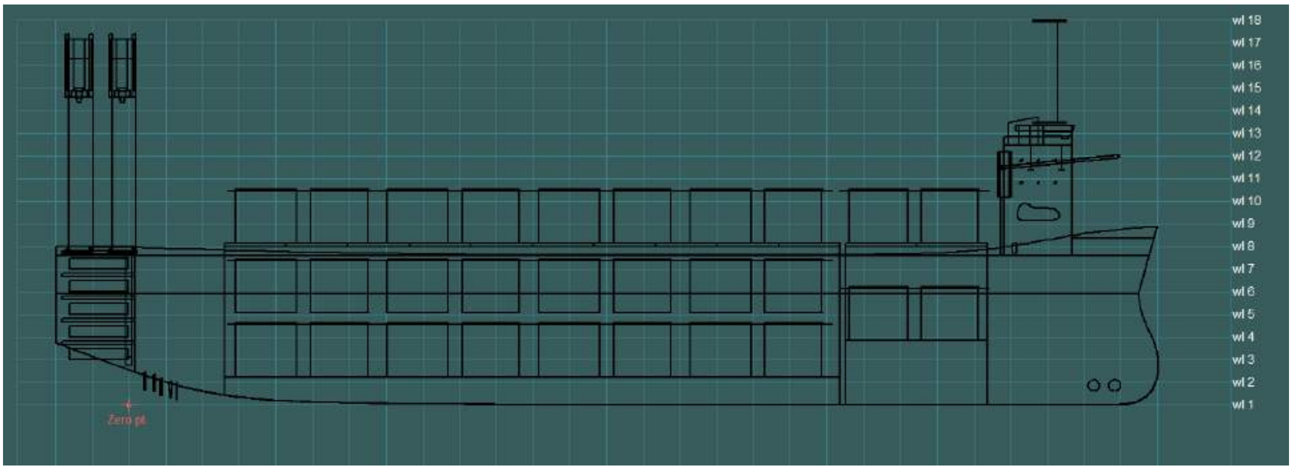


Figure 6-108 TPs loading arrangement (Side View)

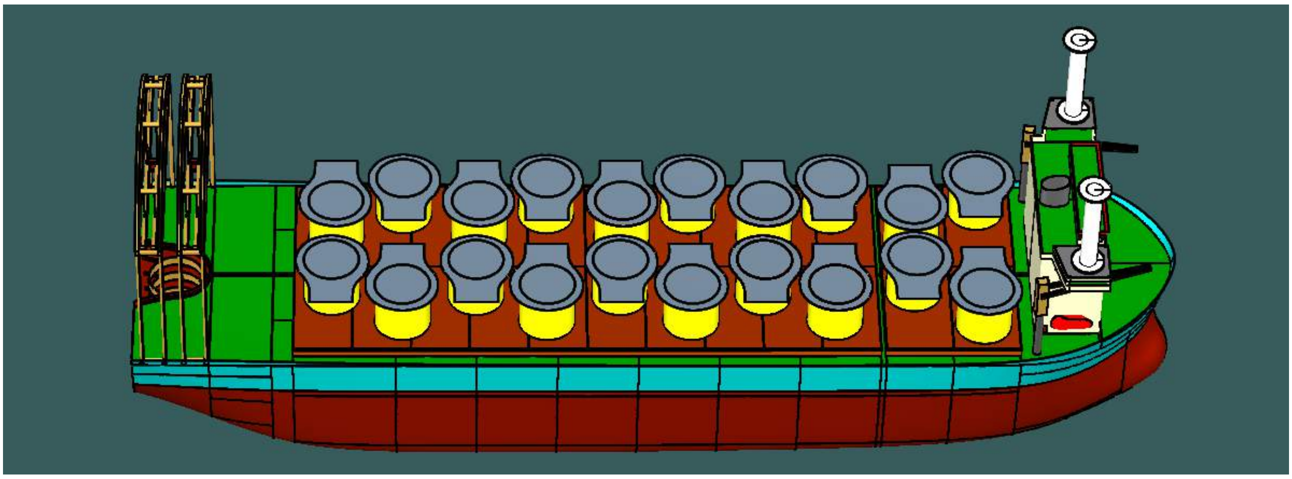


Figure 6-109 TPs loading arrangement (Bird's Eye View)

Figure 6-110 TPs loading arrangement (Bird's Eye View)

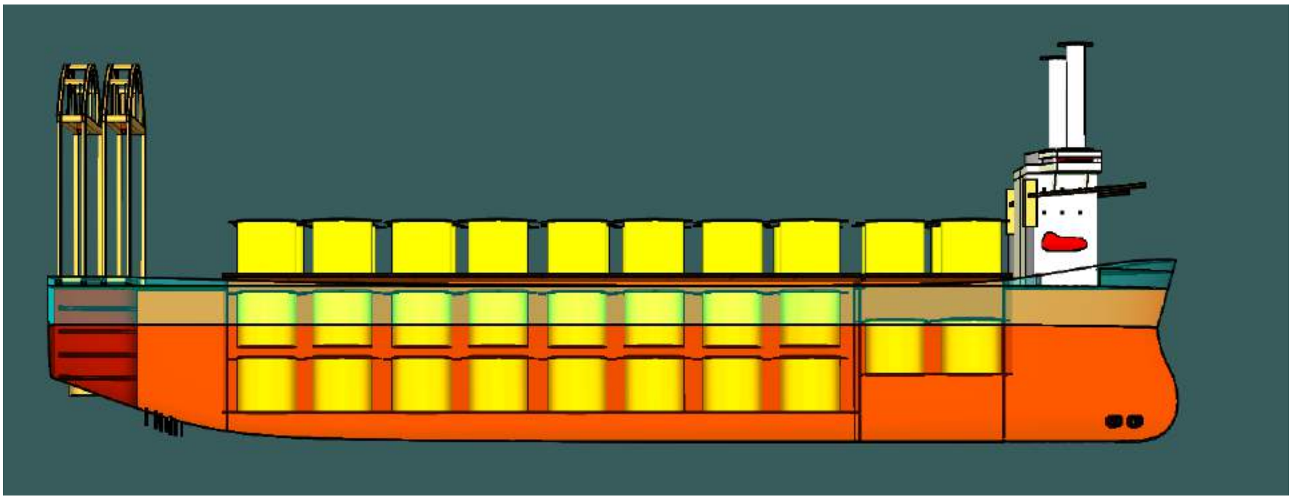


Figure 6-111 TPs loading arrangement (Side View)

Figure 6-108, Figure 6-110 and Figure 6-111 and shows how the loading on the tween deck inside holds number 2 has been performed.

The figures shows that 20 number of TPs with diameter of 10.2 meter and height of 9.5 meters are loaded on top of hatch covers, 32 numbers are loaded in the hold number 2 and 4 numbers of TPs are loaded inside the hold number one. In other words, by cutting the TPs from this level, 56 number of them can be loaded inside the holds and tween deck.

6.17.5 Time-Cost Analysis of Transition Piece Removal with Decom Tools Vessel

An analysis has been performed in order to calculate the duration, time and fuel consumption of the Decom Tools vessel during TP removal operation. Again, in this analysis, the case study is Hornsea 1 offshore wind parks. The analysis has been carried out for removal of TP of 91 numbers of wind turbine of this wind farm (this wind farm has 174 number of 7 MW WT). As it stated before, the distance of this OWP from shore is about 120 km. The diameter of TP in this project is 6.21 meter since top of monopile is conical (the diameter of MP at top is less than bottom diameter which is 8.1m).

Table 6-9 Time & Cost Analysis of Removal of 91 Numbers of TPs of Hornsea 1 with Decom Tools Vessel

Results of Pendulum Configuration in Removal of TP with Decom Tools Vessel			**Hornsea 1**
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Sailing	1.43	4.0%	$ 99,833.53
Figures of In-Field Transit	1.89	5.30%	$ 132,421.71
Figures of Offshore Construction	17.06	47.8%	$ 1,194,375.00
Figures of Offloading	5.69	15.9%	$ 398,125.00
Figures of Unplanned Activities	9.65	27.0%	$ 675,159.44
Grand Total	**35.71**	**100.0%**	**$ 2,499,914.68**

According to results of devised algorithms, the operation of TP removal has been categorized into 5 different sections as following:

I. **Sailing:** Sailing is the time that the vessel has to sail from port to the wind farm and vice versa. It consists of the time that the vessel has to arrive to the site (mobilization), transport the TP to the decommissioning yard/ port and demobilization. In this section we consider that the vessel can sail just with 60% of its maximum speed. Having consider that the maximum speed of the Decom Tools vessel is 12.62 knots, then it is considered that the vessel sail with 7.57 knots. Having considered that the Decom Tools can load maximum 56 numbers of TP, then in this case the vessel has to sail 2 times from port to OWP which will result in 480km voyage. The overall time of voyage is 1.43 days with given speed which constitute 4% of the TP removal.

II. **In-Field Transit:** In-field transit includes the time that the vessel has to sail between wind turbines. The distance between wind turbines is considered 6 times of rotor diameter which is 924m. The maximum speed that any vessel can sail in this distance can be maximum 1 knot. Then overall duration of in-field transit is 1.89 days which constitute 5.30% of TP removal.

III. **Offshore Construction:** Offshore construction includes the time that the Decom Tools vessel has to position the TP inside the grippers, closing the grippers, installation of cutting tool and cutting operation. This time for each TP is considered 4.5 hours. Then the overall offshore construction is 17.06 days which constitute 47.8% of TP removal campaign.

IV. **Offloading Operation:** After transposition of the TP to the port, the vessel must stay in the port until offloading of the last pieces. The duration to offload each piece of TP is considered 1.5 hour which in total it will be 5.69 days to offload all 91 numbers of the TP. This part constitutes 15.9% of the TP removal operation.

V. **Unplanned Activities:** unplanned activities include bad weather, waiting on client and mechanical break-down of equipment. It is devised that 35% of operation time is bad weather and 2% of operation time is waiting on client and mechanical failure. In this case, the duration of unplanned activities is about 9.65 days.

Conclusion: The overall duration of mobilization of the Decom Tools vessel from port to offshore wind park (distance of 120 km), cutting the top 9.5 meter of TP with diameter of 6.21 meter and transportation to decommissioning yard/port and offloading all of them is **35.71** days with cost of **2,499,914.68 $.**

Important Note:

The day rate of the Decom Tools vessel for transportation of rotor, nacelle and tower was considered 40000$. During TP removal operation the daily charter rate is considered 70 000$. The reason is that during TP removal, the cutting tool, fitter along with DP officers need to be mobilized. The mobilization of equipment and extra DP officers compel us to consider the extra day rate of 30 000$ for this operation.

6.17.6 Comparison of Transition Piece Removal with Decom Tools Vessel and Reverse on Installation

Table 6-10 is a table which compare the duration of operation, fuel consumption and cost of TP removal for two scenarios of reverse of installation and with the designed Decom Tools vessel.

I. As it shows, the duration of operation with Decom Tool vessel is about 85% less than removal reverse to the installation.
II. From a financial perspective, it can be argued that the cost of TP removal with Decom Tool vessel is about 94.90% cheaper than reverse installation removal.
III. From a fuel consumption stance, it can be argued that fuel consumption by Decom Tools vessel is about 82% less than reverse to the installation. One of the reasons is that the Decom Tools vessel can maintain the position by grippers and the anchor. However, the batteries and solar system improve the consumption of the vessel.
IV. Form an emission perspective, it can be stated that despite of 82% less fuel consumption, the emission is 85% less since the emission of LNG is 0.857% of emission of MGO.

The red cell in the Table 6-10 shows the worst value or inefficient method and green cells demonstrate the optimum method of removal. It is evident that all the crucial factors including the duration of project, the fuel consumption and cost of operation with Decom Tools Vessel is considerably less that performing TP removal reverse to the installation.

Figure 6-112 to Figure 6-115 shows the value of duration, cost, consumption as well as emission. These graphs compare the TP removal with Decom Tools versus TP removal reverse to the installation.

These differences are due to method of cutting and cutting location. Onboard the Decom Tools vessel, it is assumed that cutting take place with Oxy fuel cutting technology.

Table 6-10 Comparison Table for Removal of Transition Piece

OWP: Hornsea 1	Comparison Table for Removal of 91 TP	
Configuration	**Reverse of Installation**	**Decom Tools Vessel**
Parameters	**DP2 Jack Up**	**Decom Tools Vessel**
Time (Day)	**244.92**	**35.71**
	Base Scenario	**-209**
		85%
Cost ($)	**$ 48,983,650.9**	**$ 2,499,914.7**
	Base Scenario	**$ (46,483,736.3)**
		94.90%
Fuel (Tones)	**3120.49**	**556.92**
	Base Scenario	**-2563.56**
		82%
CO2 Emission (Tones)	**10004.28**	**1531.54**
	Base Scenario	**-8472.74**
		85%

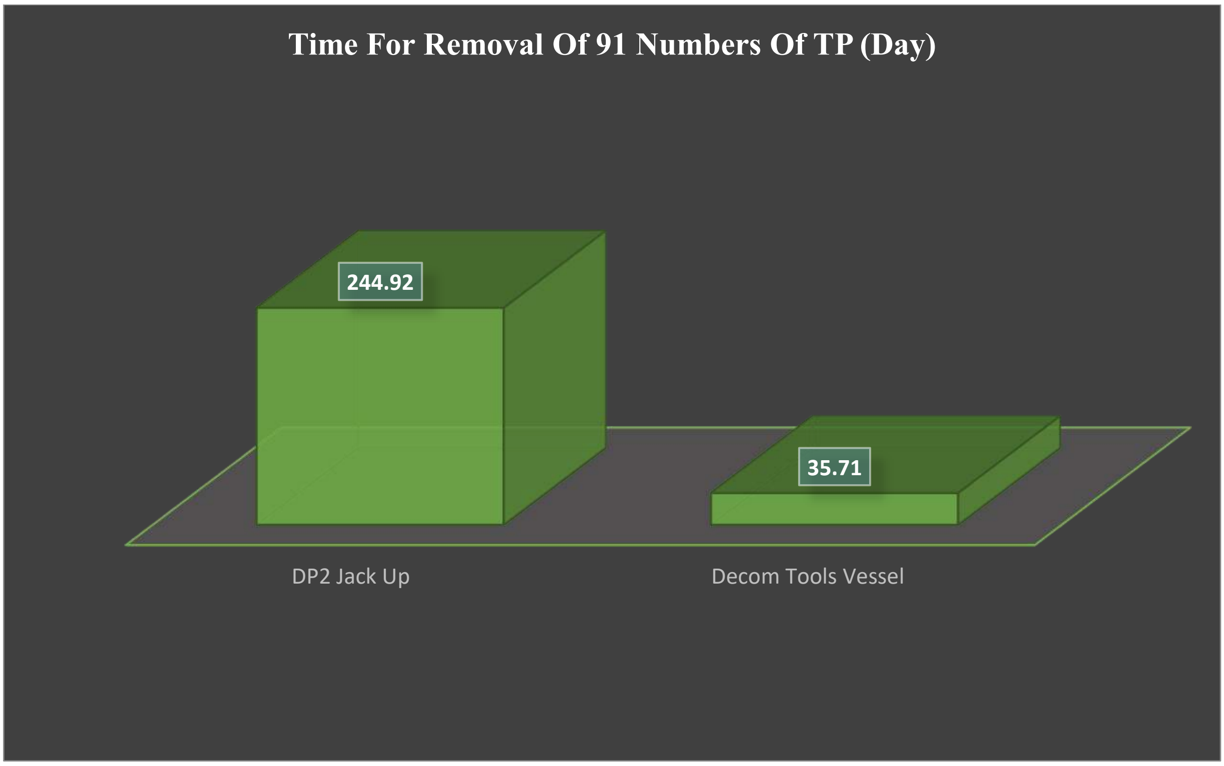


Figure 6-112 Duration for Removal of 91 Numbers of TP

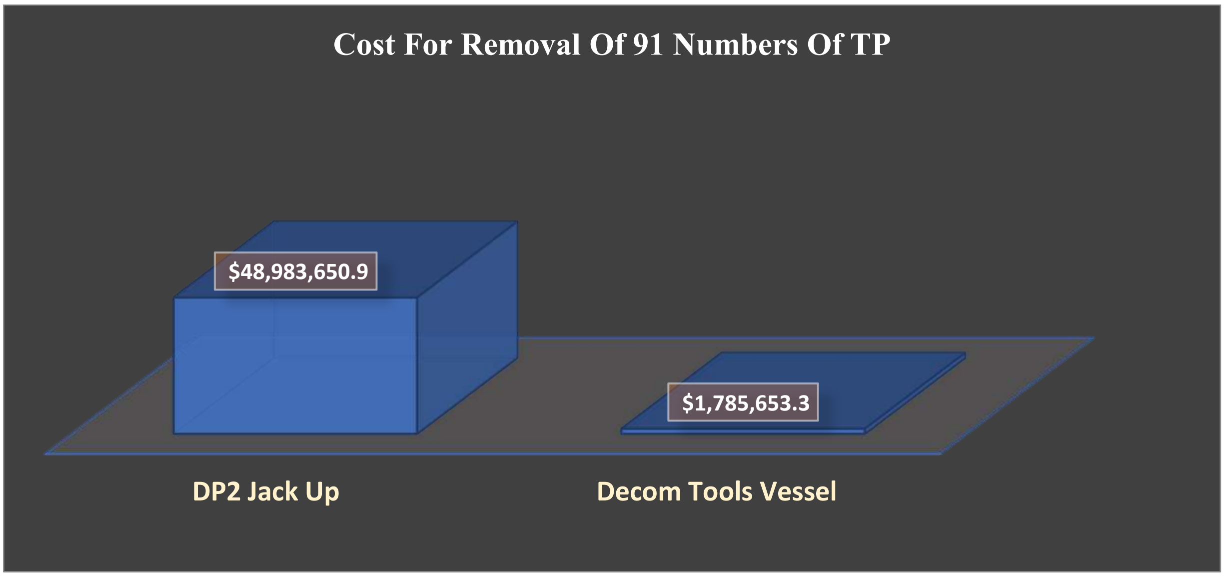


Figure 6-113 Cost of Removal of 91 number of TP

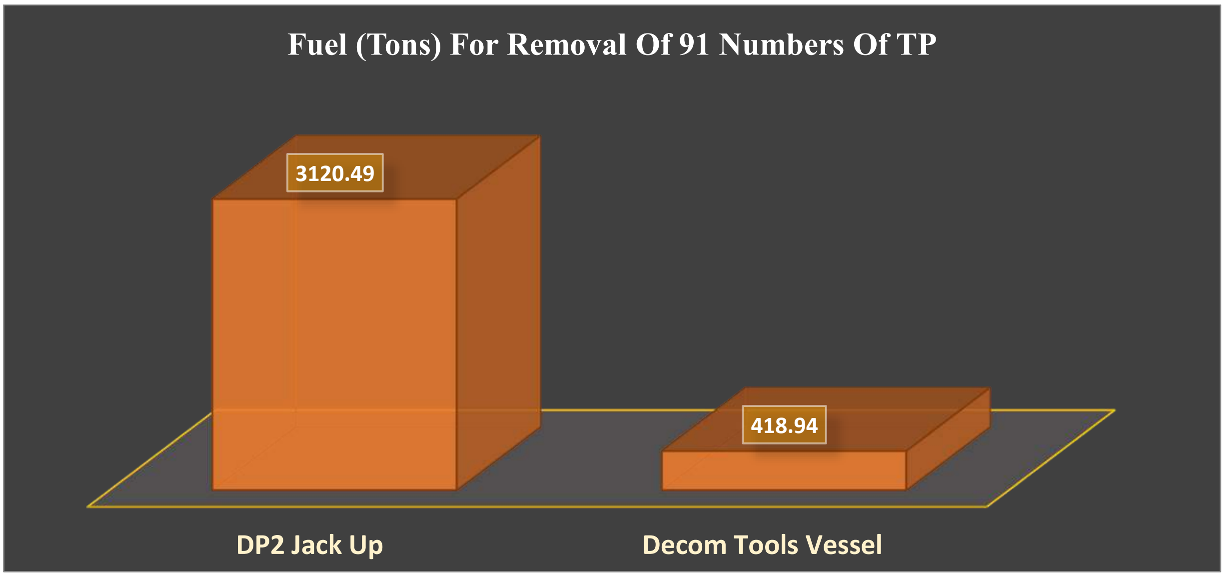


Figure 6-114 Fuel Consumption During Removal of 91 Number of TP

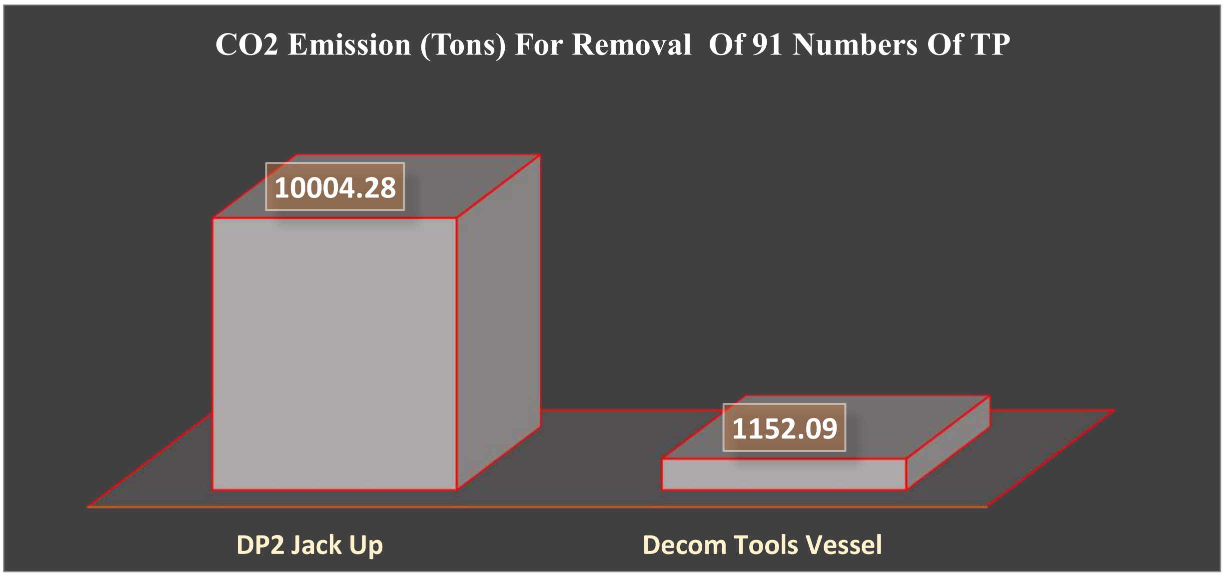


Figure 6-115 CO2 Emission During Removal of 91 Number of TP

6.18 Pile Extraction System

After removal of transition pieces, the monopiles should be extracted entirely. The reasons why the entire extraction should be performed are explained in the following section. There is one proof of concept tool for pile extraction which is vibratory hammer. An innovation method has been engineered as part of Decom Tools Vessel to extract the monopiles. The comparison has been made between pile extraction with vibratory hammer and pile extraction with Decom Tool vessel in the further sections of this document.

6.18.1 Legal, Financial and Technical Consequence of Partial Pile Removal

Most of wind farm contractors proposed to cut the foundations a couple of meters (between 2-4 meters) below the mudlines for the decommissioning operation. However, in the decommissioning of OWFs, international, regional and national regulations and standards shall be considered. Abandoning of offshore wind park's materials exert environmental impact, bearing legal and financial responsibilities to the developers as well as pose risk to the sea users.

Resolution A.672 (16) of International Maritime Organization (IMO) is a guideline and standard for the removal of offshore installations and structures on the continental shelf and in the exclusive economic zone (EEZ), which is a source of reference for decommissioning of offshore installations according to UNCLOS. Under article 3.2 of this document which is adopted on 19th of October 1989, "all abandoned or disused installations or structures emplaced on the seabed on or after 1st of January 1998, standing in less than 100 m of water and weighing less than 4 000 tons in air, excluding the deck and superstructure, should be entirely removed." However, according to clause 3.5, under four certain conditions, consent for partial removal can be granted from costal state. It is declared that "Notwithstanding the requirements of above-mentioned provision, where entire removal is not technically feasible or would involve extreme cost, or an unacceptable risk to personnel or the marine environment, the coastal state may determine that it needs not be entirely removed."

One can conclude that firstly, the primary condition of above-mentioned resolution is the entire removal of installed structures. Furthermore, based on clause 3.10, periodic monitoring of the remained material is mandatory and shall ensure compliancy with IMO standards and guidelines. Moreover, the infrastructures owner has liability for future damage and any required maintenance based on clause 3.11, which means that costal states require financial security from them to ascertain that any accident or incident resulting from left materials can be indemnified by the asset owner. From a technical and an operational perspective, it can be argued that keeping foundation in place may result in huge costs and technical problems for developers in future, assuming that a new OWF will replace the decommissioned one at the same site. More importantly, from an environmental stance, the periodic monitoring requires mobilization of vessel, equipment and crew for the survey. Conduction of the survey will result in huge amount of cost and emission of CO_2. Thus, in the long run, substantial number of resources will be wasted due to this obligation which is a consequence of keeping material in situ.

Ultimately, the mentioned resolution declared that all remained material should be entirely removed whenever it becomes technically feasible.

6.18.2 Procedure of Pile Extraction Reverse to the Installation

In decommissioning of Lely wind farm, the OWF developer used vibratory hammer for pile extraction which was successful tools for pile extraction in that project. Based on the interview that authors made with one of the vibratory hammer manufacturers, it is not possible to extract the piles of every wind farm with this tool since the extraction is heavily depends on the soil characteristic.

Furthermore, the vibratory hammer needs massive amount of energy for running. Approximately, the large size vibratory hammer needs 9200 kWh power[68]. This high demand power means conspicuous consumption of fuel which will result in considerable emission.

Figure 6-116 and Figure 6-117 show how the extraction of monopile has been executed in the decommission of Lely offshore wind park[69] which was laid in the Netherlands in 1992.

Figure 6-116 Extraction of Monopile with Vibratory Hammer During Decommissioning of Lely OWP (offshoreWIND.biz 201)

[68] Authors are not allowed to publish the source of this figure
[69] This wind farm was in service for 22 years.

The extraction of the piles of Lely wind farm took about 3 hours. The length of pile in this wind farm was about 27 meter and has diameter of 3.7 meter. Furthermore, the weight of monopile was 84 tones.

Figure 6-117 Monopile is Extracted with Vibratory Hammer (Vattenfall 2016)

6.18.3 Time-Cost Analysis of Pile Extraction Reverse to the Installation

To calculate the duration, cost and fuel consumption for removal of monopile, an algorithm has been devised. Hornsea 1 was selected as a case study in order to explain the different operations that the vessel need to be involved. Calculations for two different scenarios have been done in order to find out the most sustainable and cost-efficient method of extraction of monopiles. Prior to explain the calculation, first of all some basic information about this wind farm and its installation are given. Because if the decommissioning operation reverse to the installation take place, calculation with same vessel and logistic configuration need to be analysed.

The monopiles of Hornsea 1 offshore wind farm has diameter of 8.1 meter and average length of 63 meter. The weight of monopile (MP) varies between 800-1039 tones approximately. Some of the monopiles were installed with a DP2 Jack up vessel by the name of Innovation. In each cycle, it transported 4 number of MPs (offshoreWIND.biz 2018). The following figure shows how the transportation of MPs have been conducted by Innovation.

For extraction of monopile with vibratory hammer, it is considered that large sized hammer to be utilized which consume 97 tons per day approximately.

Figure 6-118 Transportation of Monopiles and Hammer with DP2 Jack up Innovation

If the pile extraction takes place reverse to the installation, the result of MP extraction will follow the below table.

Table 6-11 Result of Pile Extraction Reverse to the Installation

Results of Pendulum Configuration in Removal of MP with DP2 Jack Up Vessel & VLT			Hornsea 1
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Positioning	40.95	25.1%	$ 8,190,421.30
Figures of Sailing	17.25	10.6%	$ 3,449,724.02
Figures of In-Field Transit	1.89	1.2%	$ 378,347.73
Figures of Offshore Construction	62.92	38.5%	$ 12,584,234.23
Figures of Offloading	5.69	3.5%	$ 1,137,500.00
Figures of Unplanned Activities	34.75	21.3%	$ 6,949,861.37
Grand Total	**163.45**	**100.0%**	**$ 32,690,088.65**

The analysis of above table is as following:

I. **Sailing:** Duration of sailing is the time that the vessel has to sail between the OWP and the feeder port. Having considered the size and weight of monopile, the Innovation vessel carried out 4 number of piles per cycle. To transport all 91 numbers of MP, the jack up vessel has to sail and return 23 times. The distance of port to the OWP is 120 Km, the duration of sailing based on 60% of the maximum speed will be 17.25 days which account 10.6% of the pile extraction operation.

II. **Positioning:** The position is the time that the vessel starts to jack down until the legs reach final penetrations. It also contains retrieval of legs from seabed. The Innovation vessel has jacking speed of 1 m/min which is a high jacking speed. It takes 40.95 days for the vessel to position alongside each wind turbine.

III. **In-Field Transit:** It includes the time that vessel has to sail between each of 91 Turbine. with speed of 1 knot, the duration for this part of operation will be 1.89 days.

IV. **Offshore Construction:** this time includes the time that the vibratory hammer is lifted, stabbed onto the monopile, extraction and placing the monopile on the vessel deck. Therefore, this operation includes:

A. Lifting the hammer and stabbing onto the monopile (it is considered 1 hour in calculation).
B. Extraction of monopile (it is considered 14.59 hours per monopile).
C. Lifting the monopile and placing on the vessel deck (it is considered 1 hour in calculation).

The overall time of hammer installation, extraction and lifting and placing on the vessel is 62.92 days which accounts 38.5% of whole operation.

Note: The only similar operation is extraction of monopile in Lely wind farm. Just extraction operation (sequence B.) took 3 hours in that OWP. It should be noted that in the Lely wind farm, first of all the length of monopile was 27 meters and secondly the dimeter of MP was 3.7 meters. The more dimeter means more skin friction with strata and soil which obviously more force is needed for extraction.
If the soil condition of location of Lely OWP and Hornsea 1 OWP has similar specification, then the skin friction in the Hornsea 1 is 4.8 times more than the Lely OWP.

V. **Offloading:** after extraction and transportation of monopile to the port, the materials should be transferred from the vessel to the quayside. It is assumed that transfer of each piece of monopile takes 1.5 hours. In general, transferring 91 numbers of monopile from vessel to the port takes 5.69 days.

VI. **Unplanned Activities:** unplanned activities include three different parameters as following:

A. Waiting on Weather (WOW) which is 25% of the first 4 steps.
B. Waiting on client (WOC) plus mechanical breakdown which is 2% of the first 5 steps.

According to above assumption regarding unplanned activities, the jack up vessel goes to stand-by mode for 34.75 days which is 21.3% of the entire pile removal operation.

Conclusion: Pile extraction reverse to the installation (with vibratory Hammer) takes about **163.45 days** and cost about **32,690,088.65 $** considering 200 000$ as daily charter rate of the DP2 Jack up vessel.

6.18.4 Design of Pile Extraction System of the Decom Tools Vessel

The authors would like to show that entire removal is possible from a technical stance without using high energy demanding equipment like vibratory hammer. In addition, the vibratory hammer cannot extract the piles of all locations (piles in all soil condition) successfully.

One of the potentials of every floating vessel is that they have a lot of ballast tanks which can provide either negative or positive buoyancy to the vessel. Variation of ballast of the vessel caused the alteration in the draft of the vessel. To put it more simply, the draft of the vessel can be adjusted by ballasting of the vessel.

To extract the monopiles, the pile extraction system needs to overcome two forces as following:

I. The deadweight of monopile.

II. The skin friction[70] between monopile and soil strata (the skin friction can be calculated according to equations that are provided in the standard API RP 2A).

The mechanism of pile extraction in Decom Tools vessel is to extract the pile with lifting capacity which can be produced by the buoyancy of the vessel. To accomplish this, a couple of numbers of grippers are designed that can work the same as external lifting tool (ELT) to hold the monopile firmly. In the design of the ELT, the exerted force of ELT to the pile should overcome the weight of pile plus some dynamic forces due to movement of pile etc. However, in the Decom Tools vessel, the extraction grippers must apply force to the monopile not only to overcome the dead weight of the pile during the lifting but also the skin friction between the soil strata and the pile. Figure 6-119 shows external lifting tool during gripping around circumference of a pile.

Figure 6-119 External Lifting Tool (ELT) (IHC n.d.)

[70] The end bearing can be neglected.

Figure 6-120 shows the extraction grippers of the Decom Tools vessel. These sets of grippers are located at the aft of the vessel for the sake of safe manoeuvring and positioning. These grippers are operated by a hydraulic system. Therefore, hydraulic power unit (HPU) is required to provide the necessary pressure to open and close the grippers. The grippers can be adjusted to various diameter of monopiles. But in this design, the installed grippers are suitable for the piles with diameter of 10 meters. Figure 6-122 illustrates a couple of sets of grippers and the dimension of them. The length and the numbers of grippers are not engineered and analysed, and the mentioned figure just show the schematic of the grippers (conceptual design). Western Norway University of applied Science agreed to conduct a couple of research in order to design the grippers.

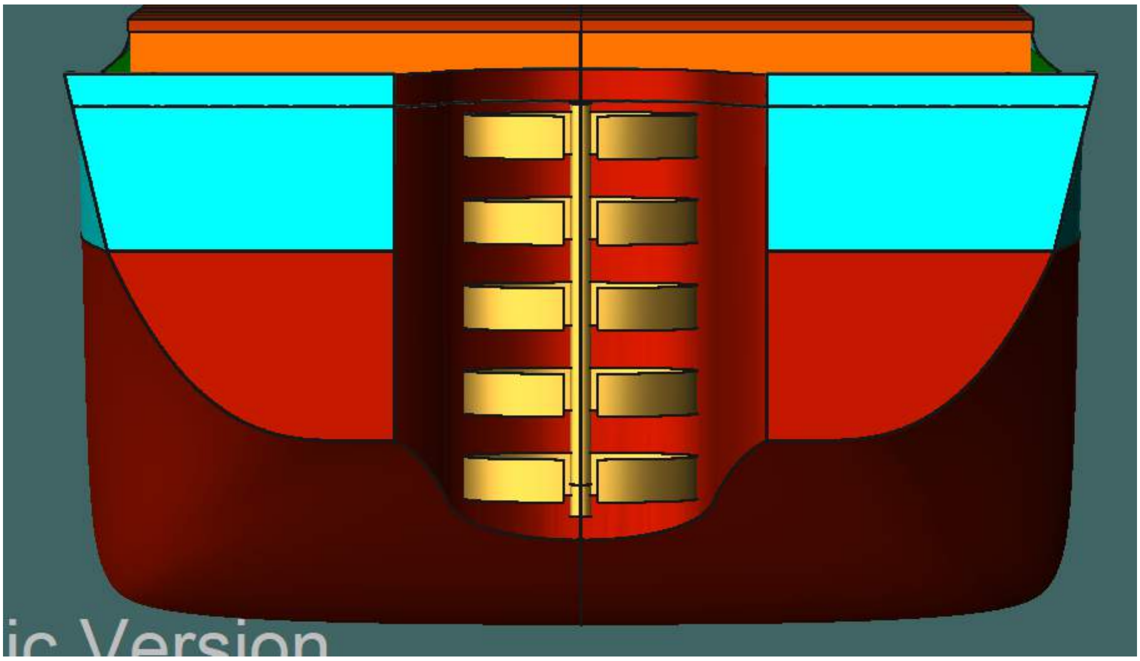


Figure 6-120 Extraction Grippers

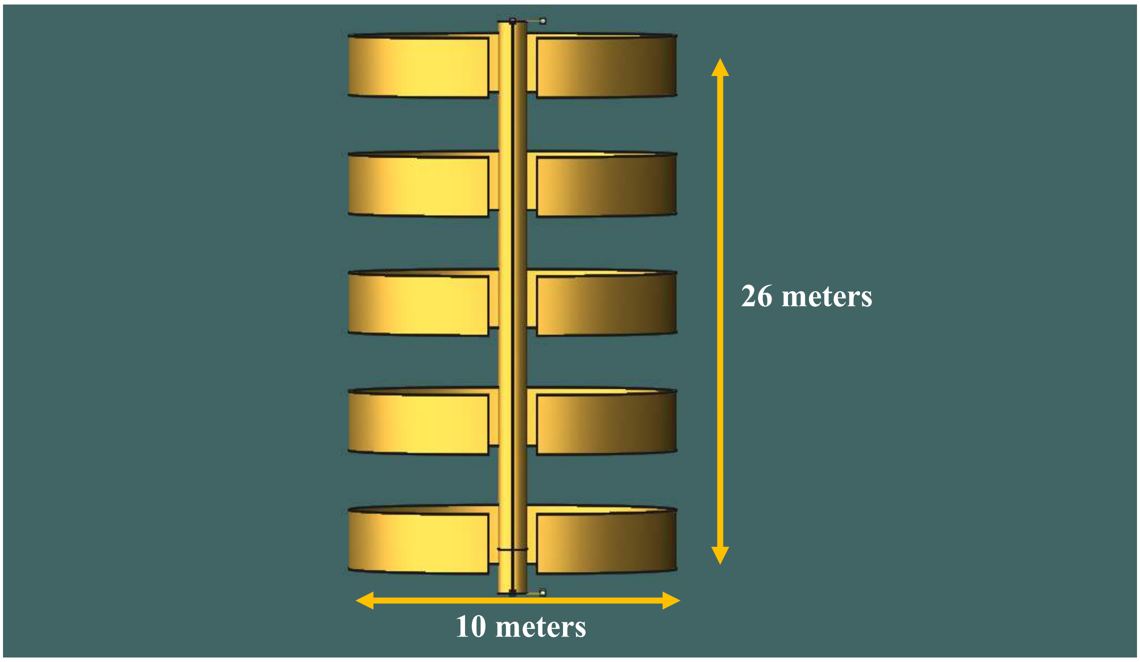


Figure 6-121 Schematic of Pile Gripper

The study that conducted by GE's consultant shows that in the water depth of 50 meter, monopile with diameter of 10 meter can be a suitable foundation type for GE X-Heliade 12MW wind turbine. Having considered this fact, the diameter of grippers is designed for monopile with diameter of 10 meter. Nevertheless, the opening which is designed at the aft of Decom Tools vessel has an opening of 26 meter and diameter of 12.8 meter at the centre which means that vessel can extract the pile diameter up to 11 meters at least. Therefore, the size of extraction grippers meets the demand of this industry for more than 12MW wind turbine. It should be noted that detail design of extraction grippers will be attached as an appendix to this document in due course. Location and dimension of hole for extraction system are shown in the Figure 6-122 and Figure 6-123.

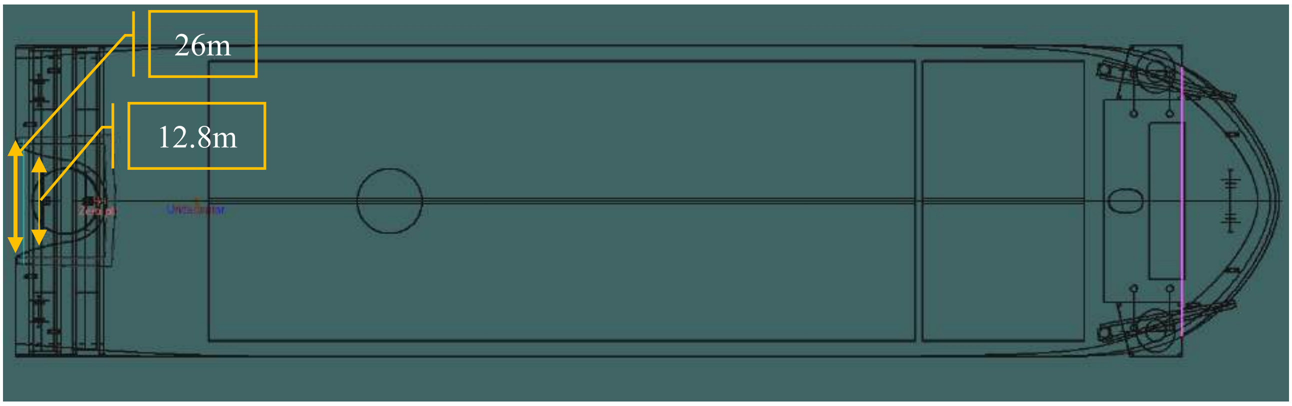


Figure 6-122 Dimensions of Pile Extraction System

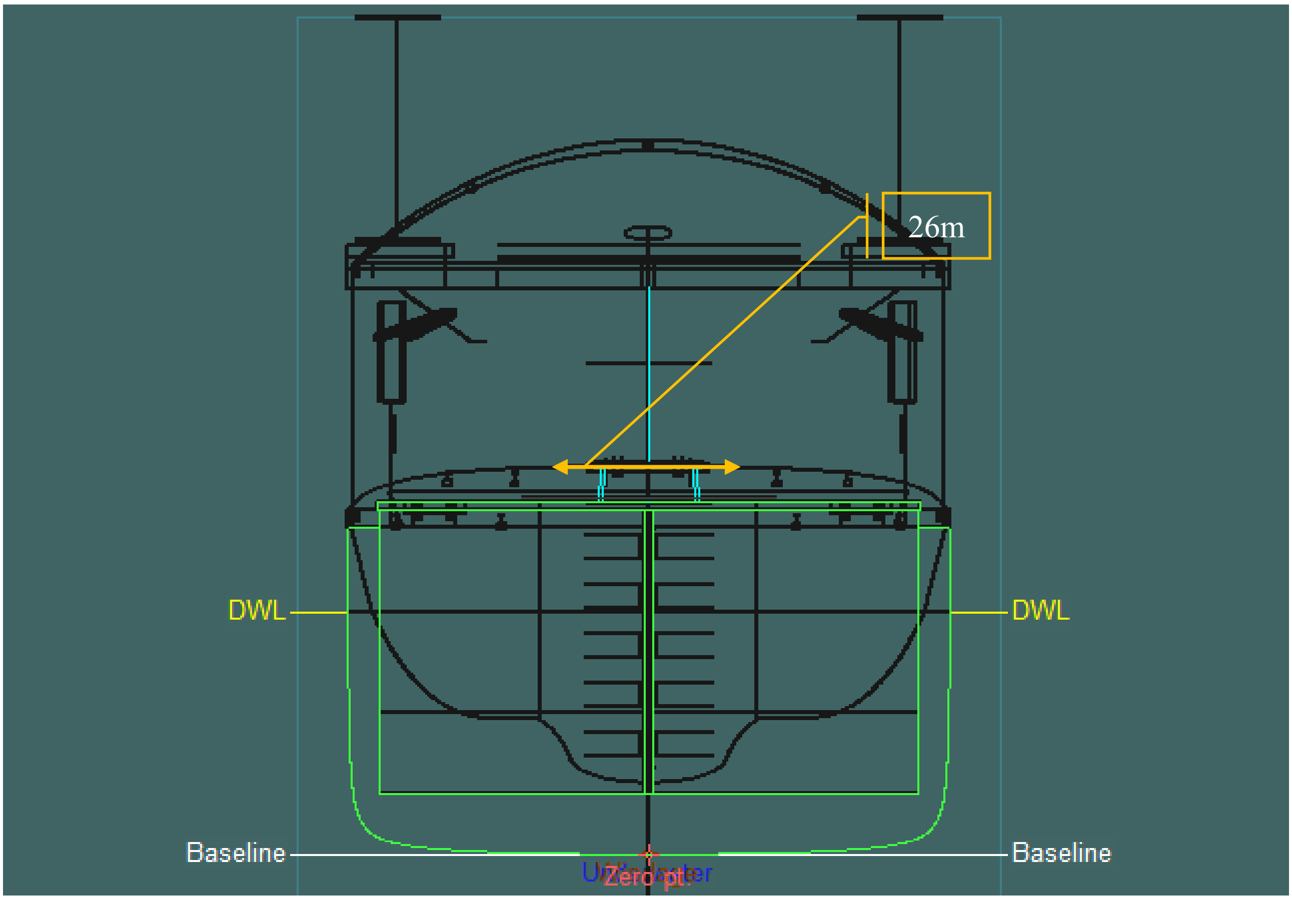


Figure 6-123 Location of Pile Extraction System

The reason to consider the opening of 26 meter for the extraction hole is safe approaching of the vessel to the monopile and transition piece.

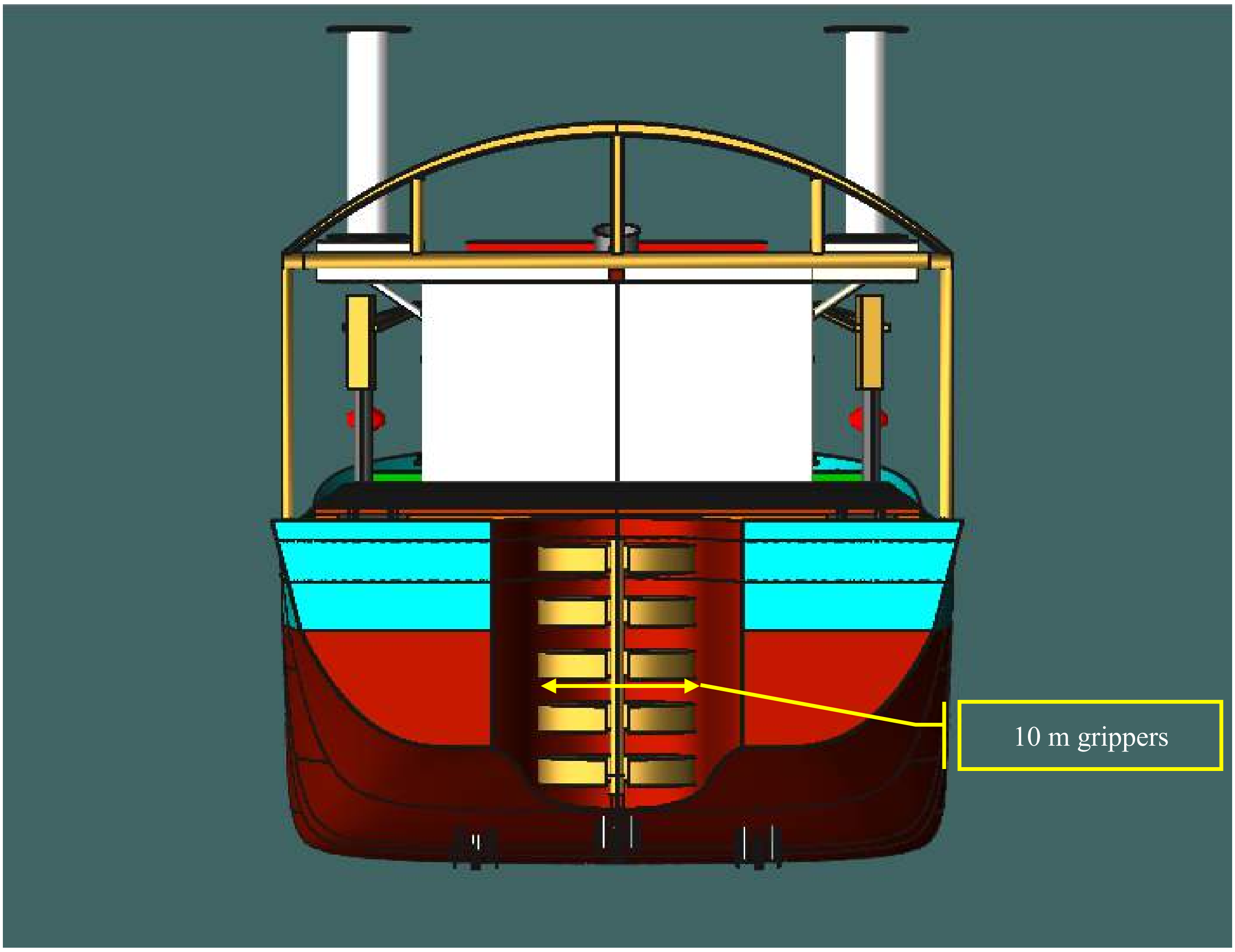


Figure 6-124 Dimension of Grippers

This part of the Decom Tools vessel has some similarities with the vessel by the name of Pioneering Sprit which is initially designed for the decommissioning of offshore oil and gas structures. The maximum lifting capacity of Pioneering spirit is 48000 tones, the following figures show some photos of this unique vessel and how it lifts the structures. Instead of grippers, this vessel has lifting yokes which moves upward and downward to lift the structures.

Having considered that the Decom Tools vessel is designed for pile extraction, therefore, instead of yokes, grippers are designed in order to hold the monopiles firmly. To put it more simply, the equipment onboard the vessel are designed based on their function and application. The Pioneering Spirit is designed for the decommissioning of heavy offshore oil and gas structure and the Decom Tools vessel is designed for decommissioning of offshore wind parks in the North Sea Region. Therefore, there are significant difference between them in terms of ship capabilities, ships dimension, installed equipment, the vessel function and so forth.

Figure 6-125 shows the vessel prior to installation of lifting yokes. The vessel is made of two oil tankers.

Figure 6-125 Pioneering Spirit without lifting Yokes

Source: (Deltamarine n.d.)

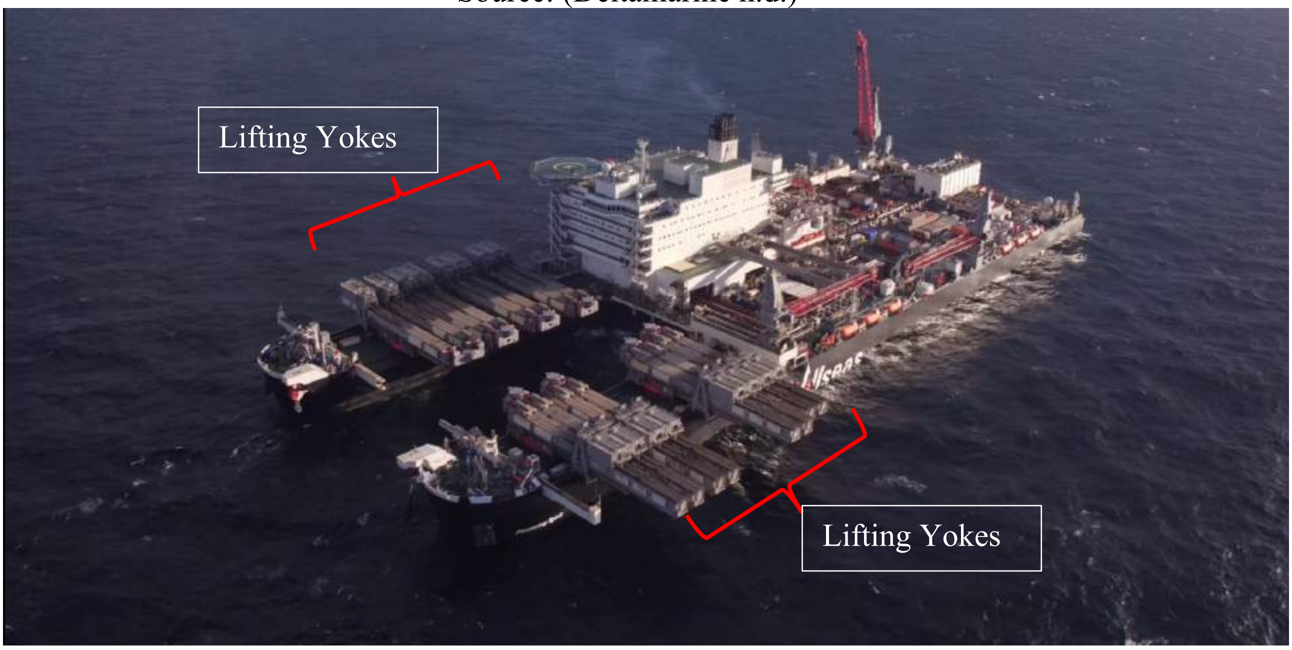


Figure 6-126 Lifting Yokes

Figure 6-127 and Figure 6-128 show how the vessel approached to the platform and how the lifting yoks adjusted and lifted the topside.

Figure 6-127 Pioneering Spirit Located underneath the Structure for Lifting

Figure 6-128 The Topside is Lifted by Pioneering Spirit

One possible problem during extraction of pile with vibratory hammer is tearing the pile where the vibratory hammer clamps are connected to the monopile. The vibratory hammer has a couple of clamps which hold the pile. The forces are transferred to the pile via the clamps. The authors did not perform any analysis in order to see whether the clamps can tear the pile or not. But due to corrosion and fatigue of monopile after 20-25 years of lifespan, it can be a possible failure. The following figure shows how the vibratory hammer is connected to the monopile with the clamps.
The problem of pile extraction with Decom Tools vessel is different. The force that the grippers apply to the monopile can exceed the permissible force since the mechanical property of pile can be changed after 20-25 years of lifetime due to the loads, corrosion and the fatigue. Applying extra

force with grippers can cause collapse of pile. To prevent this collapse and avoid the accident, a simple mechanical structure is designed in order to be inserted inside the monopile during extraction.

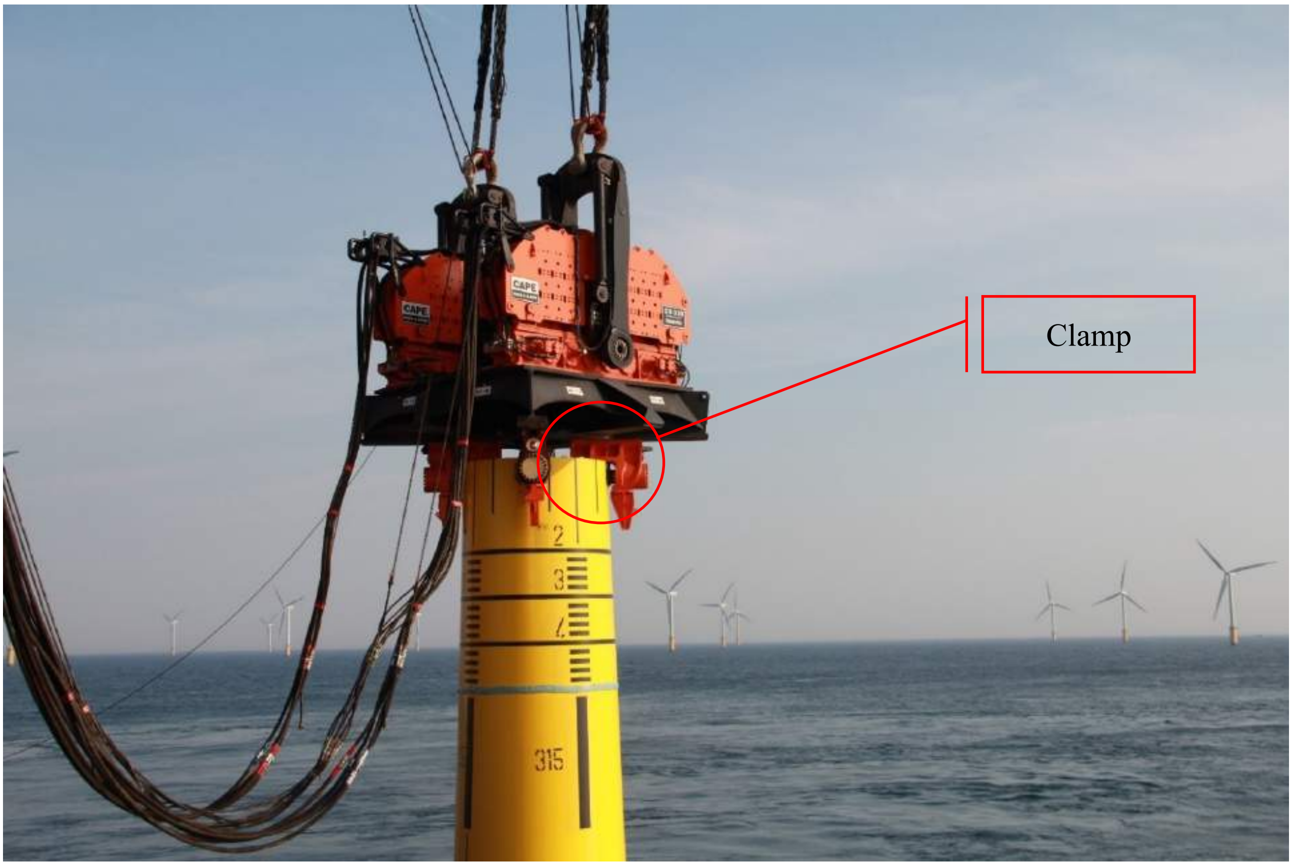


Figure 6-129 The connection of Clamps of Vibratory Hammer to the Monopile

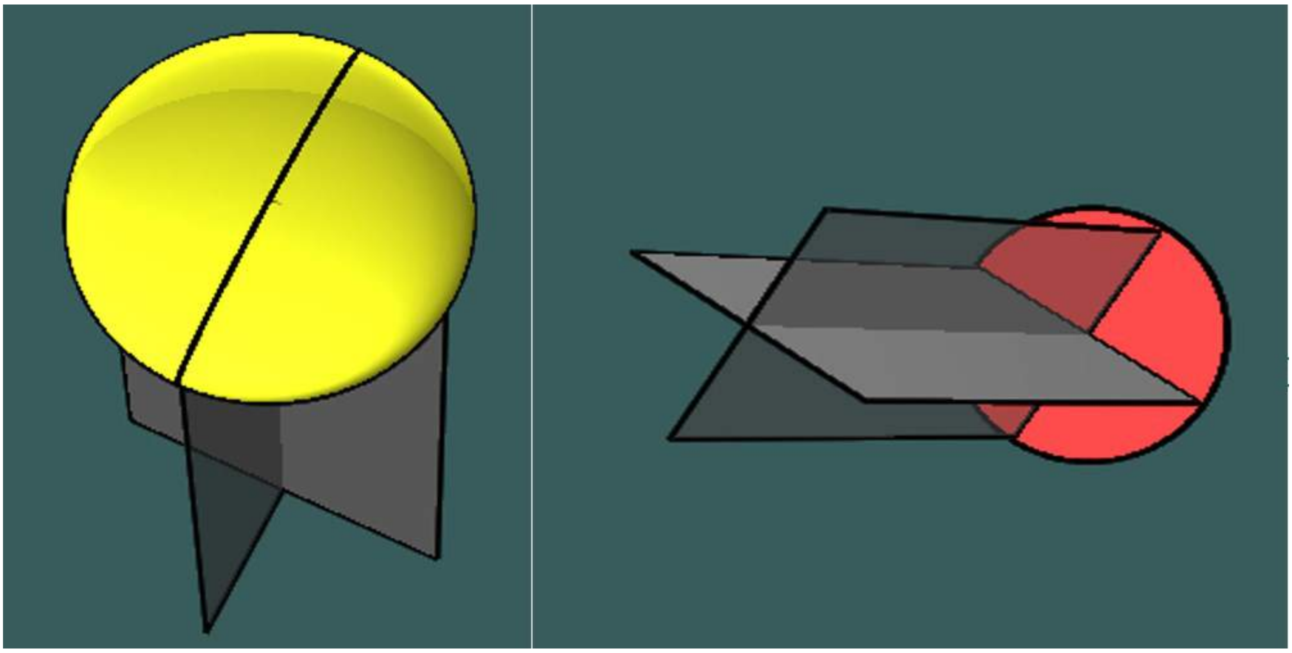


Figure 6-130 Structure to Prevent Pile Collapse (Pile Collapse Preventor)

The following figure shows the designed this structure which is called pile collapse preventor here.

Figure 6-131 shows how the pile collapse preventor need to be installed into the monopile. This is a simple structure which can prevent any possible collapse of monopile.

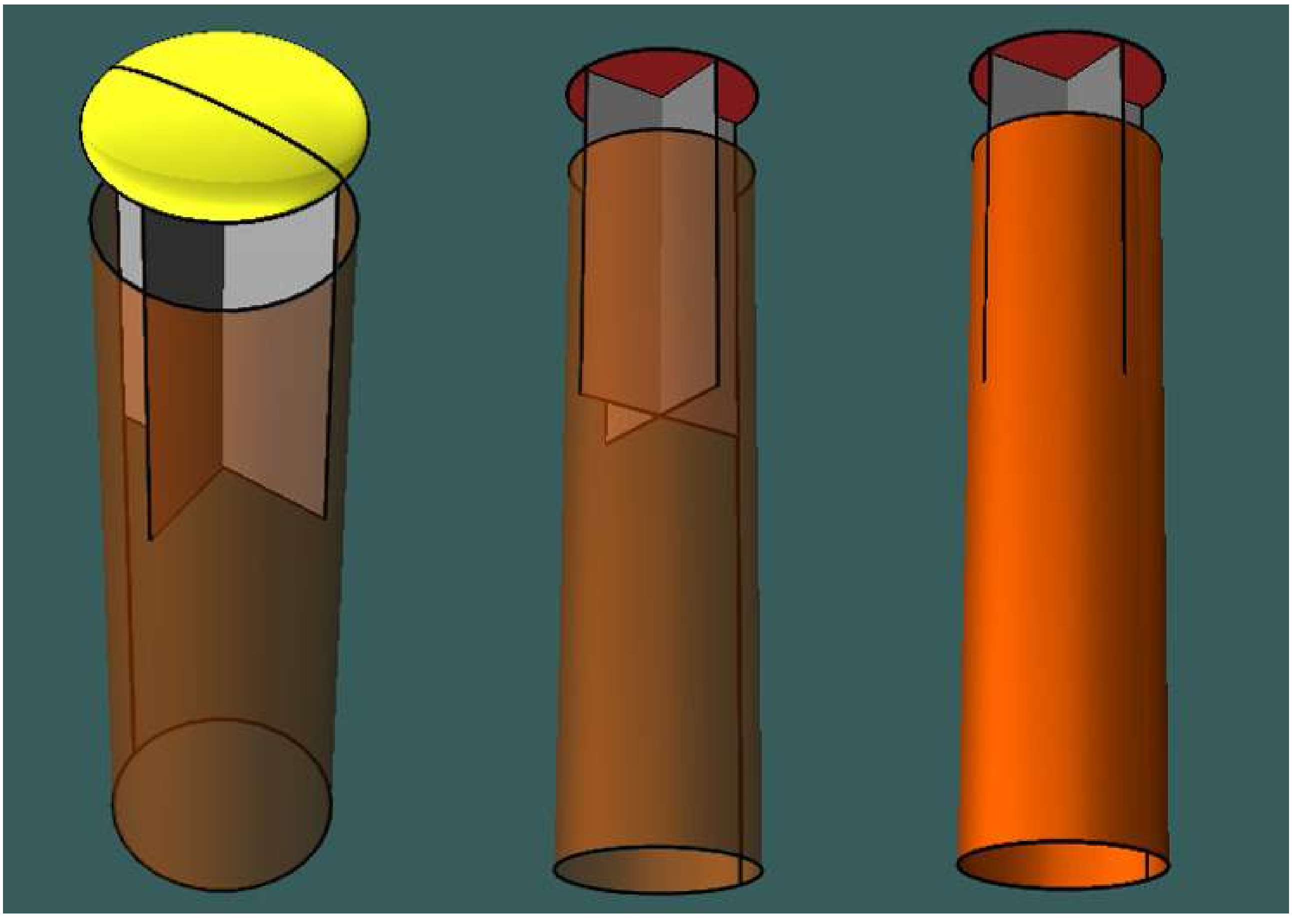


Figure 6-131 Different Views of Pile Collapse Preventer Inside Monopile

6.18.5 Ballast and Extraction Analysis of the Decom Tools Vessel

The extraction of pile will be conducted by using the buoyancy force of the vessel. Thus, in order to extract the monopile, the ballast of the vessel should be changed. Changing the ballasting should be in a way to maintain the vessel stability in acceptable range. Thus, the calculation has been made in order to sink and rise the vessel by changing the ballast tanks in a safe range. In order to maintain the safety of the ship, minimum fix ballast should be considered meaning that the ballast should not be less than this value. To achieve this, all centre double bottom tanks should be kept full. In this case, from a stability point of view the ship can operate safely. However, the rest of ballast tanks can be adjusted which means that the water inside them can be entirely removed or filled. Having the partial ballast inside the tanks cause free surface effect which can pave the way for instability of the vessel.

More importantly, to avoid damage to the gripper and extract the monopile vertically, the vessel should be raised or sunken all the time at even keel draft. In other words, the entire operation must be all the time at even keel draft.

Thus, in order to calculate the maximum extraction height, calculation has been done for the ship's draft at the equilibrium status, once for full ballast and the second time for the minimum ballast. The difference between both drafts will be the maximum possible extraction height per one attempt.

The figures of full and minimum ballast are shown in the Table 6-12.

1) Maximum ballast at even keel draft is:

- Ballast on board: 47579.678 mt.
- Capacity: 94.35%.

In the above situation, all the ballast tanks are full except AFT peak tanks which each of them has volume of 981tons.

2) Minimum ballast at even keel draft is:

- Ballast on board: 14431.006 mt.
- Capacity: 30.88%.

Table 6-12 Decom Tools at Full and Minimum Ballast for Pile Extraction

MinBall - Intact			FULLBALL - Intact		
1	Draft Amidships m	6.137	1	Draft Amidships m	10.170
2	Displacement t	40755	2	Displacement t	73893
3	Heel deg	0.0	3	Heel deg	0.0
4	Draft at FP m	6.136	4	Draft at FP m	10.170
5	Draft at AP m	6.137	5	Draft at AP m	10.170
6	Draft at LCF m	6.137	6	Draft at LCF m	10.170
7	Trim (+ve by stern) m	0.001	7	Trim (+ve by stern) m	0.000
8	WL Length m	181.899	8	WL Length m	192.347
9	Beam max extents on WL m	47.590	9	Beam max extents on WL m	47.904
10	Wetted Area m^2	8877.584	10	Wetted Area m^2	10714.054
11	Waterpl. Area m^2	7773.533	11	Waterpl. Area m^2	8221.093
12	Prismatic coeff. (Cp)	0.816	12	Prismatic coeff. (Cp)	0.815
13	Block coeff. (Cb)	0.745	13	Block coeff. (Cb)	0.767
14	Max Sect. area coeff. (Cm)	0.925	14	Max Sect. area coeff. (Cm)	0.950
15	Waterpl. area coeff. (Cwp)	0.898	15	Waterpl. area coeff. (Cwp)	0.892
16	LCB from zero pt. (+ve fwd) m	89.449	16	LCB from zero pt. (+ve fwd) m	87.174
17	LCF from zero pt. (+ve fwd) m	85.808	17	LCF from zero pt. (+ve fwd) m	82.909
18	KB m	3.402	18	KB m	5.538
19	KG fluid m	10.105	19	KG fluid m	9.878
20	BMt m	33.146	20	BMt m	19.996
21	BML m	458.151	21	BML m	292.506
22	GMt corrected m	26.443	22	GMt corrected m	15.655
23	GML m	451.448	23	GML m	288.166
24	KMt m	36.548	24	KMt m	25.534
25	KML m	461.553	25	KML m	298.045
26	Immersion (TPc) tonne/cm	79.679	26	Immersion (TPc) tonne/cm	84.266
27	MTc tonne.m	1039.474	27	MTc tonne.m	1203.028
28	RM at 1deg = GMt.Disp.sin(1) tonne.m	18808.342	28	RM at 1deg = GMt.Disp.sin(1) tonne.m	20189.457
29	Max deck inclination deg	0.0003	29	Max deck inclination deg	0.0001
30	Trim angle (+ve by stern) deg	0.0003	30	Trim angle (+ve by stern) deg	0.0001

Results:

- The different between minimum and maximum draft is = 10.17- 6.137 = **4.033 meters**.
- Therefore, the maximum extraction in each attempt is **4.033 meter.**
- Ballast needs to be pumped out is = 47579.678 - 14431.006 = **33148.672 mt**
- Therefore, the lifting capacity is **33148.672 mt.**
- Having considered that 10 numbers of ballast pump is designed for this vessel, and each of them has capacity of 3000m^3 per hour, therefore, for extraction of 4.033 m, it takes **2.15 hours** approximately (including ballasting and deballasting).
- To reduce the offshore operation duration, cutting should take place every **12 meters** (after three attempts of extraction).

6.18.6 Time-Cost Analysis of Pile Extraction with Decom Tools Vessel

In order to analyse the cost and emission of pile extraction operation with Decom Tools vessel, it needs to have a case study for such calculation. Also, to compare the cost and emission of pile extraction with vibratory hammer and Decom Tools Vessel, it needs to do the analysis of one wind park. Therefore, the case study here will be Hornsea 1 offshore wind farm. In the mentioned wind farm, the average water depth is 30.5 meters (Orsted 2018). Having considered that the monopiles have average length of 63 meter, then in average, the monopiles are driven 32.5 meters into the seabed (SAL n.d.).

The following parameters are enough to carry out the analysis for pile extraction.

I. Length of extraction per attempt = 4.033 meter

II. Ballast Pumps capacity = 10 ballast pumps of 3000$\frac{m^3}{h}$ =30 000 $\frac{m^3}{h}$

III. The volume of water (ballast) in each extraction =

$$2 * (\text{Volume of full ballast} - \text{Volume of minimum possible ballast}) = 64680.33\text{m}^3$$

(density of seawater is considered 1.025 $\frac{metric\ tone\ (mt)}{Cumbic\ meter (m3)}$

IV. Time for one time extraction = 2.156 hours

With respect to the height of extraction which is 4.033 meter it means that for extraction of this 32.5 meters pile, the extraction should be conducted 8 times.

The required time for 8 times extraction is 17.374 hours which is equivalent to 0.723 days for each pile (However, in the next section, we can see that in this period, cutting and removal of marine growth also has been done).

Furthermore, the pile should be cut after three times extraction means the length of 12 meters (after removal of pile from seabed, the pile can be lifted every 15 meters which in this case with water depth of 30.5m, 1 time cutting should take place).

So, it is considered to cut the monopile after 3 times ballasting and deballasting. The time for cutting each piece of pile with 8.1 meters diameter and approximate thickness of 3 inches is considered 2 hour which in this case, the overall time of cutting will be 8 hours.

In conclusion, the required time for pile extraction, pile cutting, and marine growth removal will be calculated with following equation.

$$t_{overall} = (n_{ex} * t_{ex}) + (\left(n_{ex} + \left(\frac{W_d}{15}\right)\right) * H_c)$$

Where the parameters are defined as following:

- $t_{overall}$: $Overall$ $t$ime for extraction of monopile.
- n_{ex} is number that the pile should be extracted from seabed excluding the length of pile in the water column.

$$n_{ex} = \frac{LP_D}{4.003}$$

$$LP_D = LP_t - W_d \text{ or}$$

$$LP_D = overall\ length\ of\ pile - water\ depth$$

- LP_D $is\ the\ length\ of\ pile\ inside\ the\ seabed\ (driven\ length)$
- LP_t $is\ overall\ length\ of\ the\ pile$
- W_d $is\ water\ depth$
- t_{ex} is the required time for ballasting plus deballasting which is 2.15 hours.
- H_c $is\ time\ of\ cutting\ of\ pile$ which is considered 2 hours here.

Based on above equations, for extraction of 91 numbers of monopiles of Hornsea 1 offshore wind farm with Decom Tools vessel, the project cost and duration will be the same as following table.

Table 6-13 Result of Pile Extraction with Decom Tools Vessel

Results of Pendulum Configuration in Removal of MP with Decom Tools Vessel			**OWP: Hornsea 1**
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Sailing	2.85	1.8%	$ 199,667.07
Figures of In-Field Transit	1.89	1.2%	$ 132,421.71
Figures of Positioning	7.58	4.7%	$ 530,833.33
Figures of Extraction	69.78	43.1%	$ 4,884,802.68
Figures of Cutting	30.33	18.7%	$ 2,123,333.33
Figures of Offloading	5.69	3.5%	$ 398,125.00
Figures of Unplanned Activities	43.71	27.0%	$ 3,059,597.76
Grand Total	**161.84**	**1.8%**	**$ 11,328,780.88**[71]

[71] During pile extraction operation, the Decom Tools vessel has to work on DP mode. Therefore, the daily charter rate is considered **70 000$.**

The analysis of above table is as following:

I. **Sailing:** sailing is the operation that the vessel has to sail between port and offshore wind farm. The Decom Tools vessel can carry out 24 number of 8.1 diameter monopile. It means the vessel has sail 4 times between OWP and the port/decommissioning yard. The distance between the port and the wind farm is 120 km, then with 60% of max speed of the Decom Tools vessel (7.57 knot), the duration will be 2.85 days. This activity constitutes 1.8% of overall pile extraction operation.

II. **In-Filed Transit:** this is the time that the vessel has to sail between 91 numbers of monopile with speed of 1knot. This activity takes 1.89 day and constitute 1.2% of overall pile extraction.

III. **Offshore Construction:** this section consists of a couple of operations. It includes the following activities:

- Positioning of the grippers of the Decom Tools vessel around the monopile, which is considered 2 hours per pile.
- Ballasting and deaballasting (pile extraction) which take 2.156 hours per extraction.
- Pile cutting which is considered 2 hours.

The formula for this operation is given in previous pages. These sets of activities take 107.7 days which constitutes 66.5% of pile extraction operation.

IV. **Offloading:** after extraction and safe transportation of monopiles, they should be discharged to the port/decommissioning yard. The time for discharging each set of pile is 1.5 hours. In overall, the duration for offloading all 91 numbers of pile takes about 5.69 days which constitute 3.5% pile extraction operation.

VII. **Unplanned Activities:** It includes three different parameters as following:

C. Waiting on Weather (WOW) which is 35% of the first 6 steps.

D. Waiting on client (WOC) plus mechanical breakdown which is 2% of the first 6 steps.

According to this assumption, the Decom Tools vessel goes to stand-by mode due to above-mentioned reasons for 43.71 days which accounts 27% of the entire extraction operation.

Conclusion: The pile extraction for 91 numbers of monopile of Hornsea1 offshore wind farm with Decom Tools vessel takes about **161.84 days**. The pile extraction cost **$ 11,328,780.88**, considering 70000$ as daily charter rate of the vessel. It should be noted that charter rate of the vessel in this operation is considered 70 000$ which is 30 000$ more than transportation of rotor, nacelle and tower due to necessitation of the pile extraction with DP mode. As it stated earlier, maintaining the vessel position with DP required mobilization of DP officers which they have high wage. Also, the rent of cutting tools is considered in this price.

6.18.7 Pile Cutting Mechanism

It should be noted that the pile cutting system is designed along with pile extraction system for the Decom Tools vessel. This is the reason why extraction mechanism is explained in the previous section.

The sequences of pile extraction and cutting is as following:

1. The ship has to be ballasted parallel sinkage (even keel) in order to increase the draft of the vessel to the 10.170 meters.
2. The extraction grippers should be opened fully. Figure 6-132 shows that grippers are fully open.
3. The vessel has to approach to the desired monopile (refer to Figure 6-133). One of the most demanding manoeuvring operations is pile extraction operation which compel us to design a Voith Schneider propulsion system along with DP system.
4. The gripper has to be closed and fully tightened in order to hold the monopile firmly. Figure 6-133 and Figure 6-134 shows the grippers that hold the monopile firmly.
5. The vessel should be ballasted parallel rising (even keel) in order to lift the monopile. On each sequence, the pile can be extracted 4.033m.
6. After attempting each extraction, the monopile should be connected to the gantry cranes.
7. The cranes have to lift the monopile and to hold the monopile.
8. After lifting the monopile with crane, the gripper should be tightened again for next attempt of extraction.
9. The stages of 5 to 8 should be repeated three times
10. The access platform should be installed in order to install the cutting tool. However, it is possible to install the cutting tool with basket too. To improve the safety of the operation, the adjustable access platform has been designed.
11. The cutting tool should be installed at the elevation above the weather deck (around 0.50-1 meter above the weather deck).
12. The cutting should take place.
13. The cut piece of monopile should be lifted and placed on the right place which can be either inside the holds or deck.

The following figures shows the drawing of above-mentioned stages.

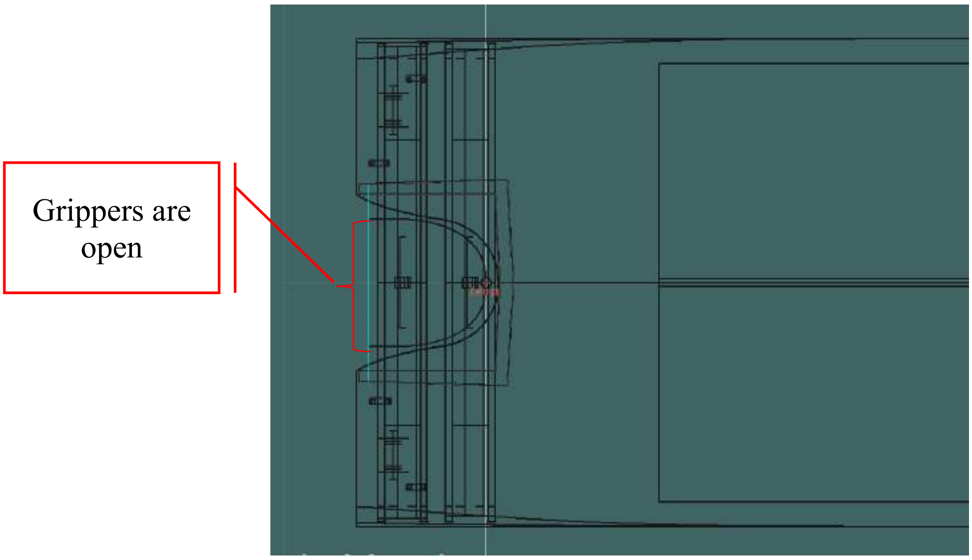


Figure 6-132 Open Status of Extraction Grippers

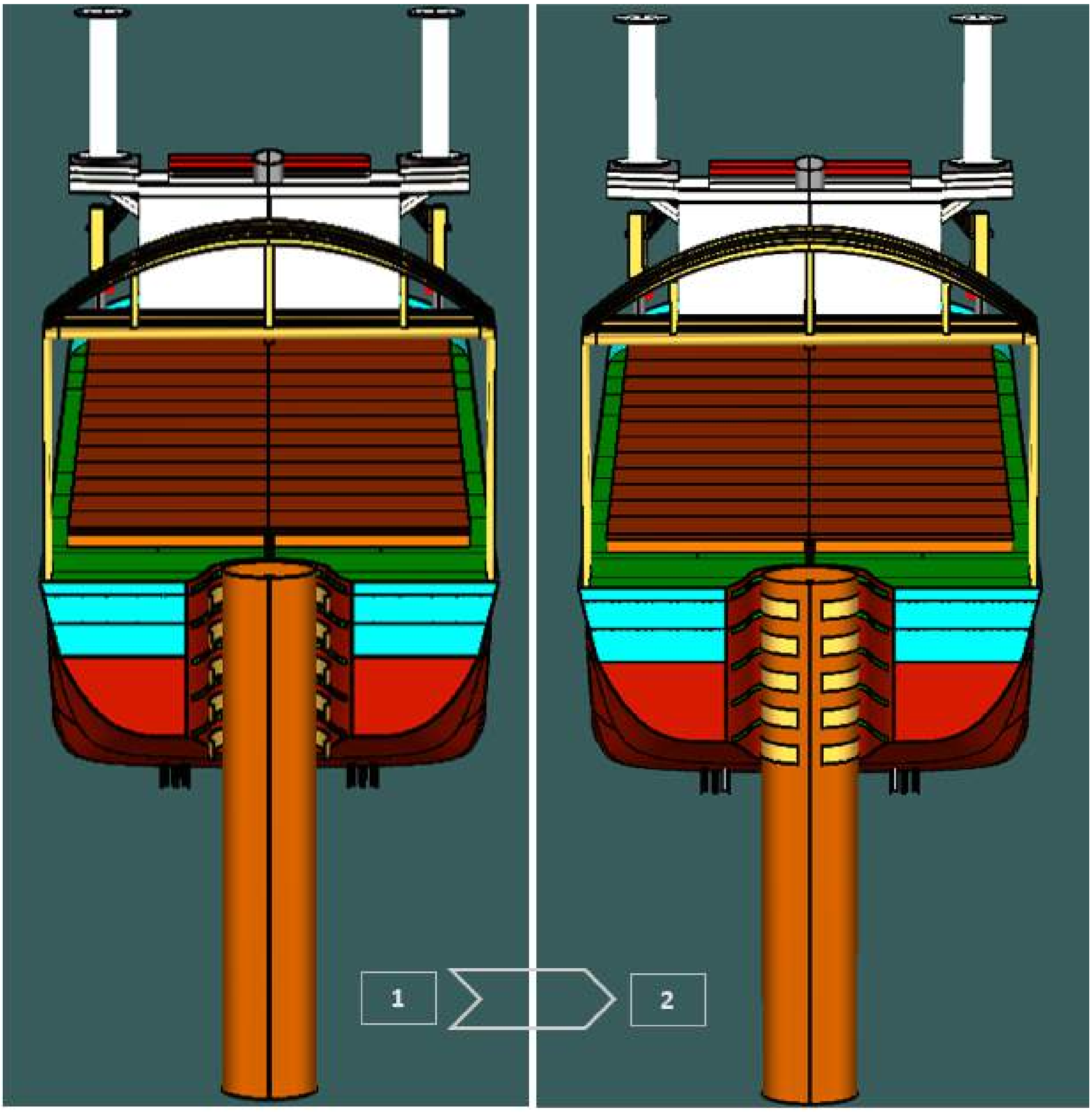


Figure 6-133 Decom Tools Vessel Positioned Around the Monopile

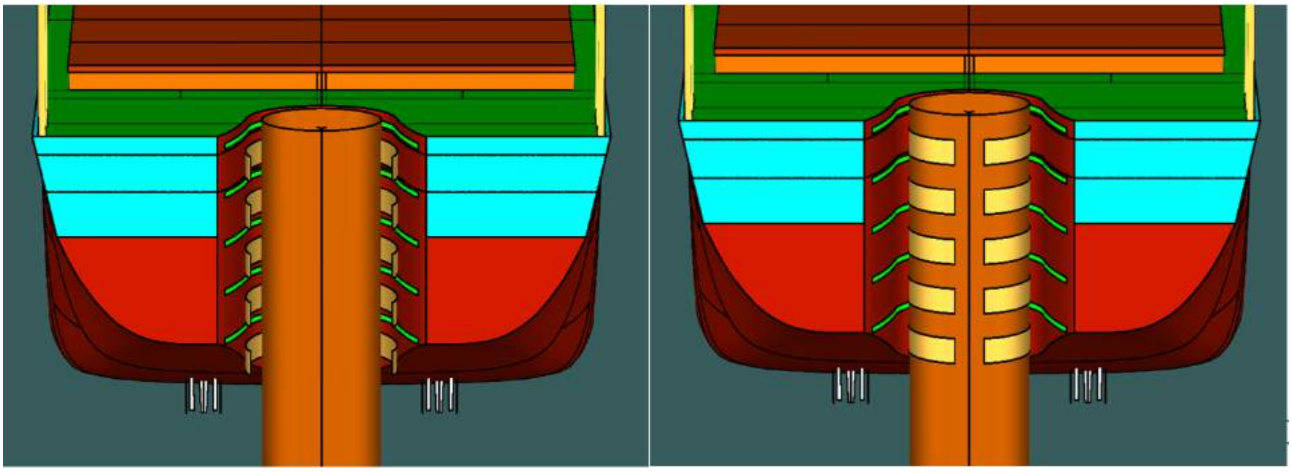


Figure 6-134 Status of Pile Grippes

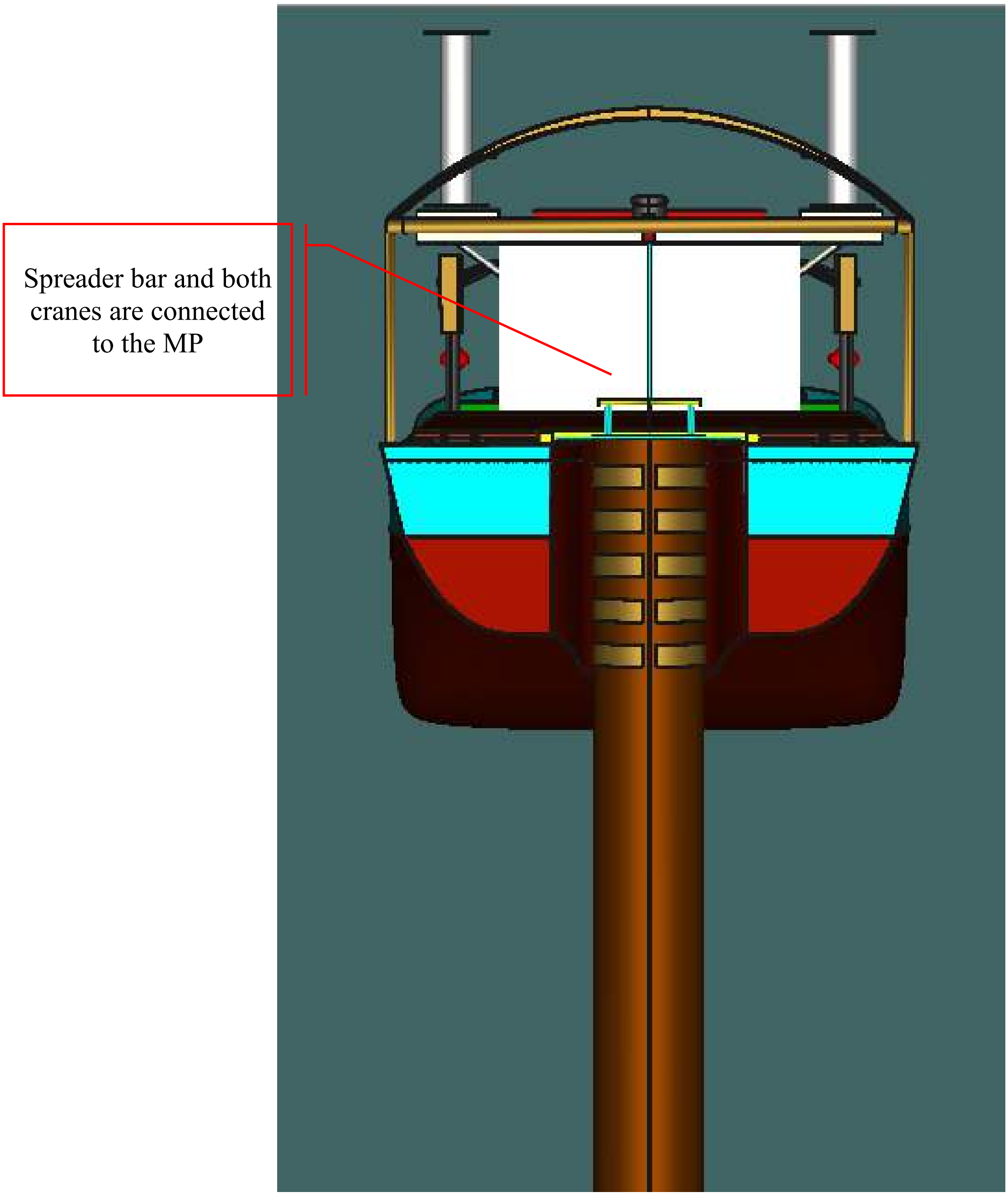


Figure 6-135 Both Cranes are connected to the monopile in tandem configuration

Having considered that SWL of each gantry crane in Decom Tools vessel is 750 tones and the weight of monopile can be more than SWL of one crane (depending on the dimeter, length and thickness of monopile), therefore, here, it is shown that both cranes are rigged to the monopile. This lifting configuration is called tandem lifting configuration. Figure 6-135, Figure 6-136 and Figure 6-137 shows that both cranes are connected to the monopile.

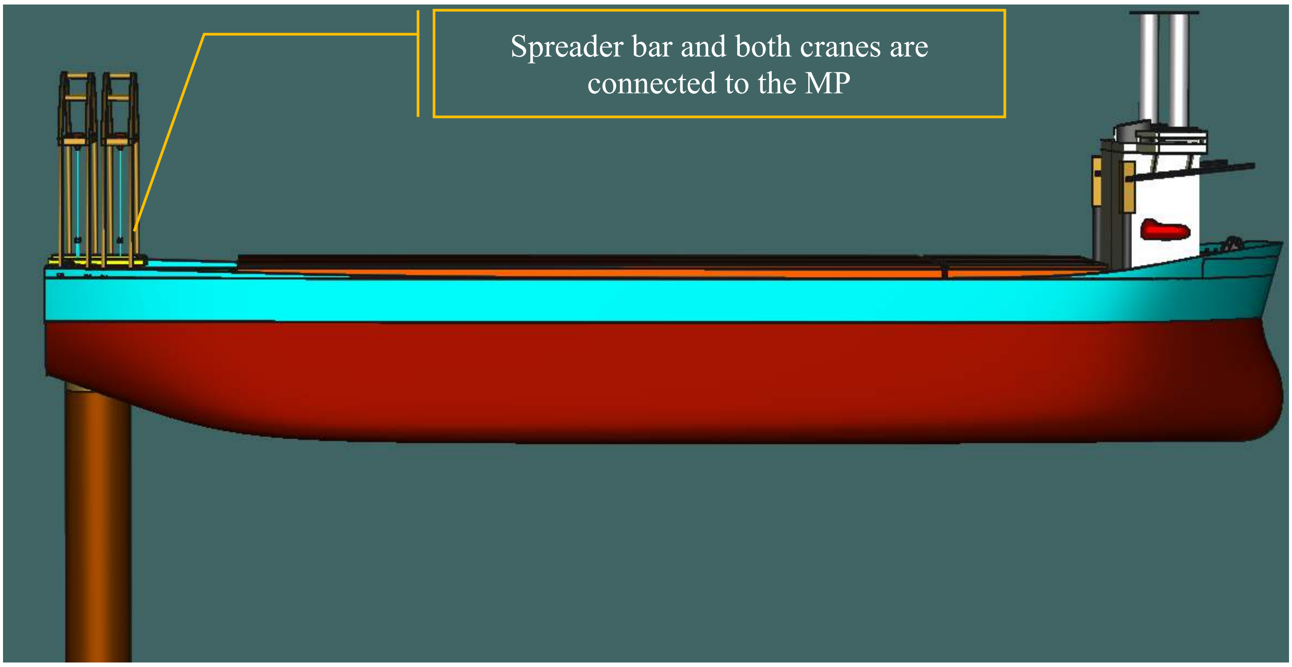


Figure 6-136 Both Cranes are connected to the monopile in tandem configuration

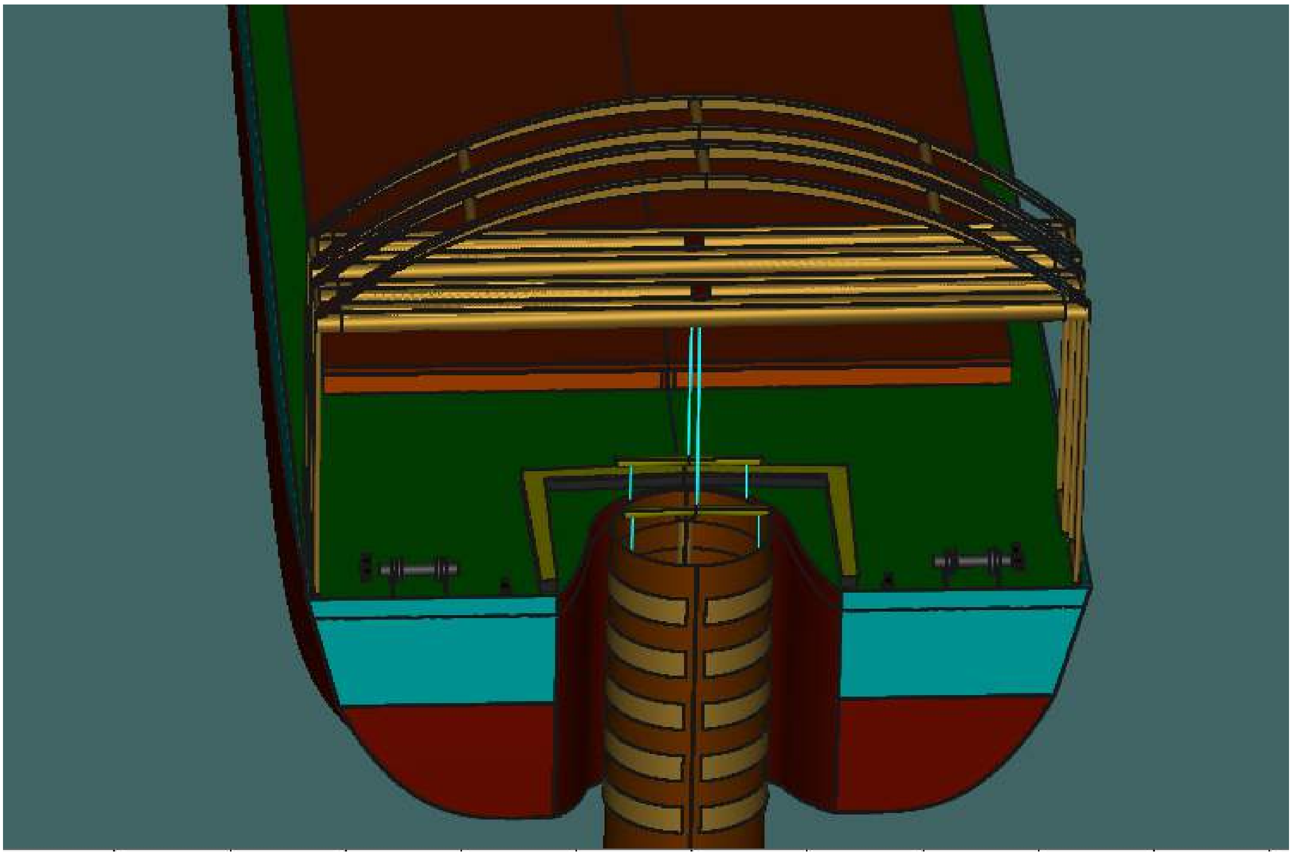


Figure 6-137 Plan of Tandem connection of Cranes to the monopile and Spreader bar

Figure 6-138 shows that pile is extracted 12 meter and the crane is connected with spreader bar to pile in order to hold it and retrieve it with crane wires.

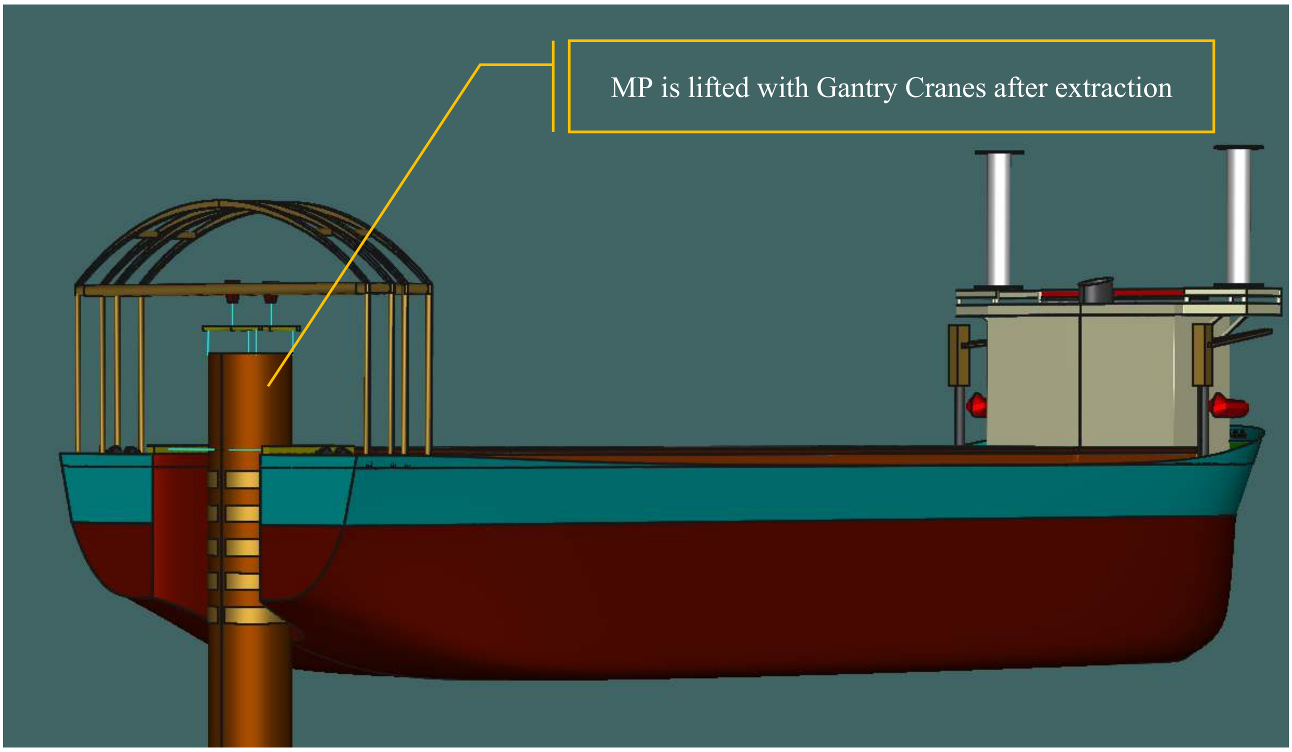


Figure 6-138 Pile is lifted with both cranes after extraction

Therefore, after lifting the monopile with gantry crane(s), the gripper should be tightened and then the cutting should take place. As it was discussed under section 6.6 there are a number of reasons why abrasive water jet, diamond wire saw, and shear cutter are not suitable techniques for this operation. In addition to mentioned reason, for cutting with abrasive water jet the following equipment are necessary to be mobilized. For the oxy fuel cutting techniques, just a couple of racks of gas, belt and cutting torch are required.

	ITEM	DIMENSIONS (L x W x H) m	WEIGHT kg
1	Downhole Cutting Head (DCH) I mounted on skid Downhole Cutting Head (DCH) II mounted on skid Downhole Cutting Head (DCH) III and IV and PCH mounted on skid	2.7 x 0.15 x 0.15 2.85-3 x 0.15 x 0.15 4.07 x 0.22 x 0.22	320 320 1030
2	A Frame/Overboard Chute	4 x 2 x 4.6	1200
3	Hose Reeler, Umbilical	2.3 x 2.6 x 2.4	6500
4	Air Compressor	6.1 x 2.44 x 2.59	9500
5	Abrasive Mixing Unit in shipping container	6.1 x 2.44 x 2.59 (4.15 H assembled)	6300
6	Control system and HPU	3 x 2.44 x 2.9	7300
7	High Pressure Pump	3 x 2.45 x 2.83	7500
8	Workshop Container	6.1 x 2.44 x 2.59	3100
9	Abrasive 4 tons for approx 22 cutting hours	3 x 2.44 x 2.59	6500

Figure 6-139 Equipment for Abrasive Water Cutting tool

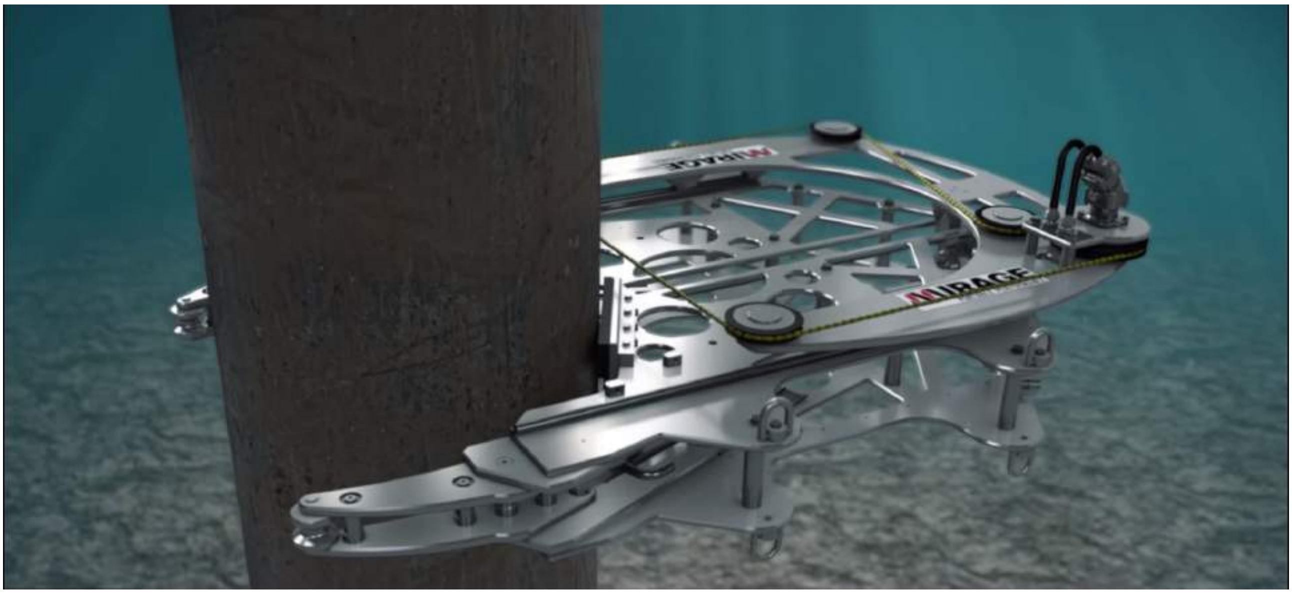


Figure 6-140 Small-Size Diamond Wire saw (MirageMachines 2015)

Diamond Wire Saw	DWS3664
Capacity	36" - 64" (915mm - 1625mm)
Weight	1132kg (without buoyancy)
Length	3912mm
Width	2670mm
Height	740mm
Pressure	190 bar
Flow range	90 l/min

Figure 6-141 Size and Weight of Diamond Wire Saw for pile diameter of 36-64" (James Fisher n.d.)

The diamond wire cutter and abrasive water jet are cold cutting technologies which does not produce heat, flame, spark. These are essential tools for cutting the pipes that contains oil, gas or flammable fluids.

Figure 6-142 Cutting the foundation of YTTRE STENGRUND OWF (Kurdve 2016)

Figure 6-143 Oxy Fuel Cutting Tools (Semi-Automatic)

Having considered that the pile extraction is one of the most energy demanding activities, therefore, considerable amount of fuel will be consumed which will result in significant amount of CO_2 emission. One way to save fuel consumption and ultimately mitigate CO_2 emission is to expedite the operation. The only way to increase the pile extraction speed without changing the power consumption is to increase the cutting speed. However, the abrasive water jetting and diamond wire cutter are less harmful since they do not produce pollutant, but the cutting duration is so lengthy at least takes 30 hours for each cut. It means that the vessel has to spend considerable amount of time just for cutting process which lead to more cost, more fuel consumption and evidently more CO_2 emission. Thus, in order to see which cutting method is more effective, not only the direct impact of cutting tool but also the influence of cutting on the offshore operation should be considered (the consequence of cutting on the duration and environmental impact of the ship need to be studied also). With regards to this fact, an arrangement with a German cutting company to design a suitable cutting system for this part of the project has been reached. The difference of the new cutting tool will be to cut the monopile, grout and transition piece at the same time. The oxy fuel technique cannot cut the composite joint due to existence of grout between annulus of monopile and transition piece. To achieve this goal and to overcome to this problem, this agreement has been made. The new cutting tool will be documented and will be attached as an appendix to this document in due course.

Figure 6-144 Grout are injected in the annulus between the pile and transition piece

An access platform has been designed for the fitter (the person who shall install the cutting tools) in order to install the cutting tool around the monopile. The following figure shows the access platform. This platform can be installed after positioning the vessel around the monopile and before cutting operation. It should be noted that the fitter can install the cutting tool with basket and crane too, but to improve the safety of the operation this platform has been designed. The platform is placed on a pair of rails which can be adjusted based on the diameter of monopile.

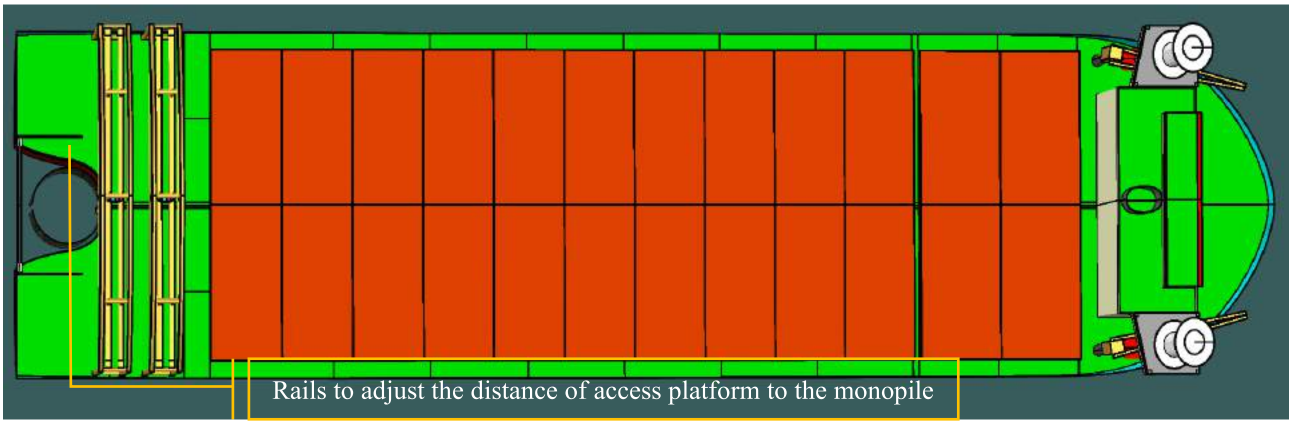


Figure 6-145 Plan View of Access Platform

Since the drawing of new cutting tool is not ready, and currently the most feasible tool is diamond wire saw, therefore, in the drawing, it is shown that diamond wire cutter is cutting the monopile. Figure 6-146 shows that cutting is going to be finished.

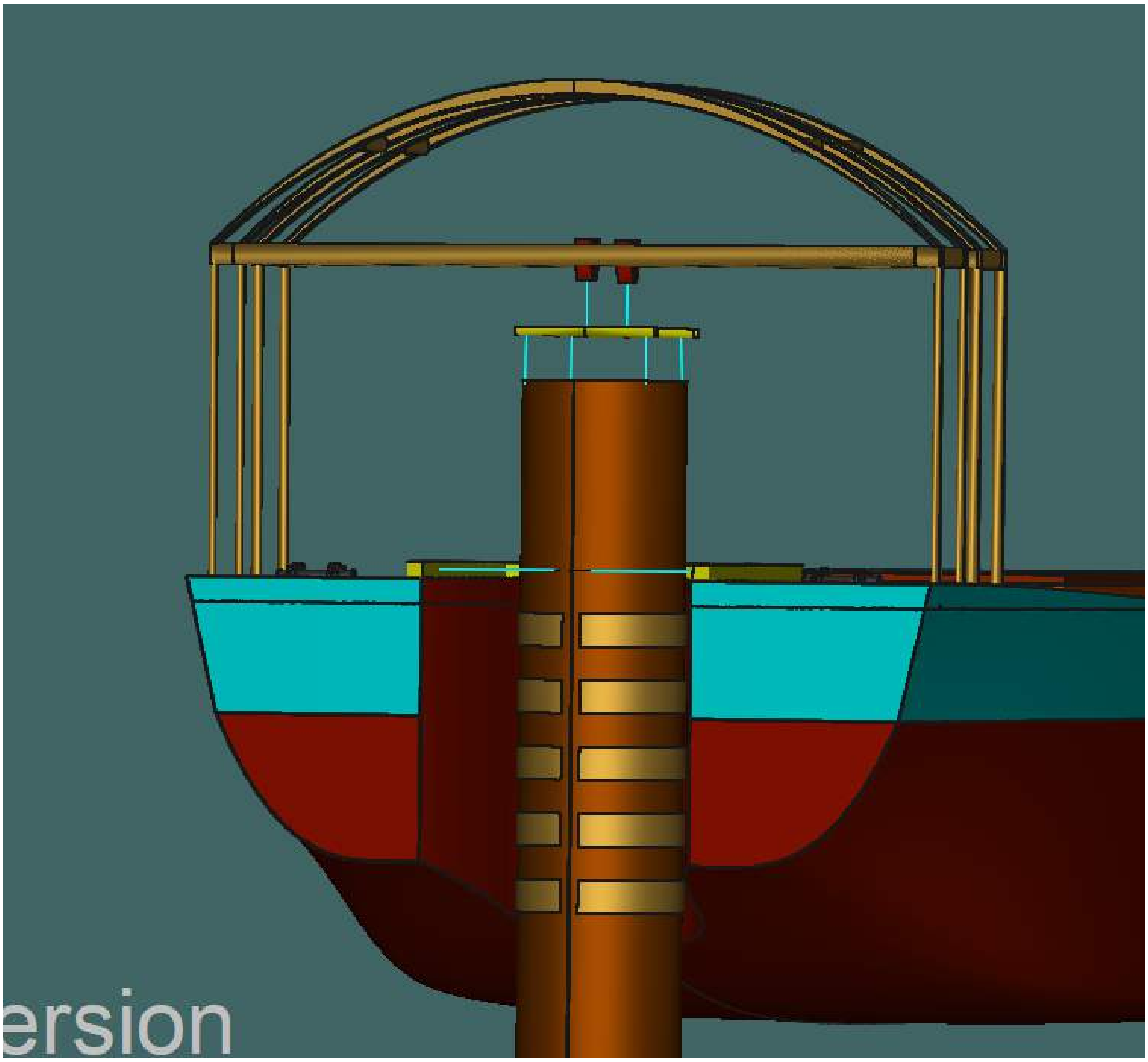


Figure 6-146 Commencement of Cutting with Diamond Wire Cutter

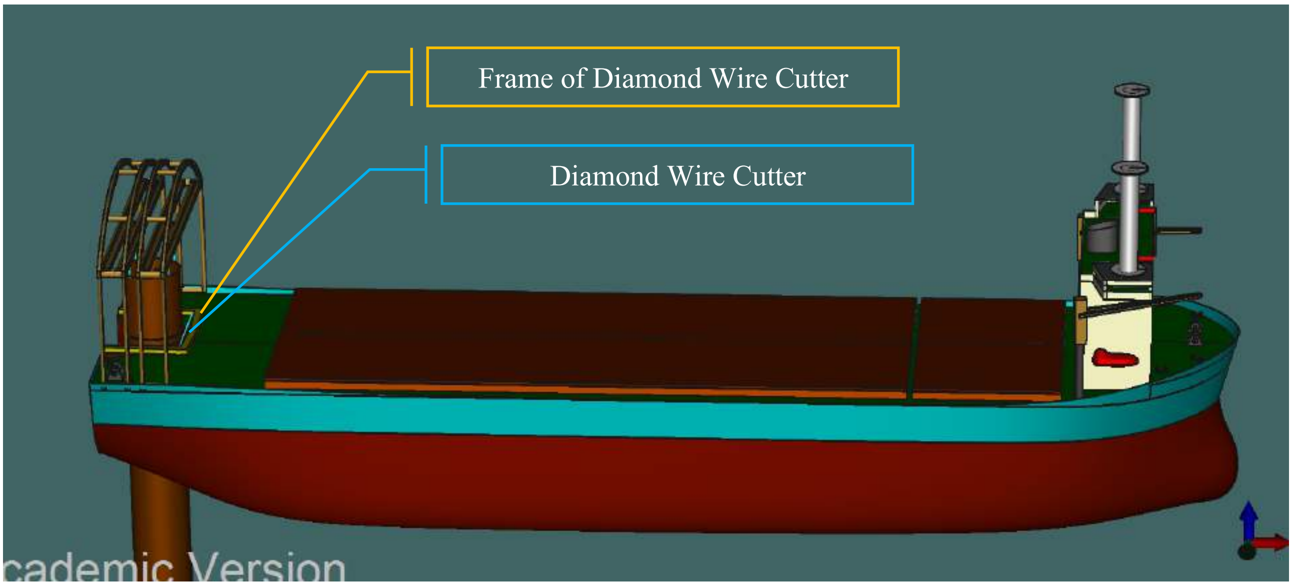


Figure 6-147 Cutting of Extracted monopile has been completed by Diamond wire cutter

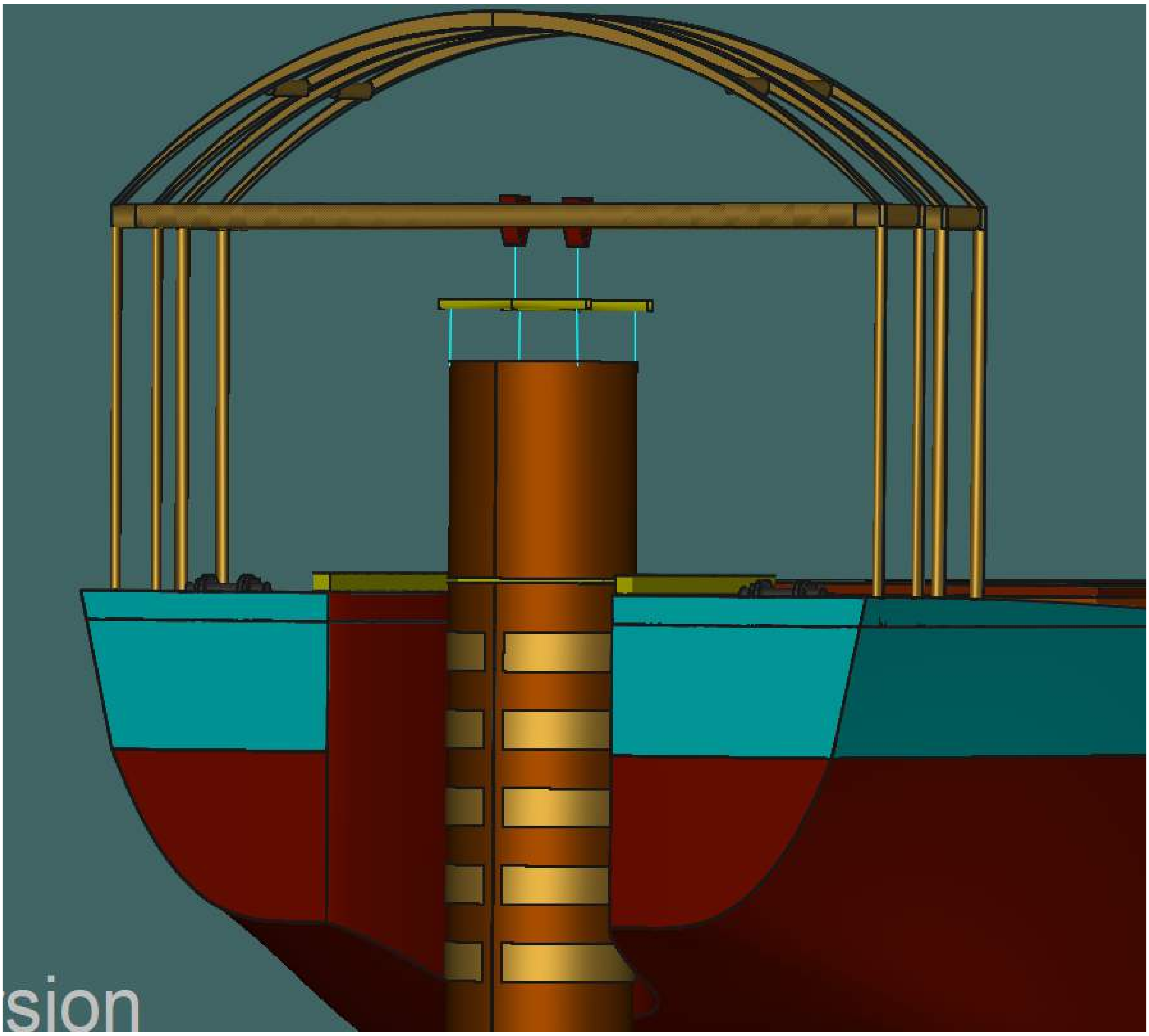


Figure 6-148 Cutting of extracted monopile is in progress with Diamond wire Cutter

The cut section should be lifted and transferred to the top of the hatch cover according to Figure 6-151, Figure 6-150, Figure 6-152, Figure 6-153 and Figure 6-154. The reason why to placing the cut section on top of the hatch cover is explained in the next section.

The sequence of blasting, extraction and cutting should be repeated until entire extraction and cutting of the monopile.

With this procedure, first of all, the foundation can be extracted entirely from seabed and secondly, cutting can be done simultaneously in order to ease offloading from vessel and further onshore transportation.

In this case, there is no need for mobilization of large size crane as well as SPMTs since the size and weight of monopile are enough small. With normal truck, and small crawler or port crane, the materials can be offloaded from the vessel and then transported by either crawler crane or truck.

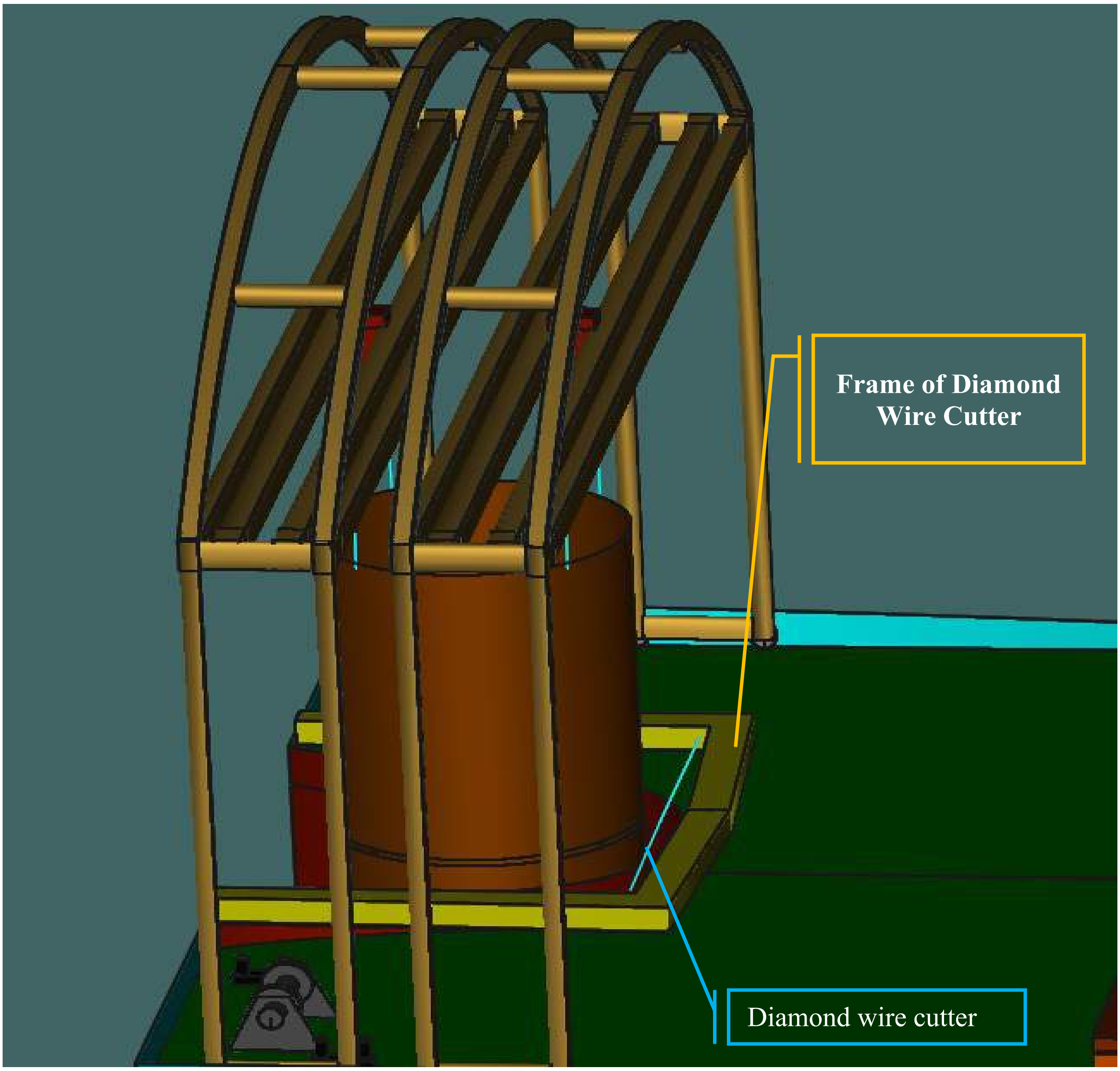


Figure 6-149 Completion of Cutting of Monopile

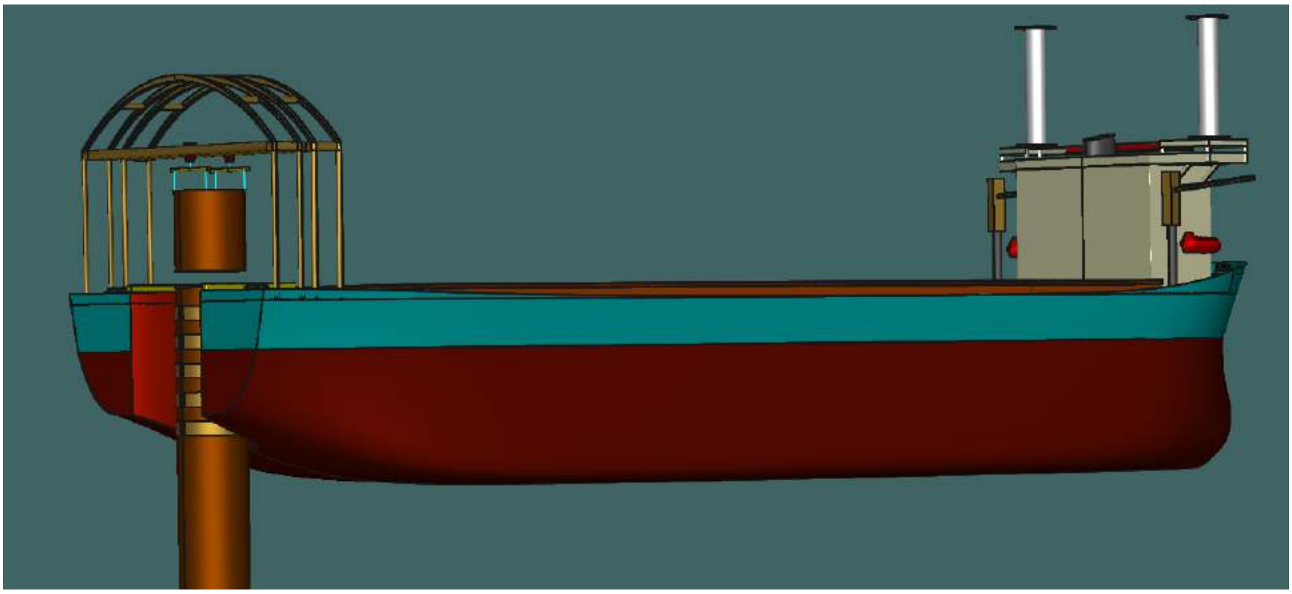


Figure 6-150 Lifting and Transferring the Cut section of Monopile

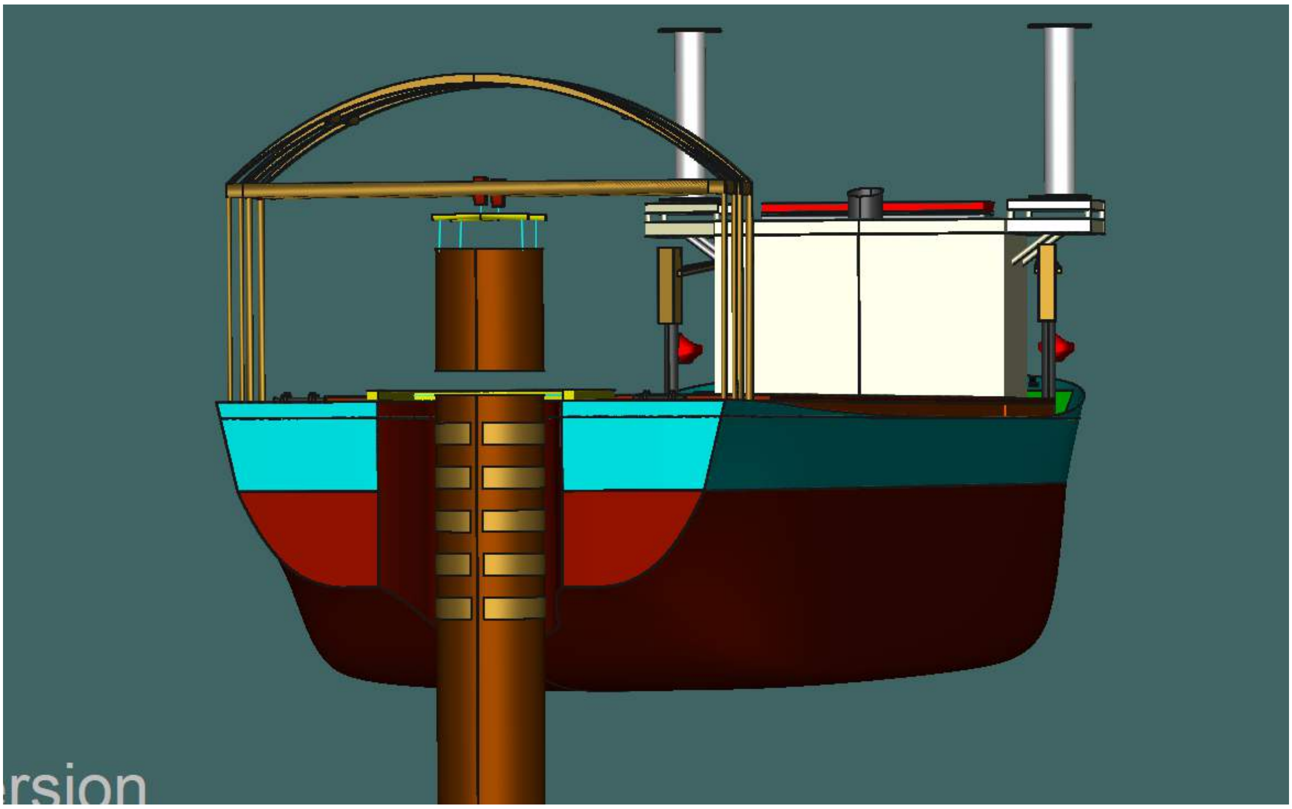


Figure 6-151 Lifting and Transferring the Cut section of Monopile (Perspective view)

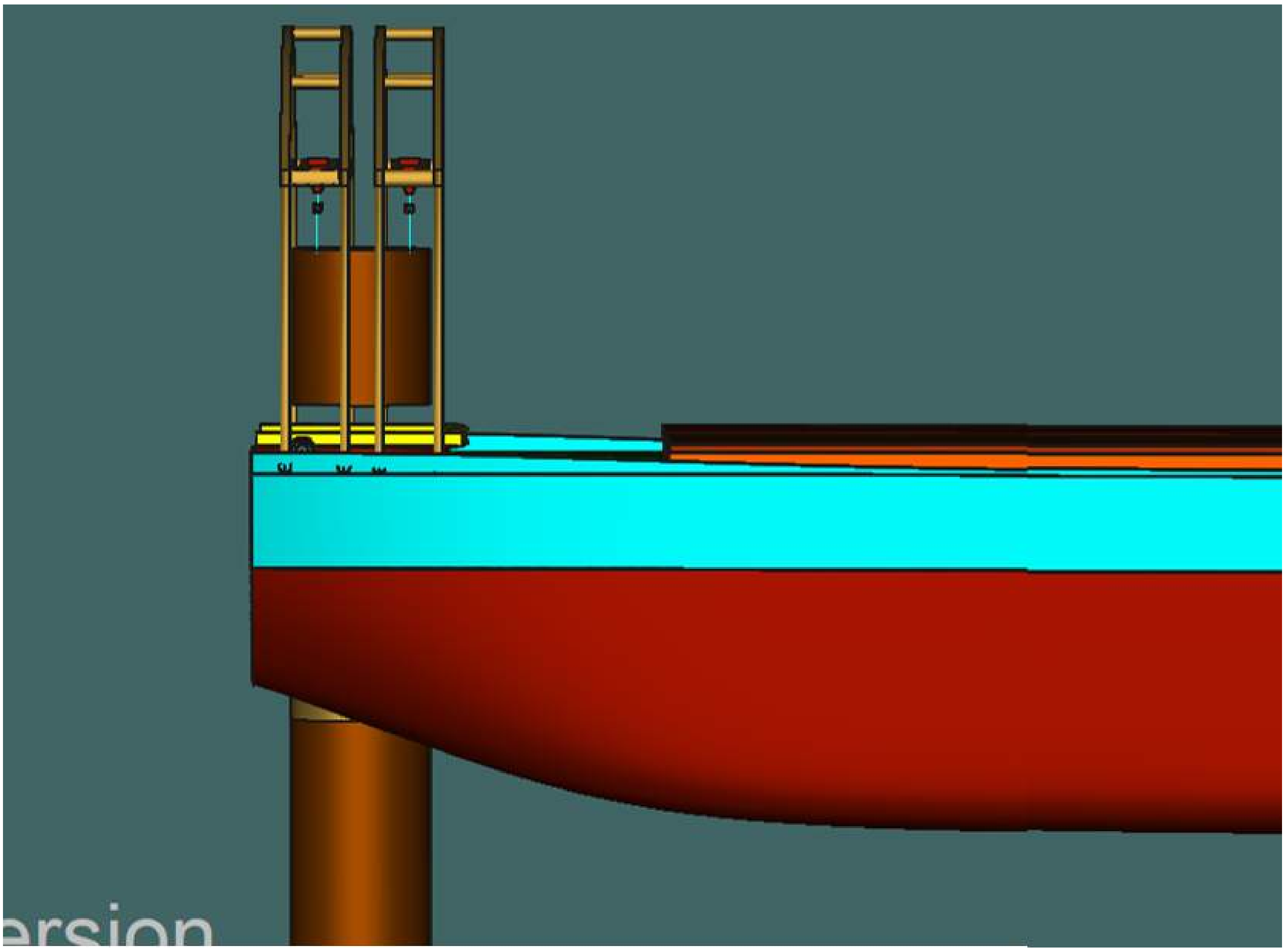


Figure 6-152 Lifting the Cut section of Monopile (Side view)

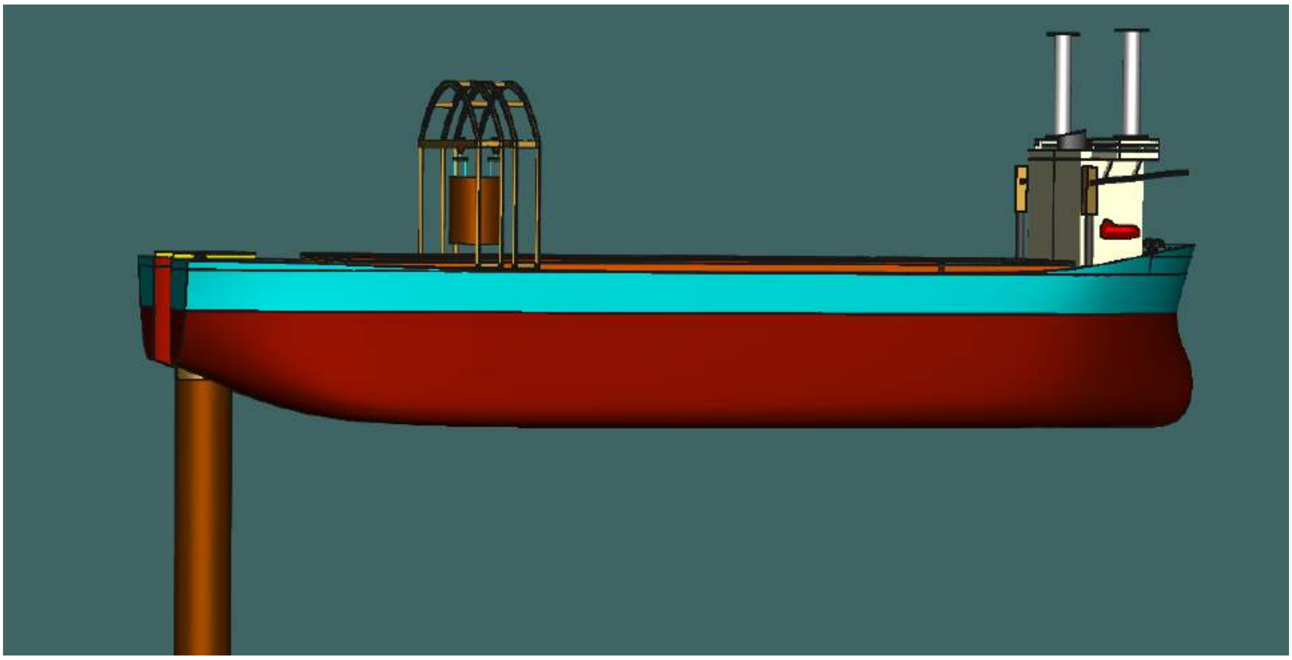


Figure 6-153 Transferring the Cut Section of Monopile

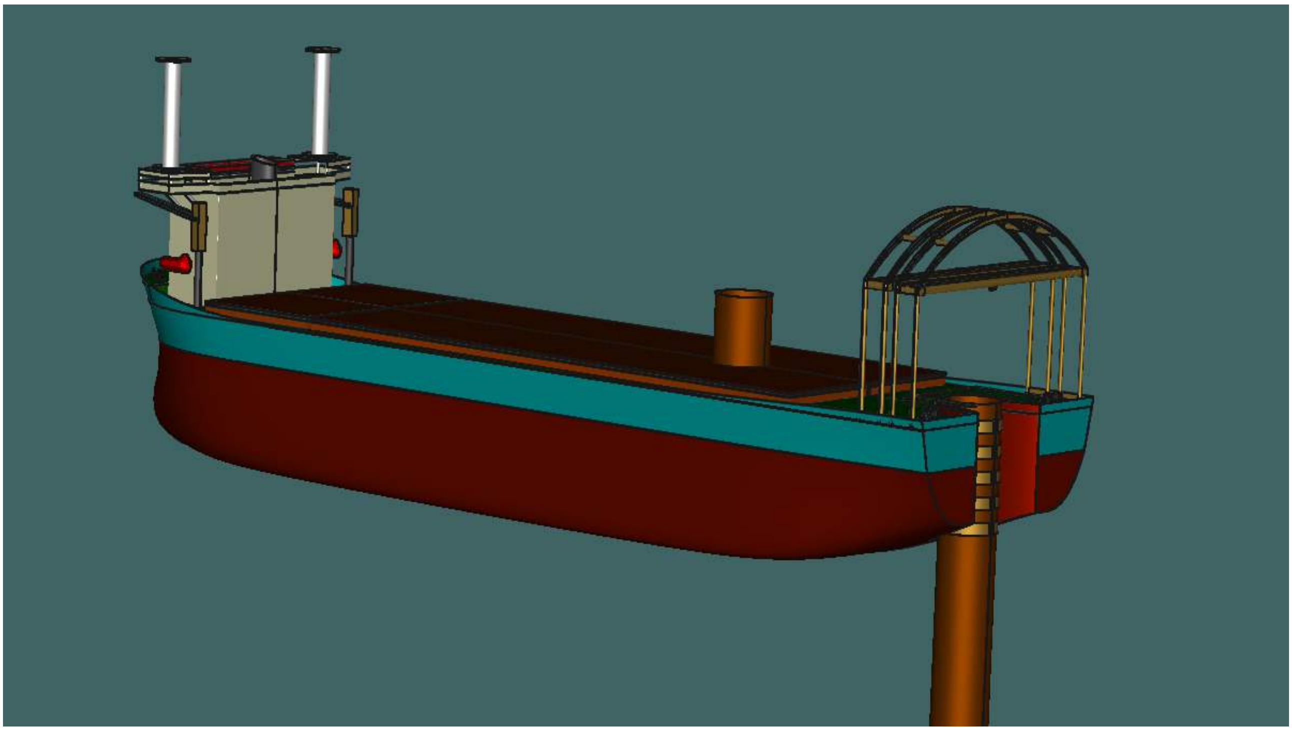


Figure 6-154 The Cut Section is Transferred for further relocation

The above figure shows that the monopile is cut for the height of 12m. It is possible to cut the monopile every 4m or 8m but in this case the offshore operation will be lengthy. It means that after three-time extraction of monopile from seabed, the cutting should take place. This also prevent pile set up phenomena (avoid sticking of soil to the shaft which the friction can be increased with the passage of time) and reduce the offshore operation resulted from cutting operations.

6.19 Marine Growth Removal (MGR)

6.19.1 What is Marin Growth?

After submersion of structures in the sea, the offshore structures are colonized by opportunistic organisms that adhere to the structure. These colonies are termed 'marine growth' and may form habitats containing a range of individuals and species on a single structure (BMTCordah 2011).
In the North Sea, marine growth comprises a variety of soft and hard bodied organisms that occur naturally on hard substrata. These organisms include seaweeds such as kelp, anemones, hydroids, mussels, barnacles, tube worms and soft and hard corals, for example the cold-water coral Lophelia pertusa (BMTCordah 2011).
The composition of marine growth on a particular structure will depend on a variety of factors such as water temperature, water depth, wave action and the season in which the structure are installed. (BMTCordah 2011)

Figure 6-155 Marine Growth attached to the Structure (Adobe Stock n.d.)

6.19.2 The Strategies to Remove Marine Growth

There are four different approaches to manage the marine growth as following. Each of the below mentioned strategies has some advantages and disadvantages.

6.19.3 Onshore Marine Growth Removal

This marine growth must be managed when it is brought onshore as part of the decommissioning project.
Onshore the management of marine growth should be handled at licensed disposal yards. A survey of disposal yards in Norway and the UK in 2011 concluded that each yard has adopted marine growth management practices that are appropriate to local circumstances. These are relatively low-tech and effective and are accepted by regulators and local communities (BMTCordah 2011).
Current practices for the disposal of marine growth at onshore yards include removal at the yard followed by landfilling or composting, or land-spreading.

6.19.4 Problems with Onshore Removal of Marine Growth

The removal of marine growth onshore comes with a plethora of disadvantages and problems as followings:

I. The port shall obtain license in order to accept the materials which marine growth are attached to them (BMTCordah 2011).

II. Identifying landfill or composting sites close by port that are willing to accept marine growth (BMTCordah 2011).

III. Transportation of marine growth from port to landfill or site incur extra cost as well as CO_2 emission (onshore transportation is 4 times less effective than offshore transport in terms of cost and emission).

IV. In some cases, the marine growth may be allowed to dry onshore and is then sent (still attached) to a recycling facility for steel smelting (BMTCordah 2011). This can reduce the cost of transportation for landfilling and landfilling cost.

V. The transportation of the marine growth onshore means transportation of offshore creature to another environment and killing them, which may have negative biological impact.

VI. Odours emit from marine growth cause nuisance to the port staff and the civilization nearby the port. However, the odour emitted from removing marine growth is more intense only under certain circumstances (BMTCordah 2011). Environmental conditions also influence the odour; wet and slightly warm conditions will prolong decomposition and during this period the prevailing winds will determine the direction and extent of the area affected by the smell.

6.19.5 Marine Growth Removal Nearshore or In The River

In this scenario, the transportation vessel should drop the anchor near shore (inshore) or moor the vessel in the river for marine growth removal. This scenario also has many disadvantages as following:

6.19.6 Problems with Nearshore Removal of Marine Growth

I. The charter rate of the vessel is high in that it is not economy to keep the vessel just for removal of marine growth.

It should be noticed that the oil and gas structures are different with wind industry. The number of structures for one oil and gas field varies between 1 to 6 structures, however, the quantity of OWPs' structures is much higher than oil and gas. It means removal of marine growth in wind industry need more effort, time and incur more cost to the contractors. Therefore, the business model should be different. Hence, the removal of marine growth near shore or in the river for the medium size, large and extra-large wind farm is not an option.

II. Normally the emission of self-propelled cargo barge or the tugboats are high since they use diesel as fuel. This means that the emission resulting from keeping the vessel for marine growth removal will be significantly high.

III. In any kind of vessels, several crews are onboard which they have different responsibilities. The MGR should be done by riggers or equivalent ranks. It means that other crews should wait onboard the vessel until they finish removal. The stand-by time of the crew that they have to wait (like barge master, officers, galley team, etc.) until completion of the removal means paying extra wage and cost to the project.

IV. Lastly the monopile or structure are loaded in a way that access to the many locations and surfaces for removal is not possible. They are on top of each other or stowed adjacent to each other etc. which provide no room and access for removal.

6.19.7 Marine Growth Removal During Transportation

One scenario of MGR is to remove them while the vessel is under voyage. First of all, it should be noted that the marine growths are attached to the submerged or splash zone of structures not all surfaces/components of wind farm. Having considered that load out of piles and transition pieces are in a way that there is no room for workers to go around the structure to removing them via water jet, so marine growth can be done partially in this scenario. The more the marine growth can be removed the higher efficiency will be attained. Because the vessel and crew are performing their main duties which is safe transportation of cargos, and this operation will be considered as meanwhile activity[72]. In general, the more meanwhile activities lead to higher efficiency.

6.19.8 Problems with Removal of Marine Growth During Transportation

There is not originally any problem with MGR during sailing, but there exist some imperfection as following:

I. The entire removal of marine growth is not possible since there is not access to all sides and corners of the components.

II. In order to have access to the aloft surfaces, the scaffolding should be erected. This is not a safe and common practice to erect large scaffolds around transition pieces or monopile for the MGR operation.

6.19.9 Offshore Marine Growth Removal

Finding of the conducted research on the decommissioning of oil and gas structures in the North Sea shows that risk of transportation of structures which marine growth were attached to them is

[72] Meanwhile activities are those activities that does not hamper the progress of overall operation and they are conducted as simultaneous operation. In contrast, the main or critical activities are those that directly they change the duration of project. therefore, any changes in the main activities lead to changes in overall duration of projects.

considered low (BMTCordah 2011). Nevertheless, it can be considered as low risk operation, but these organisms are offshore creature which they lose their life by transportation of them to onshore. Exploitation of natural resource by human being in the sea provide this opportunity to them to attach to the structure, now by transporting them onshore the ecology of the area may alter. If new eco-sustainable method to remove the marine growth at offshore site is exited, it can solve all the above-mentioned problems of previous methods.

The designers of Decom Tools vessel come up with a sustainable solution to remove the marine growth as a meanwhile activity. It means that this operation can be done in parallel with other operation of the vessel at the wind farm. One of the most effective and safe equipment to remove the marine growth is water jet system which has been used in oil and gas industry, marine industry as well as wind industry. Figure 6-156 shows a marine growth removal tool for monopile. The exerted water pressure on this tool can be between 1000 to 2000 bar.

In the Decom Tools vessel, the automatic marine growth removal tool is incorporated as part of pile extraction system. Between the grippers, sets of nozzles are designed in order to remove the fouling while the pile extraction is in process. This system is an automatic system which does not need the operators to get a water jet in hand and do the removal, however, an operator is needed to adjust the pressure, turn it on and off. The problem of this automatic system is that access to all surface of MP is not available. Then the remaining fouling should be removed on the deck.

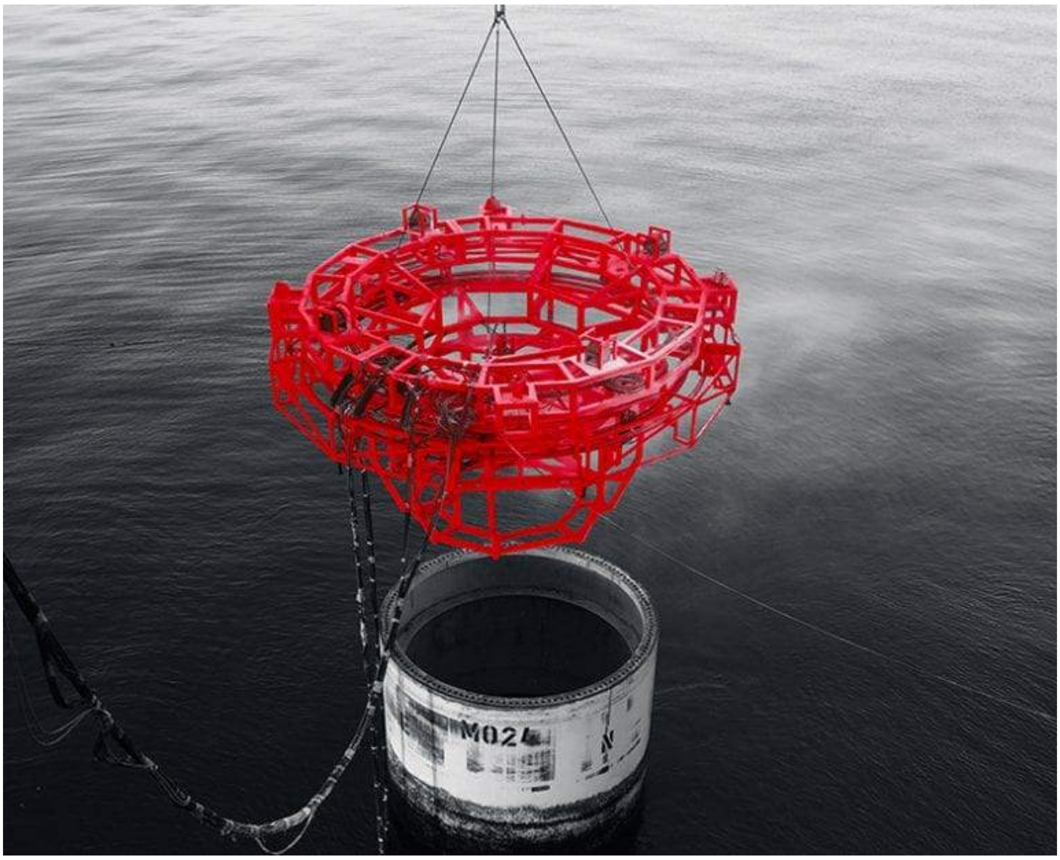


Figure 6-156 Marine Growth Removal Tool (CLAXTON n.d.)

Not only can the removal of fouling take place during extraction, but also, the remaining part can be done on the main deck of the vessel since the pile is cut every 12 meters. Having considered that the pile can be cut into 12m, it means, after cutting, the crane can put the cut pile on the main deck and the riggers can remove the marine growth on the deck easily. After completion of MGR of the top surface of monopile, the piece of monopile need to be rotated a 180-degree for removal again. Then the removed marine growth can be dumped into the sea.

There are a couple of advantage and disadvantage to cut the monopile at the length of 12 meter as following:

- ☑ Since the monopile cut into the pieces of 12 m, it can be rotated easily on the deck. Therefore, erection of large scaffoldings can be avoided.
- ☑ The offloading of 12m monopile from vessel to the port/decommissioning yard is easier and safer.
- ☑ Onshore transportation can be done by the conventional trucks in the market.
- ☑ Cutting, shredding and recycling will be easier.
- ☑ With a 12-meter cutting, the entire removal of marine growth is so easier.
- ☒ The number of transportations from vessel to port will be increased.

Regardless of cutting at 4/8/12m, this strategy paves the way for full removal of fouling offshore without any cost and environmental impact. Therefore, the automatic and manual marine growth removal system is designed as part of Decom Tools project. Already the technology for such system is available. Authors strive to incorporate the tool on the right place by defining the right procedure for removal of fouling.

The nozzles of marine growth removal system are installed on the fixed piping system which are shown in green colour in the Figure 6-158, Figure 6-159 and Figure 6-157. The green pipes the same as grippers can be opened and closed around the monopile and transition pieces.

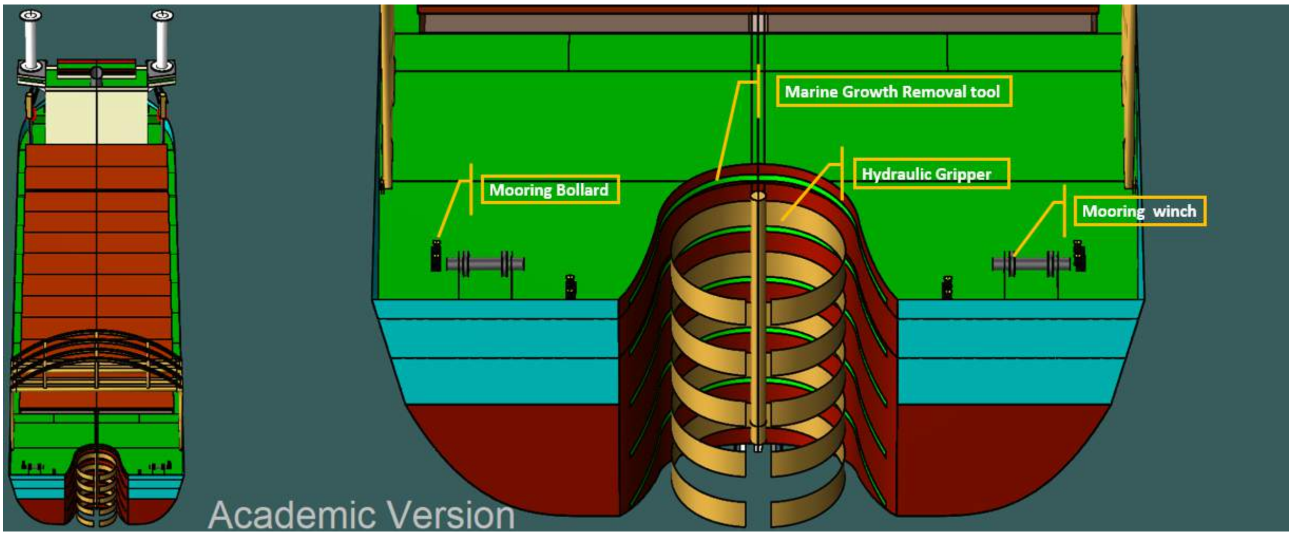


Figure 6-157 The Marine Growth System (In green colour)

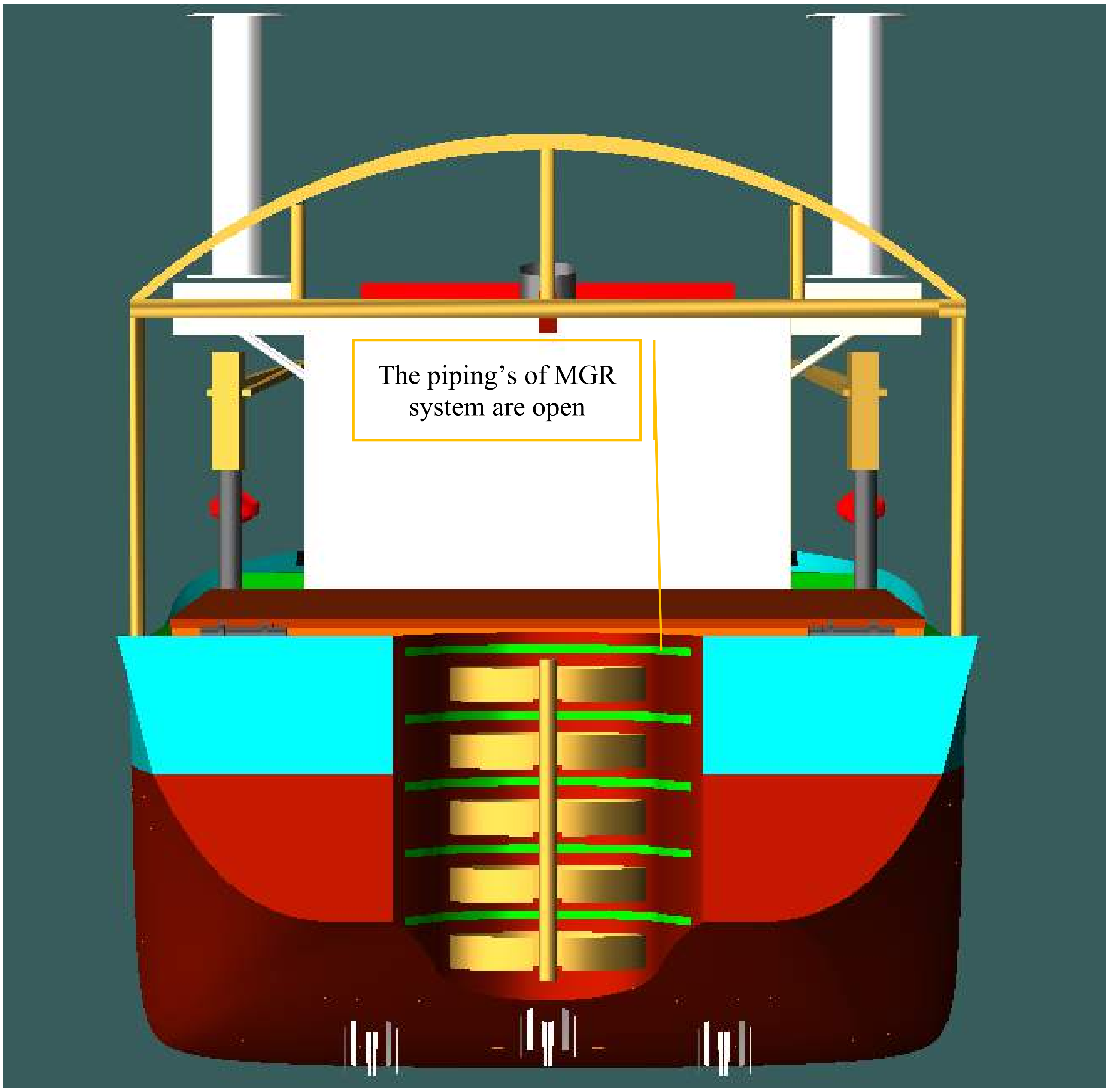


Figure 6-158 The Marine Growth System (In green colour)

Figure 6-159 The Marine Growth System (In green color)

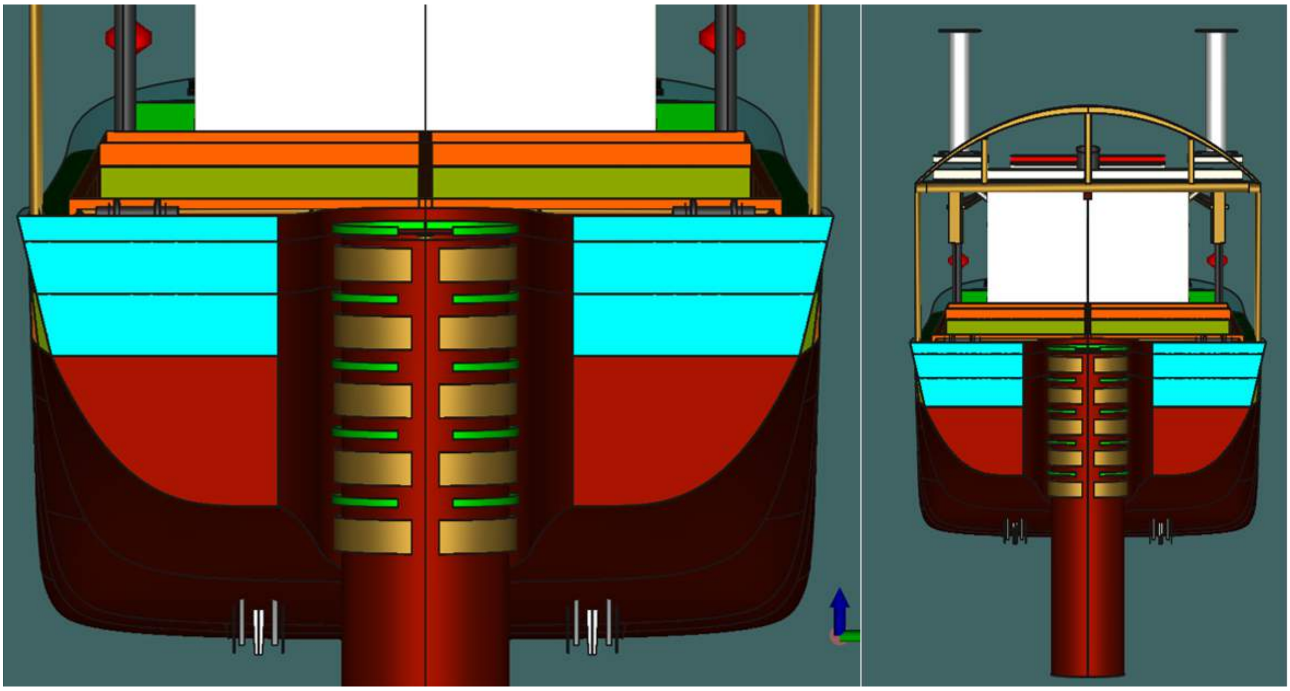


Figure 6-160Marine Growth Removal Piping's are closed around the monopile

The pump room for this water jet system are located in a space behind the grippers which is shows in the Figure 6-161.

As it explained above, with the fixed and automatic marine growth removal system, marine growth can be removed partially. The benefit of the automatic system is that without using any personnel MGR can take place. Also, the MGR can be undertaken simultaneously with pile extraction system. Furthermore, based on author experience, when a part of marine growth is removed, it will be easier to remove other section of marine growth too. So basically, removal of first part is more difficult. The remaining part of the monopile which marine growth are attached to it can be removed when the cut section is on the deck.

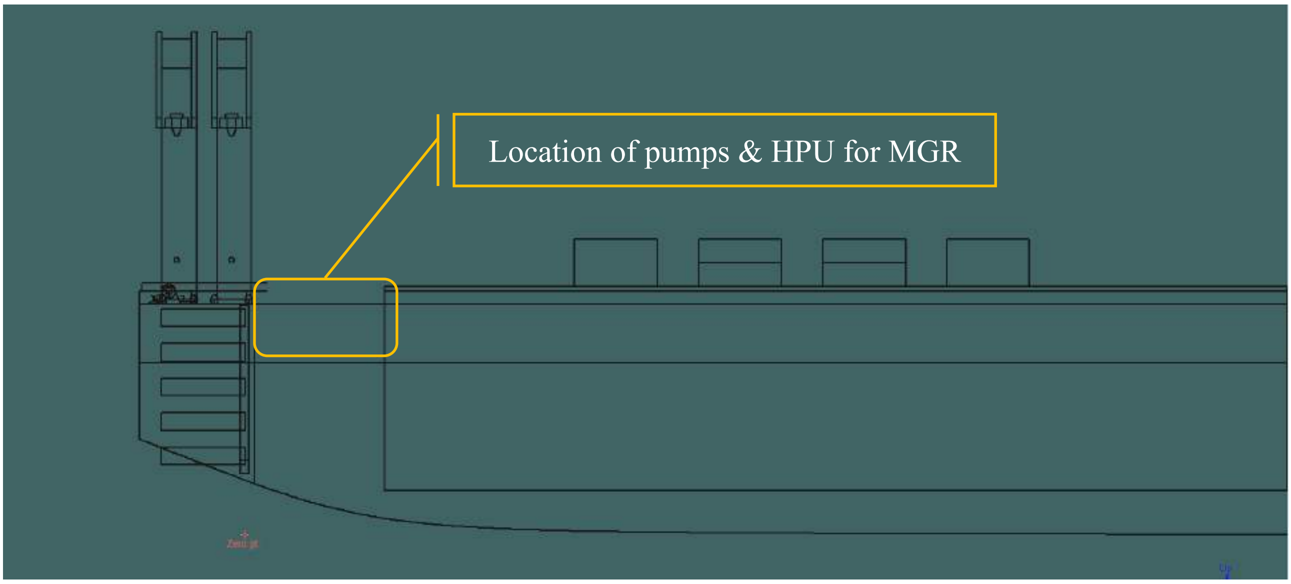


Figure 6-161 Pumps and HPU Rooms

Figure 6-162 shows the sequence of MGR after cutting the MP for 12m and placing on the deck. The green colour shows the cleaned monopile and the orange colour shows before removal.

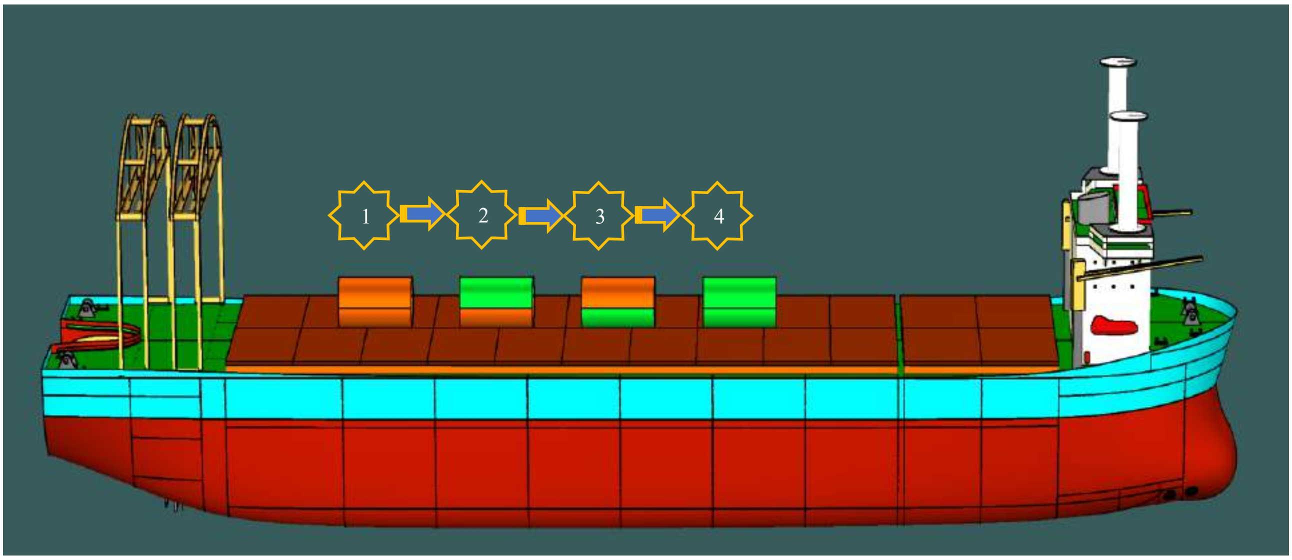


Figure 6-162 Sequence of Marine Growth Removal On the Decom Tools Deck

The removal of fouling does not need specialist and riggers can do that. Having considered that the length of cut section is 4 meters, then the access to top of the pile is not provided. In lieu of erection of scaffold in order to provide access to top part of monopile, authors suggest rotation of monopile with crane. So, there will be no need for erection of scaffolds, to get permit for working aloft and finally no risk of working aloft.

Figure 6-163 shows the sequence of marine growth removal on the deck. Obviously, after conduction of MGR, the fouling can be dumped into the sea.

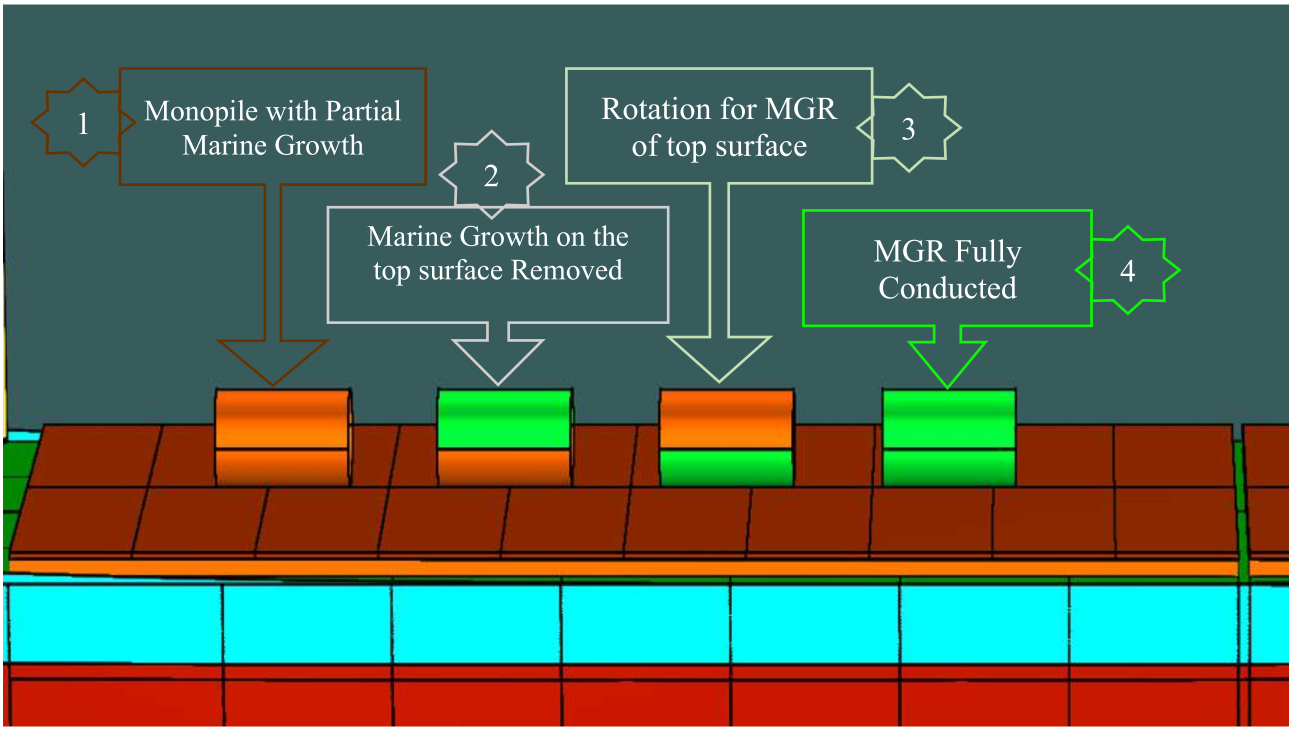


Figure 6-163 Sequence of Marine Growth Removal On the Decom Tools Vessel

Therefore, after 3 times extraction of monopiles, they need to be cut to the length of 12 meter and then after removal of marine growth loading and securing of them can take place. Figure 6-164, Figure 6-165, Figure 6-166, Figure 6-167, and Figure 6-168 shows the loading of monopile and transition piece onboard the Decom Tools vessel.

As it stated before, monopiles of Hornsea1 offshore wind farm has length of about 60 meters with diameter of 8.1 m. TP has the length of 24m. In the previous section it was discussed that 9.5 meters of TP were cut. Therefore, the remaining TP length is 14.5m. Cutting of TP should be made from the level that there is not any grout between the annulus of TP and MP.

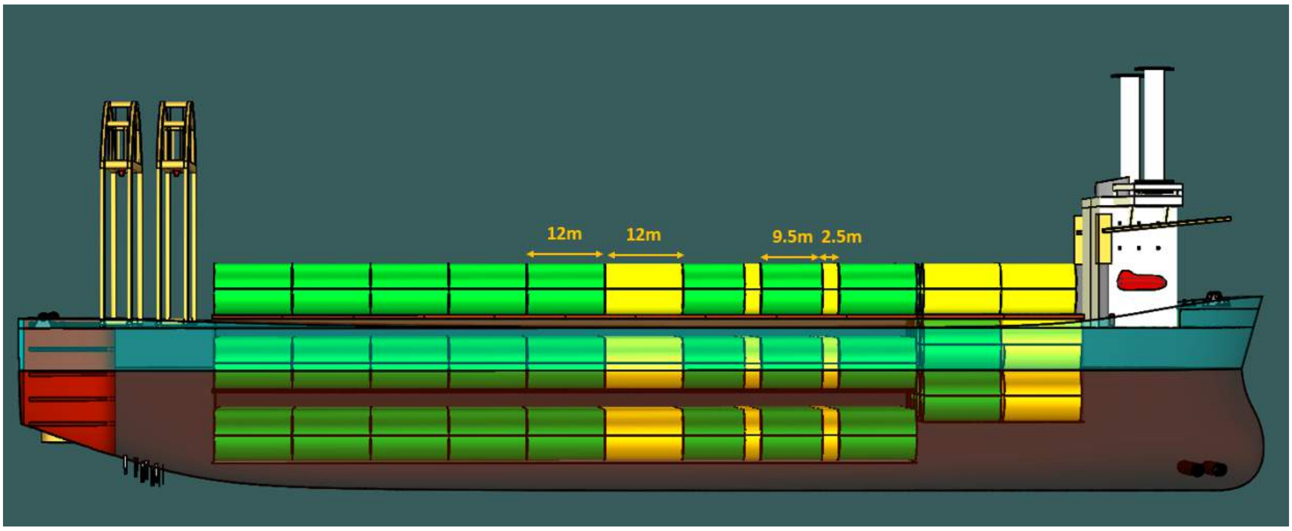


Figure 6-164 Load out of 44 Numbers of MP plus TP (side View)

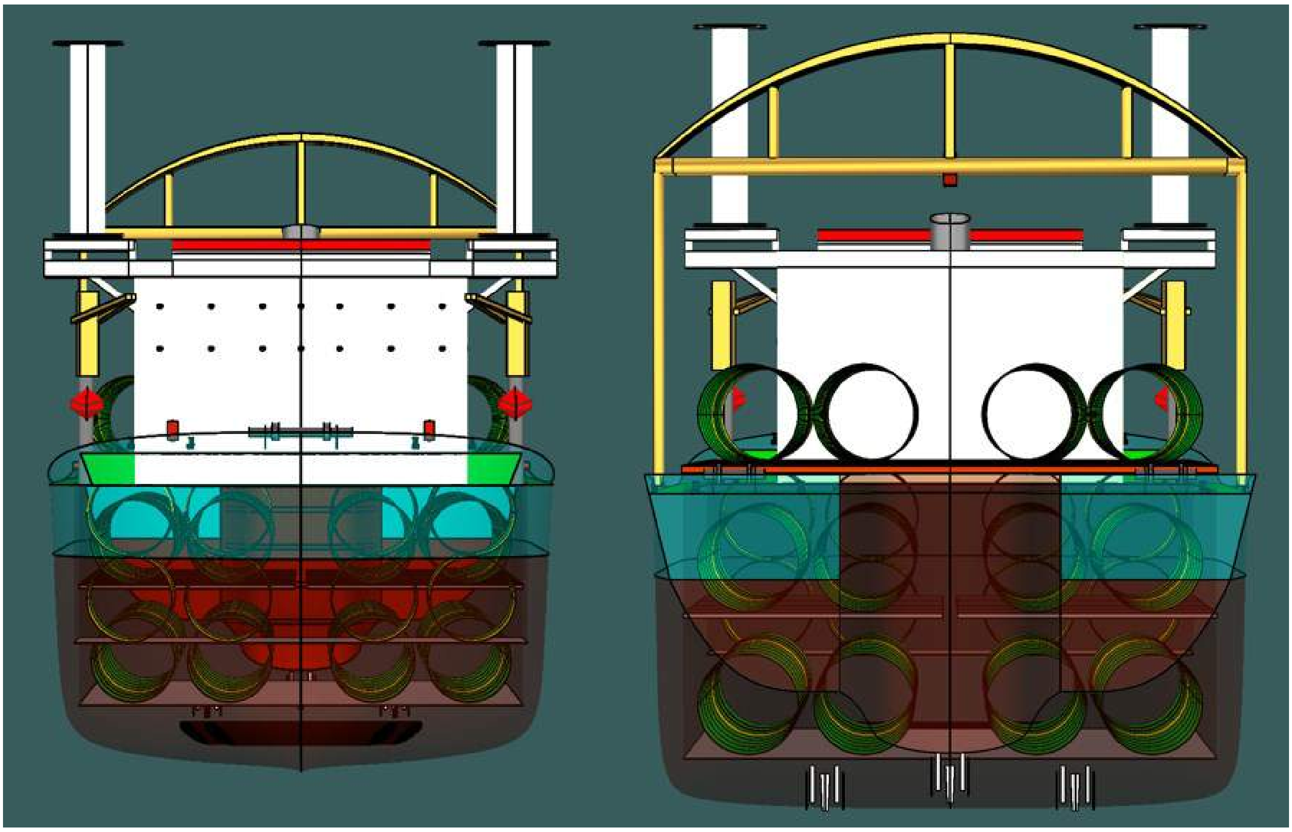


Figure 6-165 Load out of 24 Numbers of MP plus TP (Bow View)

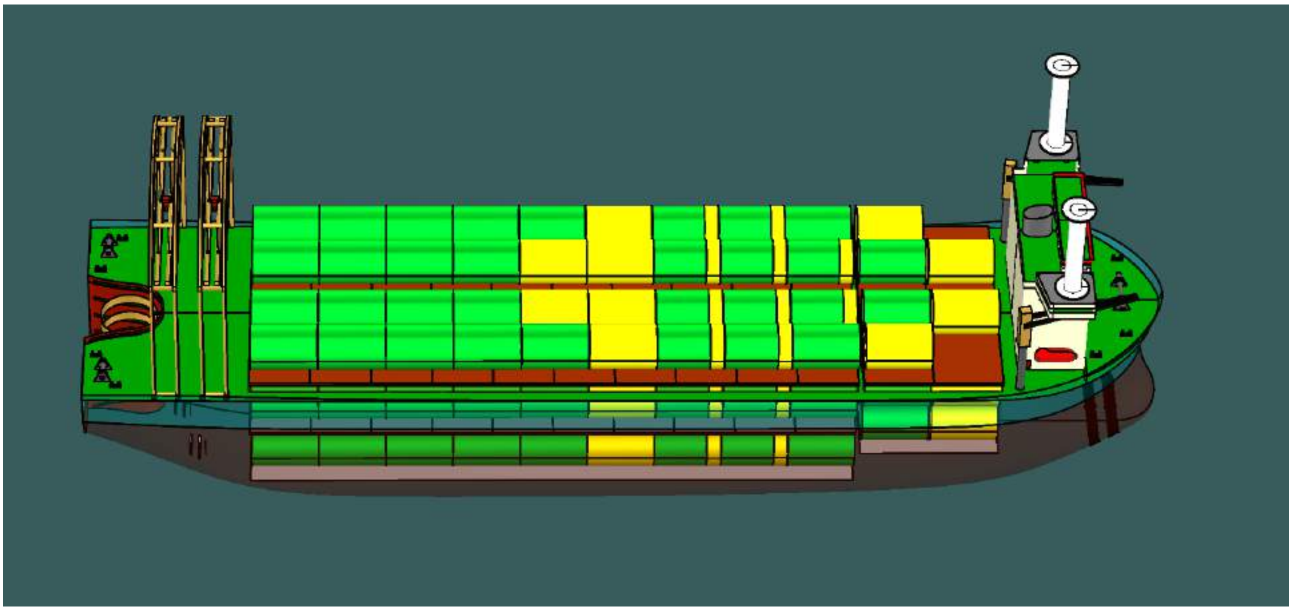


Figure 6-166 Load out of 24 Numbers of MP plus TP (Perspective View)

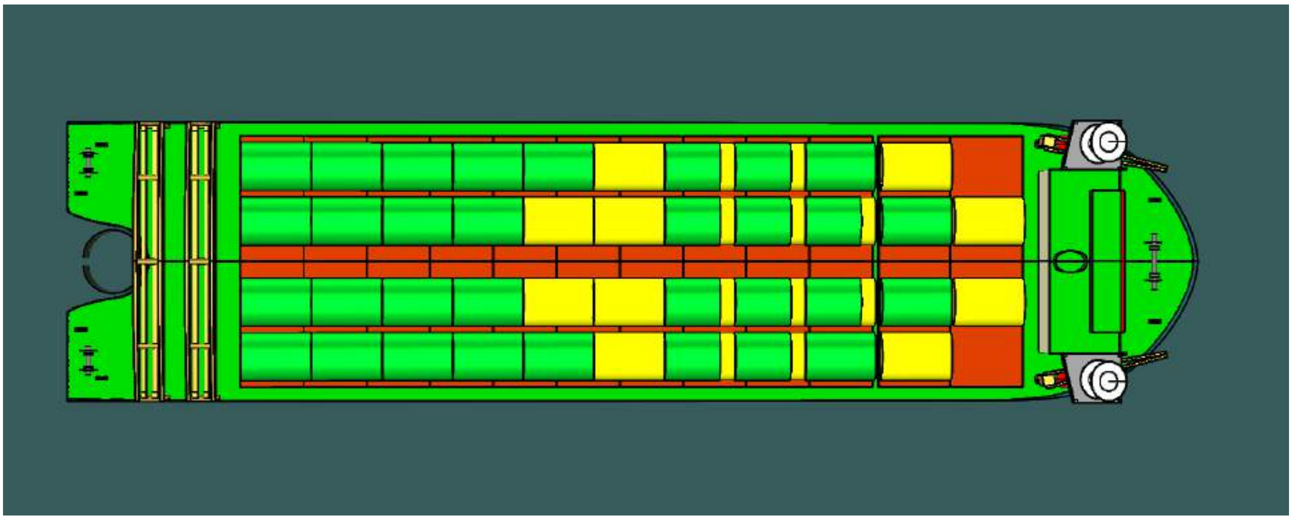


Figure 6-167 Load out of 24 Numbers of MP plus TP (Plan View)

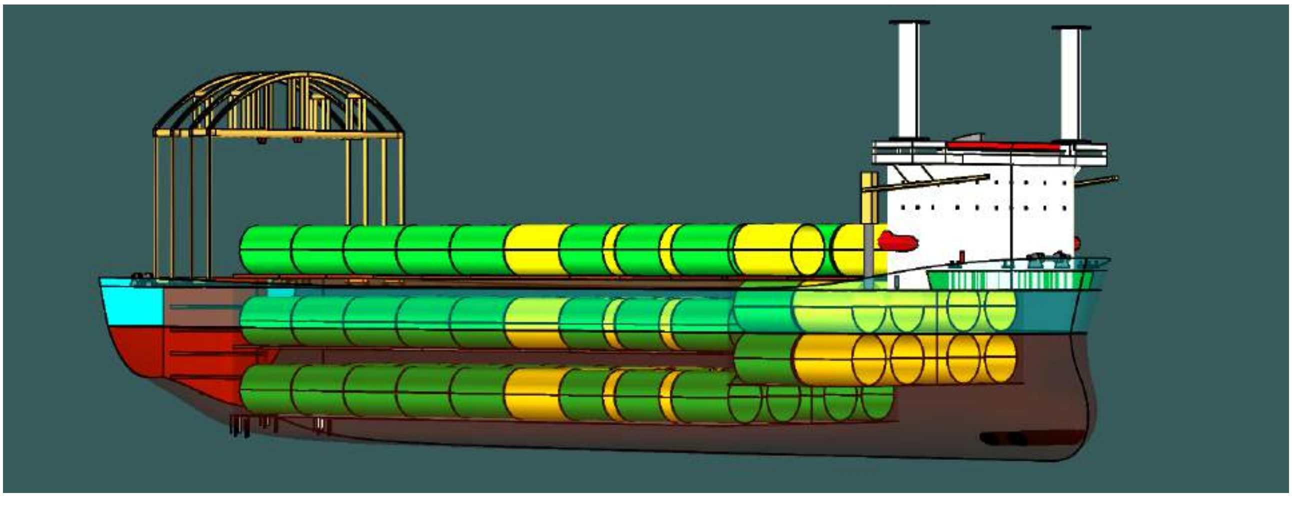


Figure 6-168 Loading of 24 set of MP plus TP (Perspective View)

With this cargo arrangement, 130 pieces of 12m pile/TP can be loaded onboard the vessel safely and quickly. In other words, 1560 meters of monopile can be loaded with this arrangement. If the overall length of monopile and transition piece is 62.5m, then 24 set of monopile along with transition pieces can be transported. In this drawing and calculation, it is assumed that the TP is stabbed 12 meters over the monopile.

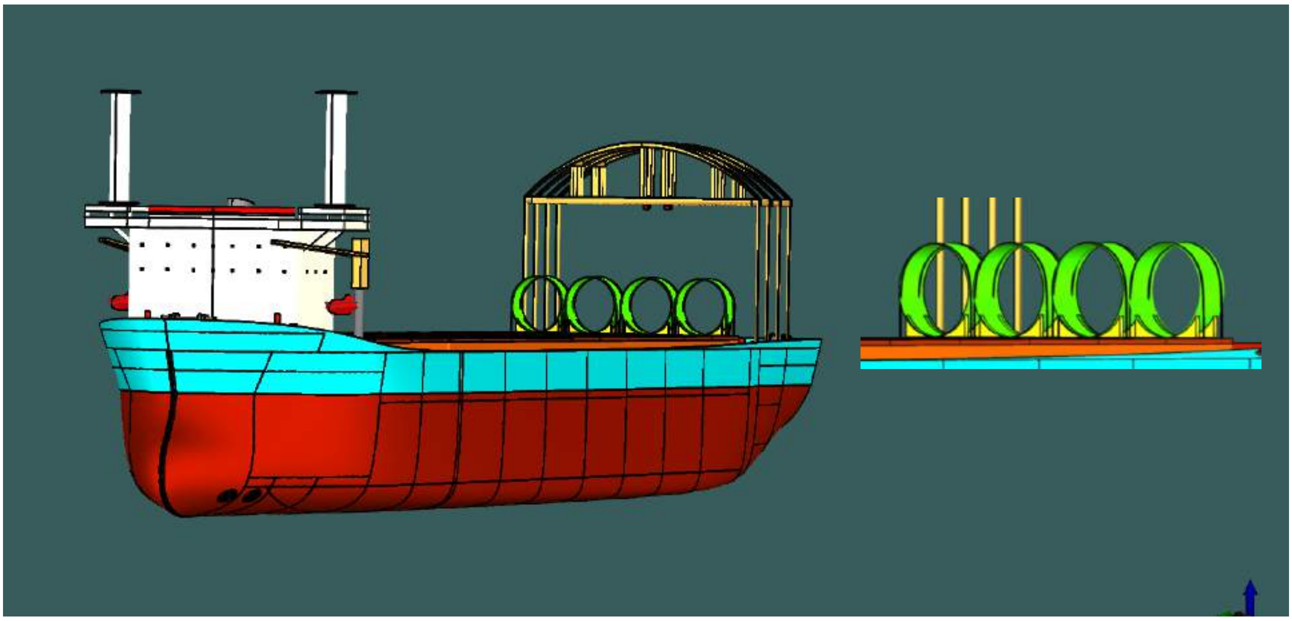


Figure 6-169 Seafastening of MP & TP After Cutting & MGR (Perspective View)

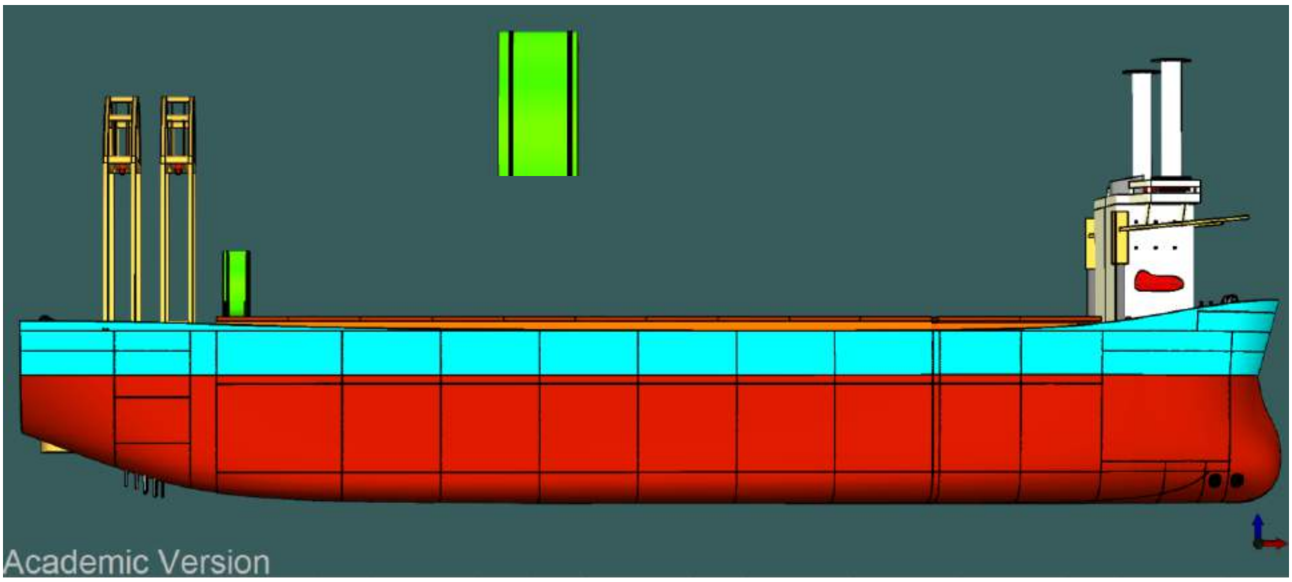


Figure 6-170 Seafastening of MP & TP After Cutting & MGR (Side View)

The above-shown lashing and seafastening method which is common in the oil and gas industry as well as wind industry. Figure 6-171 shows how the lashing of monopile is take place onboard the cargo vessel.

Figure 6-171 Lashing of the Monopile

6.20 Advantages of Pile Extraction System, Cutting and Marine Growth Removal

1. With implementation of this system onboard the Decom Tool vessel, full extraction of monopile is possible. This design and mechanism will absolve the developers from the further responsibility and commitment resulting from keeping the materials in situ.
2. Entire removal absolves the developers from liability for the regular and frequent survey of left in-situ materials which means less cost, less environmental impacts and increase the safety (based on IMO, in case of keeping the materials in-situ, the survey must be conducted regularly).
3. Execution of entire removals pave the way for developers not to allocate any budget as a security to the government (if materials left in-situ, the developers as a security shall allocate money to the government)
4. With this mechanism, there is no need to mobilize diving team and ROV team for installation of cutting tools, removal of scour protection, specialist and so on (the cost of diving and ROV team is so high, especially in deeper water).
5. Entire removal provides this opportunity to develop a new wind farm in the same leased area.
6. Entire removal prevents crossing of pipelines and cables in the future with existing monopile or cables etc.

7. Entire removal avoid accident of spudcans of jack up legs with remained foundations.
8. There is no need for mobilization of either jack up vessel or heavy lift vessel for lifting and extraction (or cutting) of monopile.
   - Having considered that the charter rate of heavy lift vessel is more than 150 000 $ daily, so huge amount of money can be saved by implementing this system onboard Decom Tools Vessel. The cost analysis for pile extraction with Decom Tools vessel and reverse to the installation has been made according to Table 6-14.
   - In addition, due to lack of need to HLV or jack up vessel as well as vibratory hammer, which is a high-demanding energy equipment, the fuel consumption as well as emission will be mitigated enormously.
9. The cutting mechanism leads to cut the monopile to smaller sections during extraction.
   - The smaller sections are lighter in weight which means for offloading from Decom Tools Vessel to quayside, smaller crane is needed.
   - In addition, cut segments of monopile can be transported easier for further recycling.
   - Moreover, a part of recycling which is cutting has been done onboard the vessel.
   - Lastly, the lighter and smaller cargo contribute to the safer lifting and handling operations.
   - Cutting of small section pave the way for removal of marine growth on the deck of the Decom Tools Vessel.
10. There is no need to handle and manage the scour protection since pile extraction can be done in presence of scour protection. Removal of scour protection can bear huge cost to the contractors.
11. The marine growth removal will give the chance to remove all the fouling offshore and in case of remaining, removing during sailing.
    - It prevents extra cost of erection of scaffolding onshore for removal,
    - Minimize the cost of MGR removal. Because some parts are removed automatically offshore.
    - Prevent the transportation for landfilling (from port to landfill).
    - Minimize the cost of landfilling.
    - Moreover, the resulted emission from above mentioned transportation will be decreased.
    - More importantly no odour and nuisance for port staff and nearby civilization will be emitted.

- From an environmental perspective, it avoids the ecological problems resulting from shifting these creatures from offshore to onshore.

6.21 Comparison of Monopile Extraction with Decom Tools Vessel and Vibratory Hammer with Installation Vessel

Table 6-14 shows the duration of pile extraction, cost, fuel consumption and emission for two scenarios of pile extraction with Decom Tools Vessel and pile extraction with the vessel that conduct the installation of the monopile and using vibratory hammer. As it stated during the above sections, these figures represent the parameters (time, cost, consumption and emission) for extraction of 91 numbers of monopiles of Hornsea 1 offshore wind farm.

Table 6-14 Comparison Table for Pile Extraction

OWP: Hornsea 1	Comparison Table for Removal of 91 Monopiles	
Configuration	Reverse of Installation	New Method
Parameters	DP2 Jack Up	Decom Tools Vessel
Time (Day)	163.45	161.84
	Base Scenario	-2
		1%
Cost ($)	$ 32,690,088.7	$ 11,328,780.9
	Base Scenario	$ (21,361,307.8)
		65.34%
Fuel (Tones)	7366.54	3168.52
	Base Scenario	-4198.02
		57%
CO_2 Emission (Tones)	23617.13	8713.44
	Base Scenario	-14903.69
		63%

The above table can be analysed as following:

I. From a time perspective, the duration of pile extraction with Decom Tools vessel is about 1% more than extraction reverse to the installation. One of the reasons is that the Decom Tools is lifting the monopile with its buoyancy without using crane and hammer. Huge volume of water should be ballasted and deballasted in order to extract the monopile. Extraction in less time is possible, if the number of ballast pumps increased. Currently 10 numbers of ballast pumps with capacity of 3000m^3/h are considered for ballasting and deballasting. The problem is that the ballast pumps are so energy demanding equipment which result in more fuel consumption and more emission.

II. From a financial stance, the cost of extraction with Decom Tools vessel is 65.34% less than reverse to the installation. the reason is that the charter rate of jack up vessel is considered 200 000$ daily. Innovation vessel is a large DP2 Jack up vessel which this charter rate can be assumed for this vessel. Decom Tools vessel is a cargo vessel with a charter rate of 70 000$. As it stated before, the charter rate for operations such as pile extraction and TP removal which need DP officers are considered 70 000$. For transportation of rotor, nacelle and tower which does not need DP officers, it is considered 40 000$.

III. From a fuel consumption perspective, it can be argued that the consumption of the Decom Tools is less than jack up during pile extraction operation. One of the reasons is that during extraction, the Decom Tools vessel maintain the position just by the grippers and bow anchor. So, the DP is not needed to be in service during extraction around the clock. Also, by using the battery and solar system, huge amount of saving can be achieved when the engines do not work on maximum load. Furthermore, vibratory hammer is an energy demanding equipment, based on one of the manufacturers, it needs 9200 KW power unit to operate large-sized vibratory hammer which approximately consume over 90 tonnes per day. This machine impacts the fuel consumption as well emission considerably.

IV. From an emission stance, since the Decom Tools vessel run on LNG, the emission is 63% less due to less emission of LNG, use of solar energy and batteries as well as and lack of use of vibratory hammer for pile extraction.

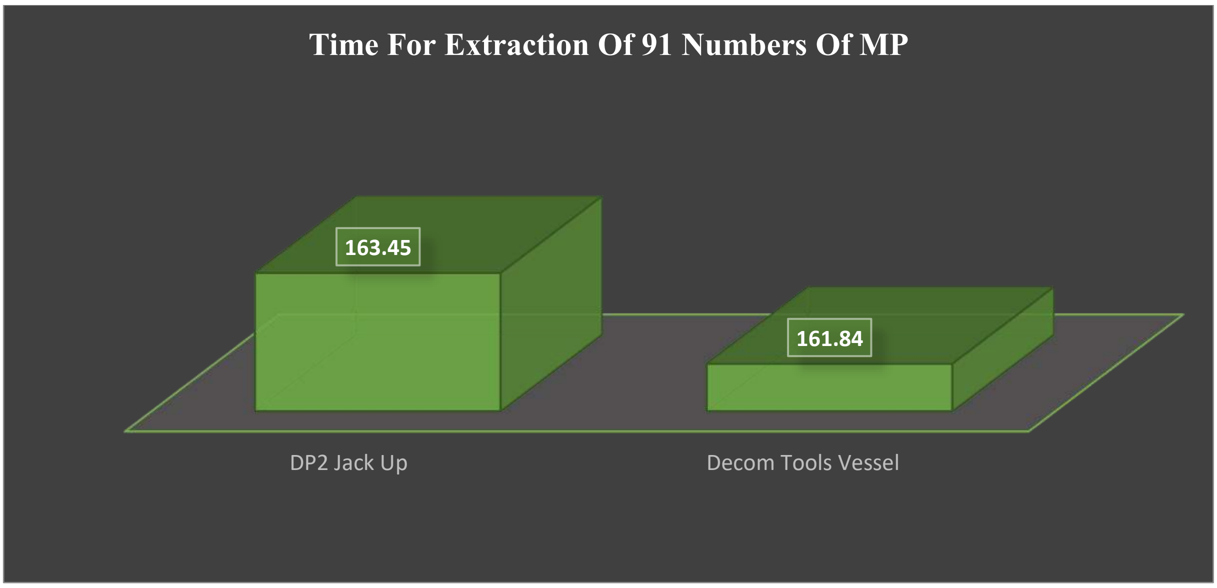


Figure 6-172 Comparison of Duration for MP Extraction

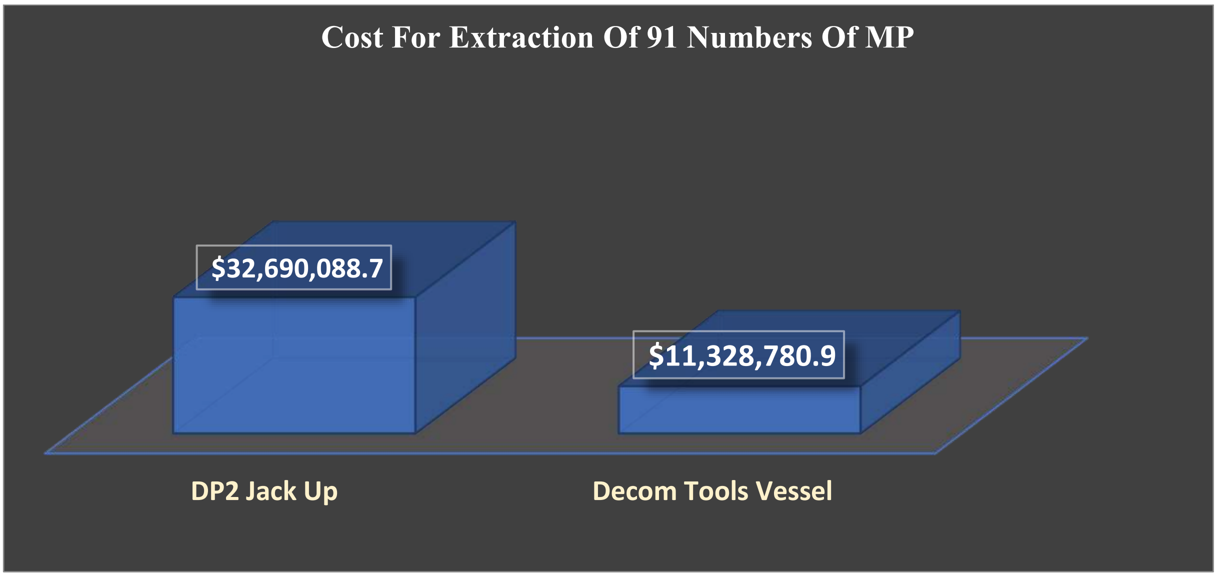


Figure 6-173 Comparison of Cost for MP Extraction

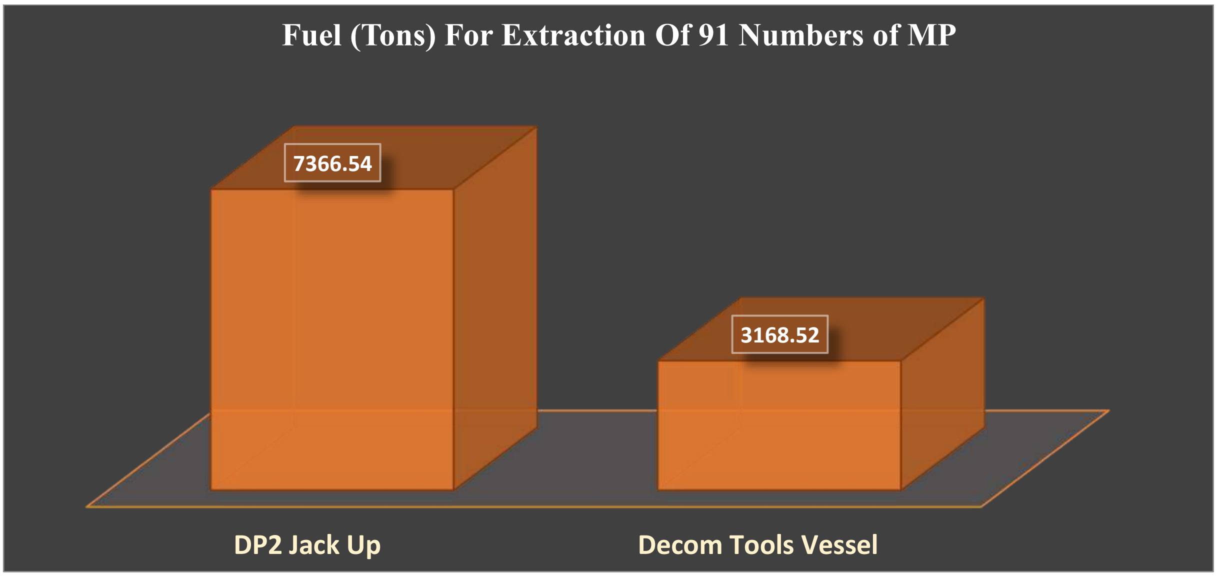


Figure 6-174 Comparison of Fuel Consumption for MP Extraction

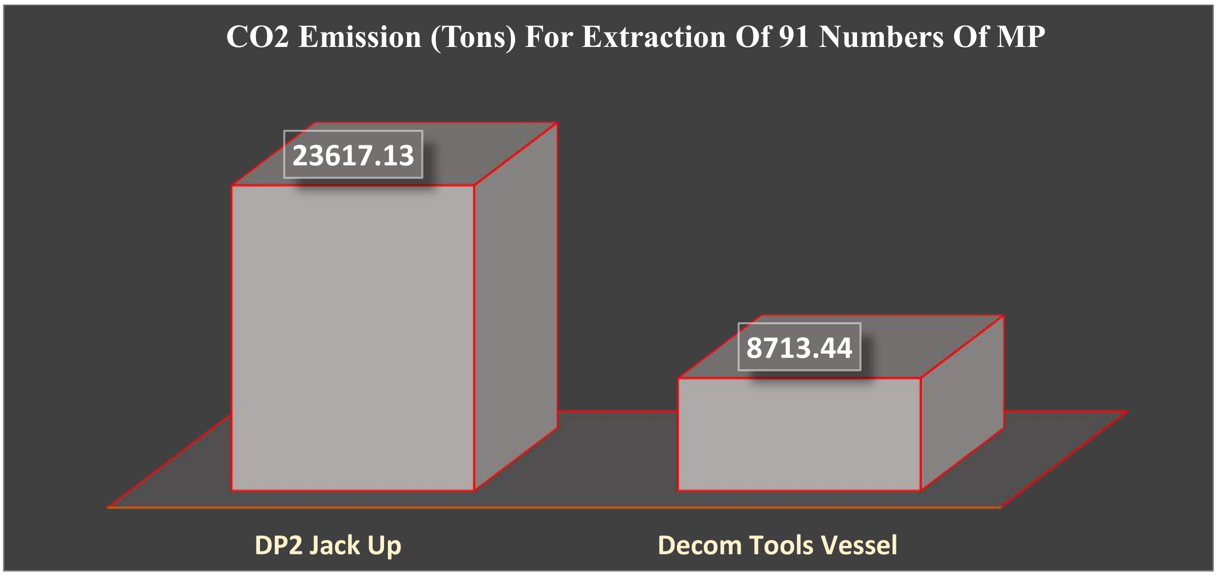


Figure 6-175 Comparison of CO_2 Emission for MP Extraction

6.22 Cable Removal Reverse to the Installation

So far transmission of the generated electricity by the wind turbines are performed by using submarine power cables from the offshore wind farm to the onshore. There exist two types of cables in any wind farm namely infield array (or inter array) cable and export cable. For example, in the Nordsee one project (Figure 6-176), the fifty-four turbines are connected by ten strings of aluminium cables, with an overall length of around 70 kilometres. The cables of these strings are called array cable (or inter array cable or in-field cable). In this project two different cable cross-sections for inter array cables are used: 240 mm^2 and 800 mm^2. The function of export cable is to transmit the electricity from either the strings or the offshore high voltage substation (OHVS) to the shore. Figure 6-177, shows a schematic of inter array and export cable as well OHVS.

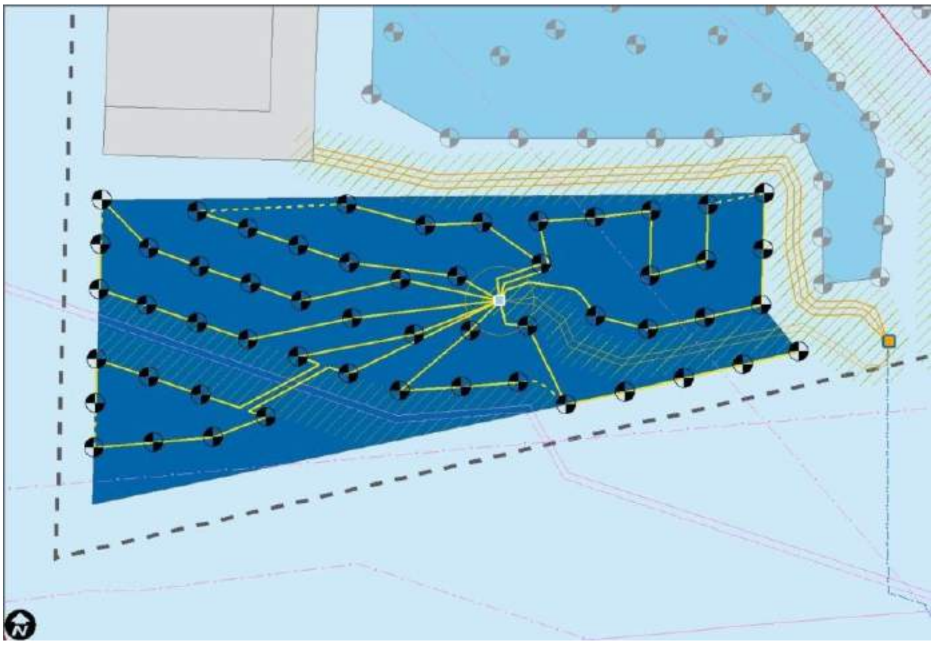


Figure 6-176 Topology of Nordsee 1 wind farm

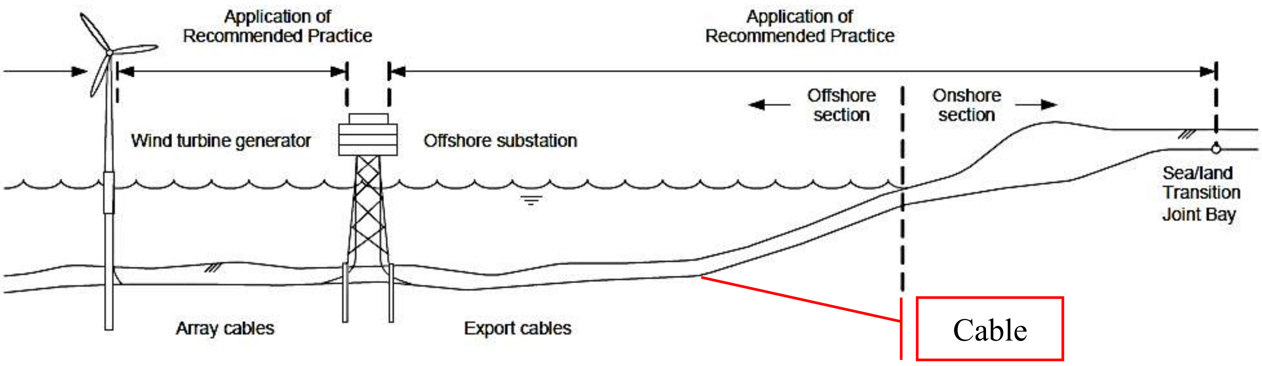


Figure 6-177 Transmission of Generated Power by OWT to Shore (DNV.GL 2016)

Figure 6-177 shows a schematic of a wind farm and gives the view of the buried submarine power cable.

From a regulation perspective, more or less similar regulations which are applied to the foundation are exited for the cables. Keeping the cable has more risks to other sea users than foundation since they are laid in the larger area. Therefore, removal of them need to be conducted finally.

To extract the cables, first of all one shall know what obstacles the contractor would face in cable extraction in order to recommend how to extract the cables. Despite of fibre optic cables, all of the submarine power cables are buried or protected by external means. The main method of cable protection is cable burial which is shown in the Figure 6-178. The depth of burial depends on a couple of factors as following:

- The national regulation[73].
- The characteristic of seabed and soil.
- The location where the cable is laid like close to the shore or anchorage area etc.

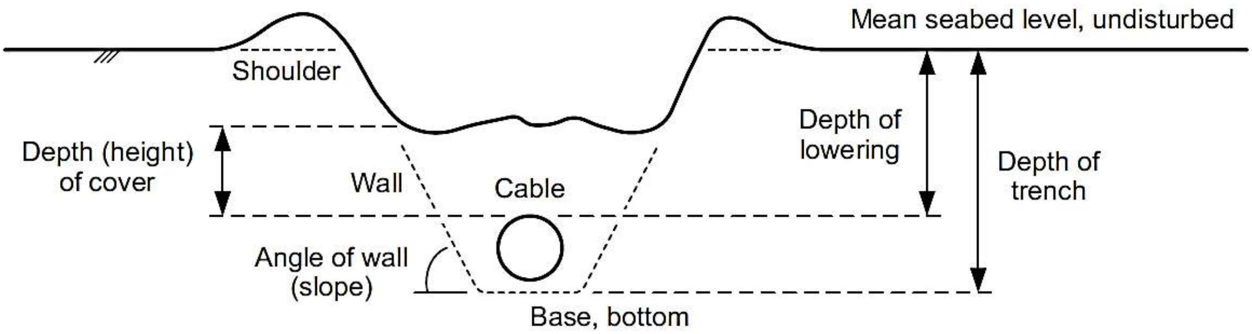


Figure 6-178 Burial of Submarine Cables (DNV.GL 2016)

The depth of lowering of cable can be changed during lifetime of cable. The thickness of the cover layer can be increased or decreased. Figure 6-179 shows how the depth of burial may change during lifetime of the project.

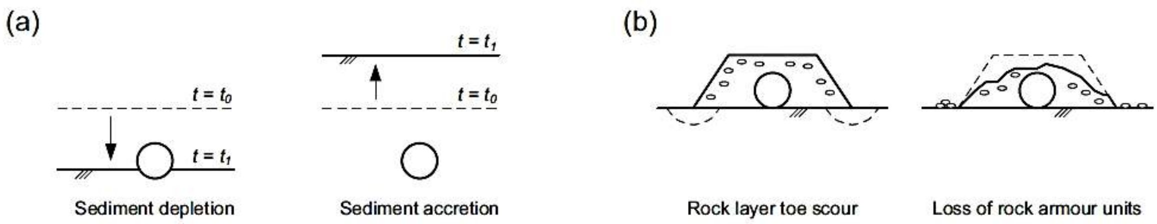


Figure 6-179 Change of Depth of lowering of the Cable during lifetime (DNV.GL 2016)

Therefore, prior to decommissioning and extraction of the cable, a survey needs to be conducted to measure the thickness of soil cover and other measures which are shown in the Figure 6-180.

[73] With regard to depth of burial for cables, countries may follow a prescriptive or a risk-based approach:

- Germany: the required minimum burial depth is based on 2K criterion, i.e. the maximum allowed temperature rise of 2 Kalvin at a reference point, e.g. 20 cm below the seabed in exclusive economic zone (EEZ), should not be exceeded as required by the German authority (DNV.GL 2016).
- United Kingdom: Burial depth may be determined employing a risk-based approach (DNV.GL 2016).

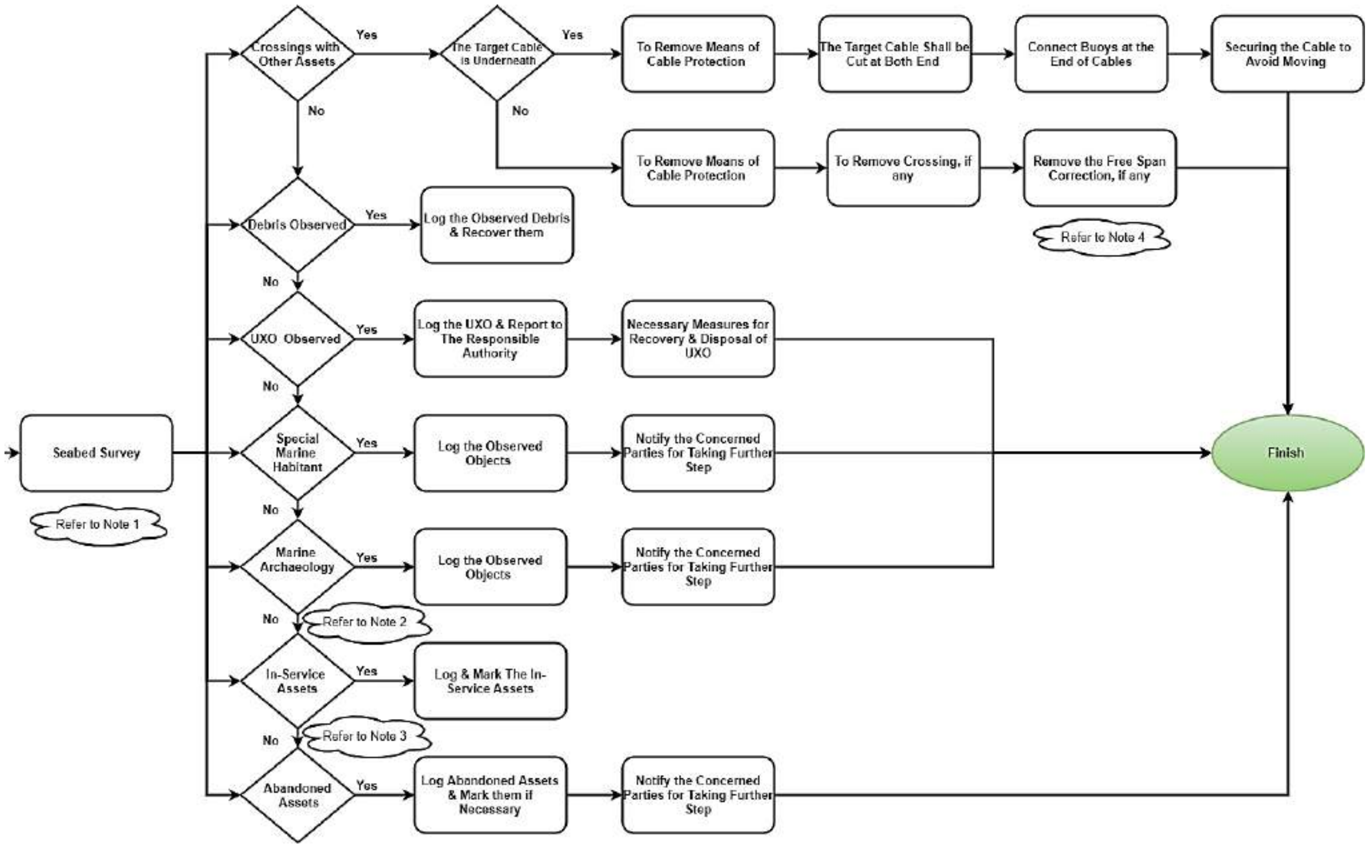


Figure 6-180 Pre-decommissioning Operation for Cable Extraction

Therefore, execution of above survey prior to removal of cable is necessary in order to make the site ready for cable extraction. These set of activities can be executed by small vessel and ROV in order to minimize the working hours of cable laying vessel.

During installation of cable, in case the cable burial was not possible to carry out, one of the below scenarios or combination of them were conducted. Figure 6-181, Figure 6-182, Figure 6-183 and Figure 6-184 shows how the external protection of cable can be performed. The question of why not to bury the cable in lieu of external protection depends on site condition.

6.23 External Protection Methods of Submarine Cables

There are four various methods of protection of cable, if burial is not possible to conduct which are listed below.

I. Rock Dumping

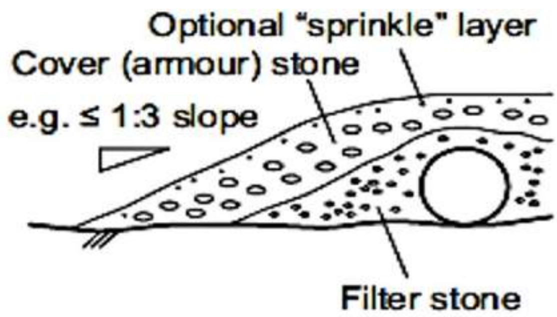


Figure 6-181 Rock Dumped on the cable as means of protection

II. Concrete mattresses

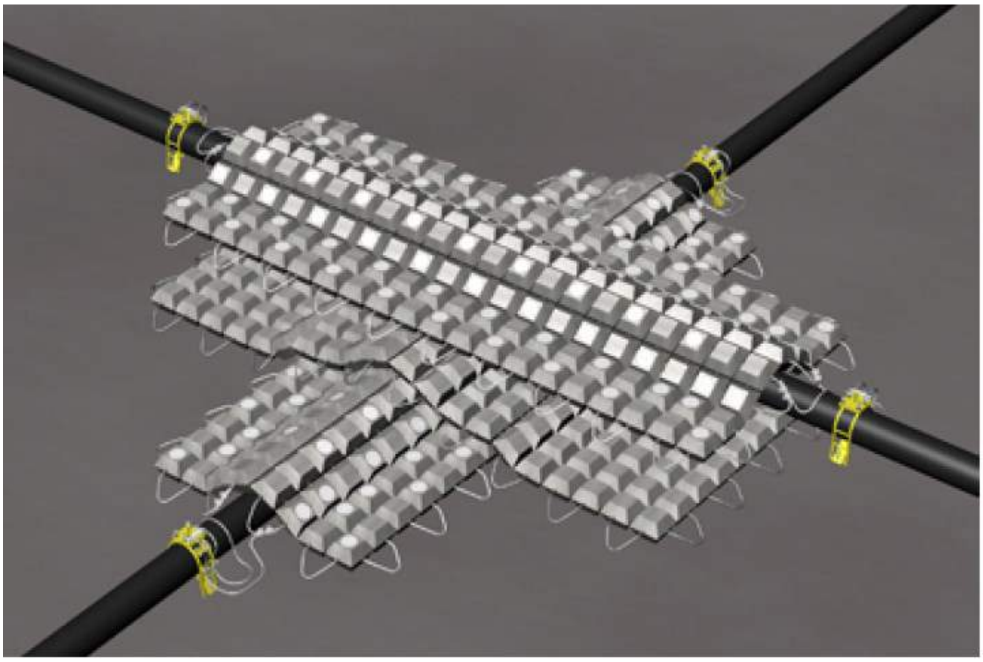


Figure 6-182 Mattress installed on the cables as means of protection

III. Cast iron shells and ducts and pipes etc.

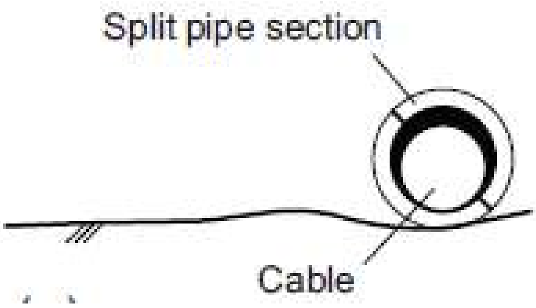


Figure 6-183 Cable is installed inside the Tubular for the protection

Figure 6-184 Near Shore Cable Protection (Tubular Protection) (TAGU OFFSHRE n.d.)

Cable extraction can be done in any condition regardless of cable protection methods. The cost of cable extraction and the environmental impact of various method can differ. For example, if the cables are protected by mattress, the first stage is recovery of the mattress. So, in this case diving or ROV team need to be mobilized to connect the mattress to the crane for lifting operations. Also, the vessel which planned to recover the mattress need to have a certified sea water crane. All of these extra measures incur cost to the project.

Given the fact that majority of cables are protected by burial means, therefore, we consider burial method as a default method of protection.

Cable laying vessels (CLV) are used for laying sub-sea cables including fibre optics as well as power cables which are large marine assets of 110 meters or larger (Axelsson 2008). In addition to installation of subsea cables, CLV are able to retrieve broken or damaged subsea cables and repair them on board. The charter rate of CLV is normally high (between 70 000$ to 150 000$)[74] and this kind of vessel is fully booked for the projects 1-3 years in advance.

From a propulsion systems perspective, most of cable laying vessels are now equipped with powerful propulsion systems and a dynamic positioning system (Global Renewables Shipbrokes 2020). The use of DP system led to high fuel consumption and finally higher CO_2 emission.

6.24 Removal of Cover Soil

As it stated earlier, the base scenario for the decommissioning of OWP in Decom Tools project is exactly reverse to the installation methods. In majority of cases, during the installation operation first the trench is made, then the cable is buried.

Reverse to the installation means that first the soil covers should be removed then the cable should be retrieved. There are a couple of tools that can be used for removal of soil cover which is placed on top of the cable. Each of them has its own merits and demerits. Each of them is designed to work for specific soil condition and so on. But it can be said that in most locations of the North Sea Region the mass flow excavator can remove the soil cover. However, as it said, due to soil condition in some location mechanical trenchers need to be used to remove the soil cover. The following figures shows some of the common tools for excavation of soil.

Thus, the normal procedure to extract and retrieve the cable is first to excavate the soil cover by means of mass flow excavator (Figure 6-187 and Figure 6-188) or airlift (Figure 6-189) or mechanical trencher (Figure 6-191) in order to provide access to the cables which is laid underneath soil.

[74]This charter rate is given by one professional broker in the Hamburg. The charter rate depends on the specification of the vessel, the time of chartering and the duration of chartering

However, it should be noted for the installation of the cable, normally cable plough is used to bury and lay the cable. The benefit of this tools is burial and laying at the same time. One of the problems is that it cannot cut all soil condition. Also, the burial speed is not so fast. Figure 6-185 and Figure 6-186 show the cable plough and how it is used during laying the cable.

In many projects, first the cables were laid by CLV and then the burial took place by another fleet. Burial after lying may pose risk to the cables.

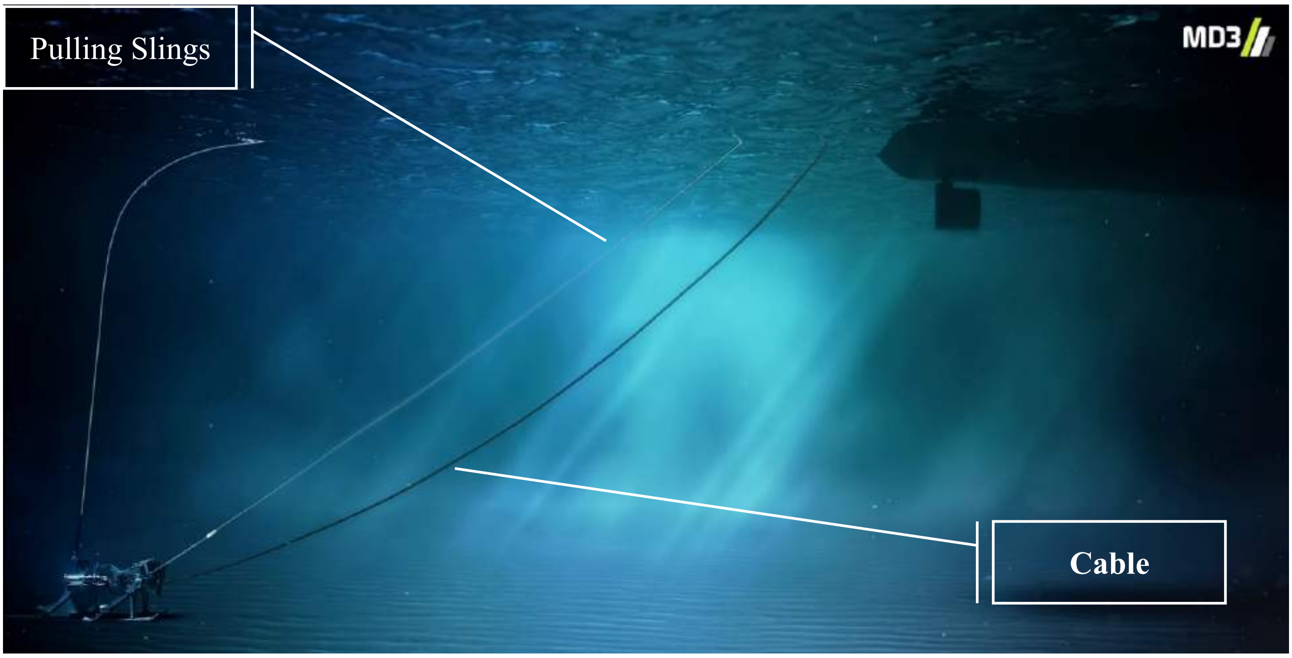


Figure 6-185 Cable Plough (SMD - Subsea Technology 2014)

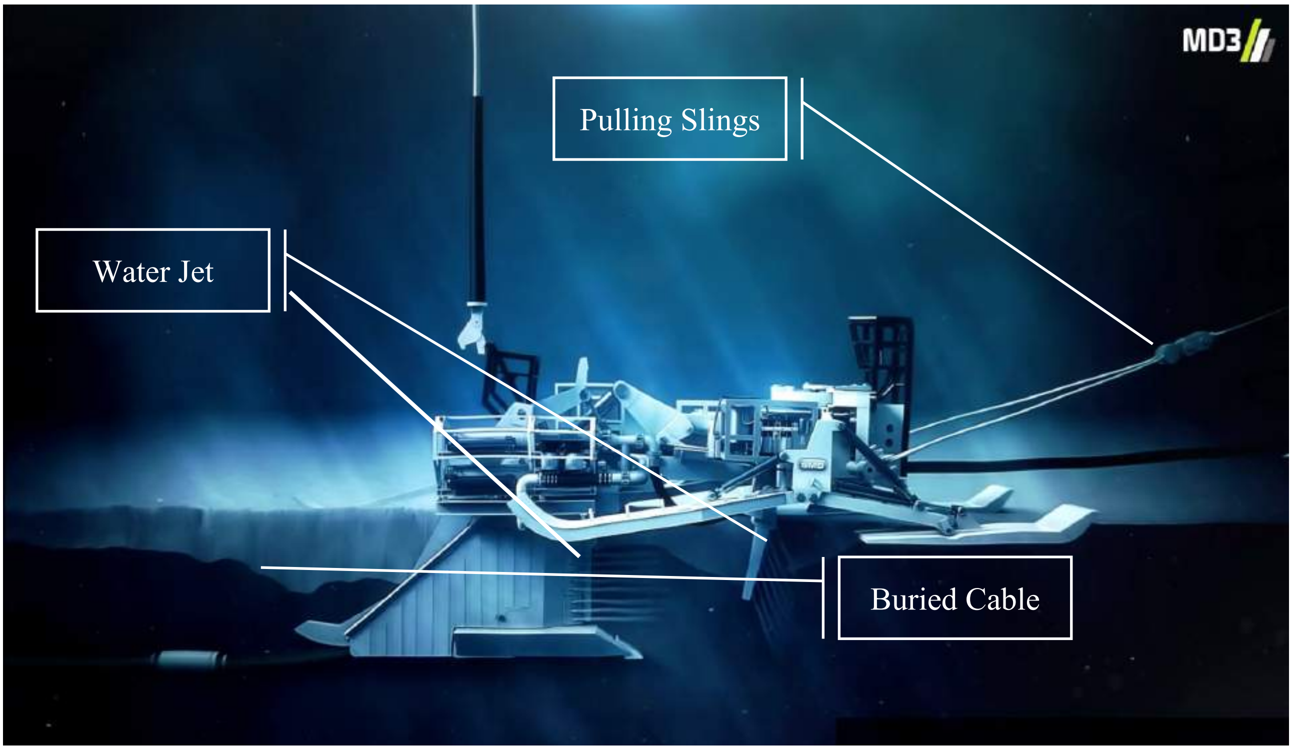


Figure 6-186 Cable Plough (SMD - Subsea Technology 2014)

Figure 6-187 and Figure 6-188 shows the mass flow excavator. One of the problems of the mass flow excavator is that it does not have propeller, therefore, the excavation through the length of cable shall be done by moving the vessel across the route of the cable. Furthermore, in order to monitor the excavation operation, ROV should be launched. The weight of existing mass flow excavator is not more than 5 tons. They have their own launch and recovery system (LARS). But the weight of cable plough is high (the dry weight of above-shown plough is 27 tons based on the spec of the tool), they need to be lifted and lowered by vessel crane.

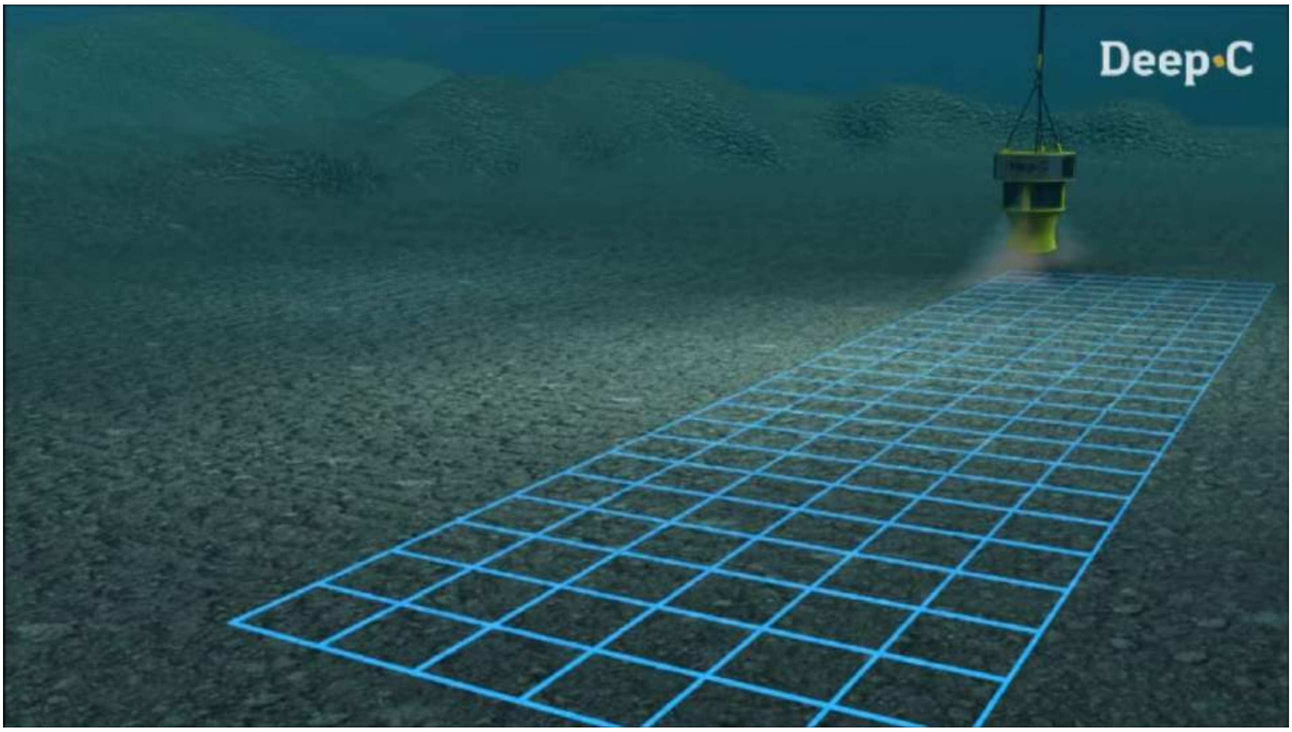


Figure 6-187 Mass Flow Excavator (Cable Rout is identified for excavation) (Deep C Blower 2015)

Figure 6-188 The Soil Cover on top of the cable is excavated by Mass Flow Excavator (Deep C Blower 2015)

Figure 6-189 and Figure 6-190 shows two different types of airlifts. One of the problems of airlift is that diver is needed to operate the airlift which make the operation so expensive, complex and riskier. Also, based on experience of author, it is not feasible to excavate the soil cover of all the length of cable with this tool. For small area, such as excavation around monopile, this tool can be used.

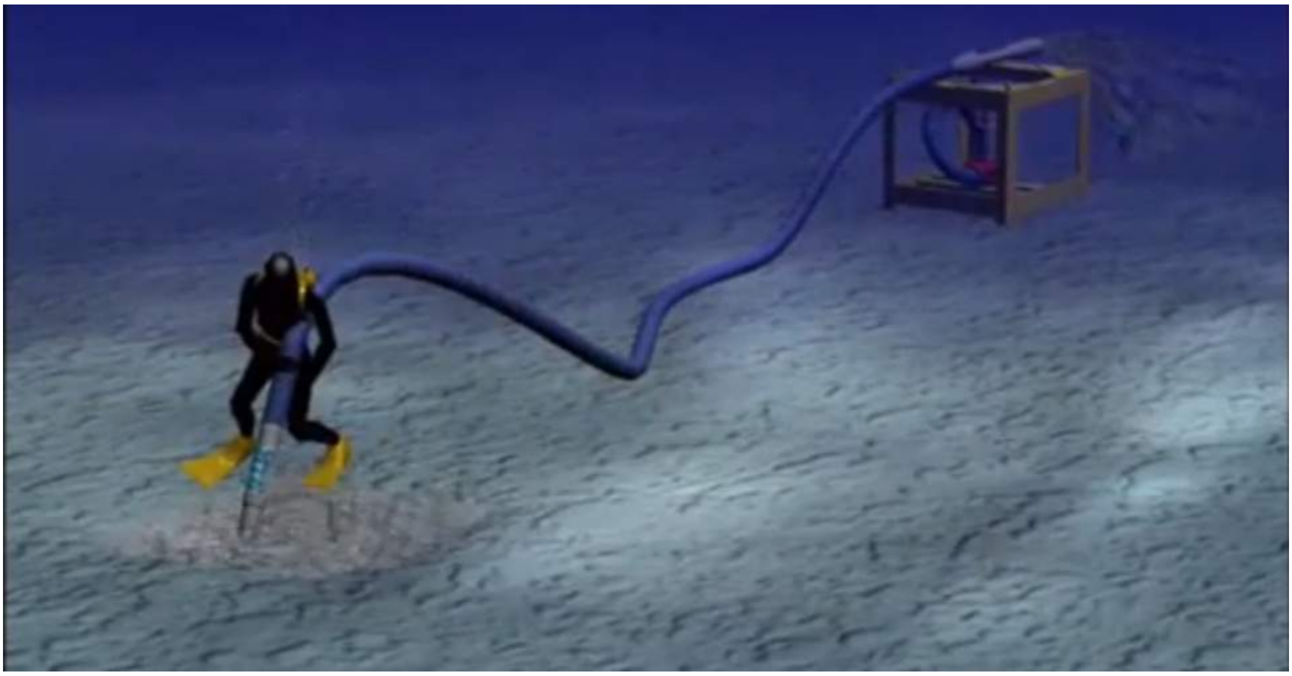


Figure 6-189 Excavation Operation with Airlift (SediCon AS 2017)

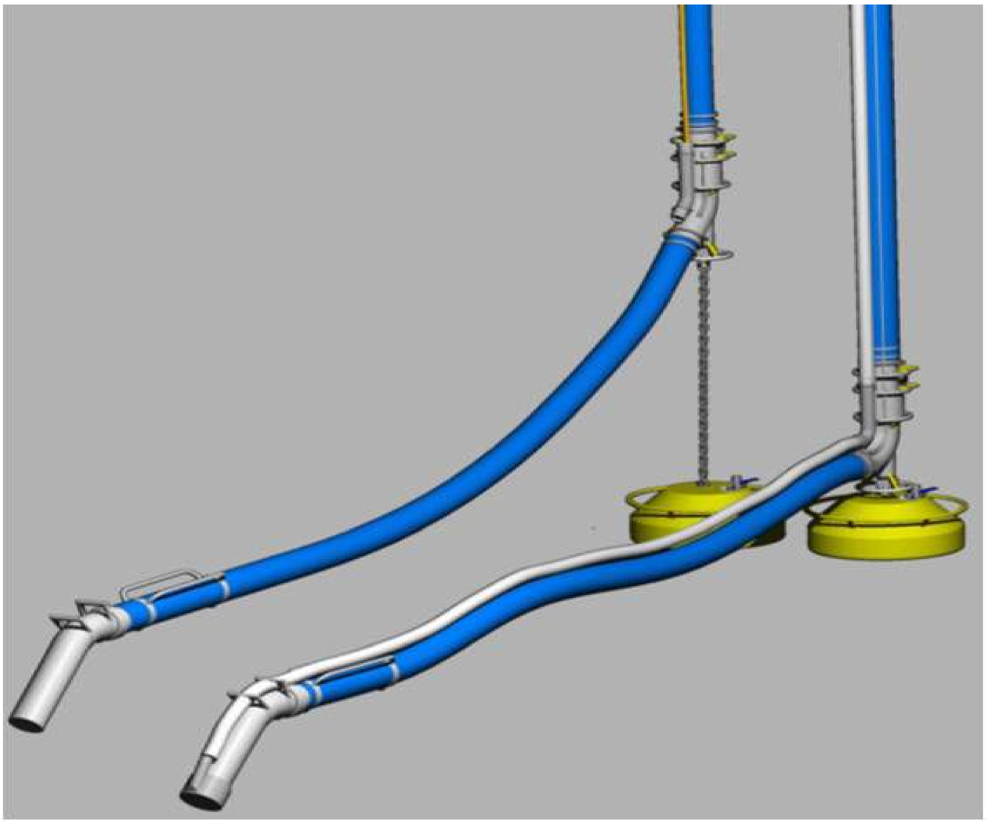


Figure 6-190 Common Type of Airlift (inzenjering n.d.)

Figure 6-191 Mechanical Trencher

Figure 6-191 shows mechanical trencher. The charter rate of mechanical trencher is so high. In addition, there are not so many manufacturers of this machine in the market. Due to these reasons, it is used whenever it is necessary. The benefit is that it can cut the hard soils too which other two mentioned techniques cannot do that. Another advantage is high speed of burial and laying.

6.25 Cable Retrieval

After excavation of soil cover from top of the cable, the next step is retrieval of the cable with cable laying vessel (CLV). As it stated the CLV has high charter rate, they are not available all the time and they can carry out specific weight and length of the cable. More importantly, since it operates on DP, it consumes considerable amount of fuel which result in significant emission.

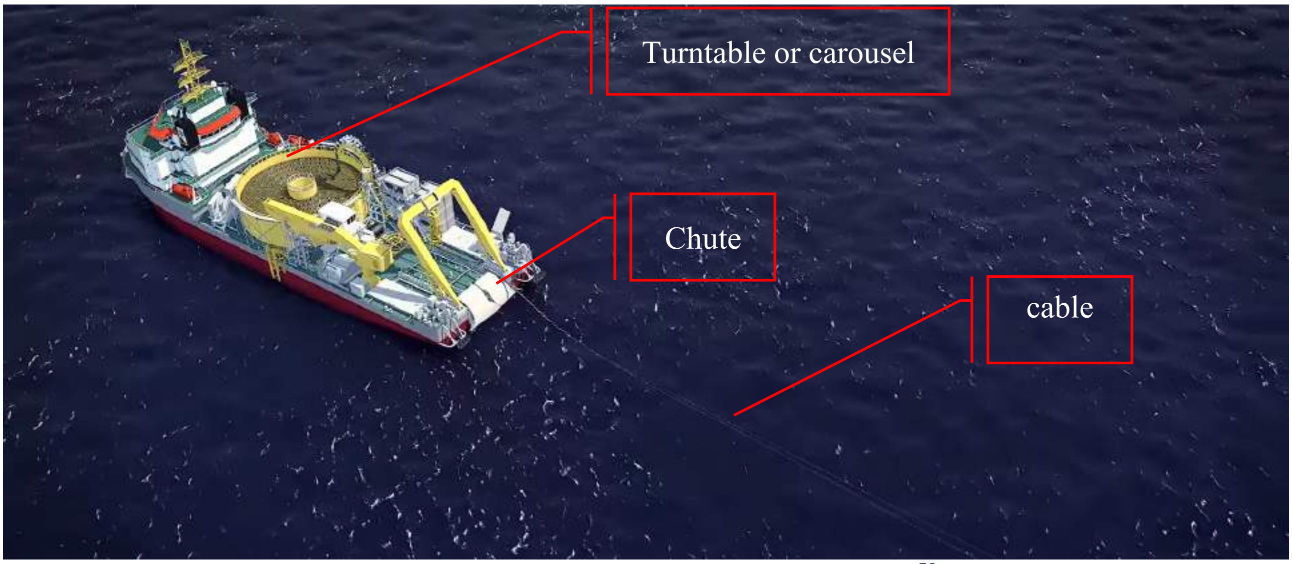


Figure 6-192 Cable Laying Vessel (Boskalis 2017)[75]

[75]Chute: a curved channel for passing a cable from a higher to a lower level, e.g. overboard a vessel, which does not compromise the mechanical parameters of the cable

The analysis of cable removal reverse to the installation has been carried out which shows that the cost of operation as well as environmental impact of the retrieval is significant.

Figure 6-192 shows a cable lay vessel during laying operation. The different parts of the ship are marked and explained in the figure. Figure 6-193 shows another cable laying vessel.

Figure 6-193 Cable Laying Vessel

Another equipment which is existed onboard the CLV is tensioner or caterpillar. Figure 6-194 shows the two tensioners onboard the vessel.

Figure 6-194 Tensioner to hold the cable during laying operation

The tensioner is used to hold the cable and control the pay-out of the cable[76]. Holding force of tensioner depends on track length, pad shape, the squeeze force acting on the cable and the friction

[76] The high tension can cause failure of mechanical properties of the cable and low tension can cause the kink in the cable on the sabed.

between pads and cable surface (DNV.GL 2016). Figure 6-194 shows the tensioner or caterpillar of two different vessels.

There are a couple of reasons that cable laying vessel has high charter rate. The following are some of the reasons:

1. The operation needs at least 60 number of crew. The high number of crew means more cost to the project.
2. The ROV tool and the ROV team are mobilized onboard the CLV in nearly all operation for survey and laying monitoring.
3. In some cases, diving team need to be mobilized like shore pulling.
4. The operation is sensitive, and a minor mistake can lead to acute problems and incur high cost to the project.
5. The vessel is normally equipped with DP system. The DP system is expensive also the crew who are running the DP have high wage.
6. The installed machineries onboard the CLV are special and need special team to operate like carousel, quadrant and the tensioner.

The CLV installed both inter array and export cable. But the procedure of laying for the inter array and export cable is different.

For the initiation of export cable installation, normally the CLV position in the sea in a suitable water depth, then the cable is pulled by onshore winches. The cable should be released from vessel and then should be pulled by winches that are located close to the transition pit in shore. It means that under some certain conditions, the cable is pulled with winches and some other accessories. Therefore, cable pulling is common and acceptable operation. In addition, for maintenance and repair of the damaged cable, the cables are pulled to the vessel deck for necessary rectification.

Figure 6-195 shows the overall view of shore pulling operation in that the vessel positioned 2200 meter in sea and the cable was pulled by winches that were installed onshore.

Figure 6-196 shows how shore pulling operation can take place. The required equipment and personnel are shown somehow in this photo. This operation is so sensitive and important.

As it stated earlier, in order to pull the cable, some tools and accessories need to be installed at the end of cable for pulling operation. These accessories can be pulling head/ pulling eyes or Chinese finger. They are mechanical device attached to the end of a cable for pulling the cable from a vessel, pulled along the seabed or pulled into an offshore unit (PCS Italiana n.d.). Figure 6-197 shows the drawing of a common pulling head and Figure 6-198 shows that the vessel is pulling the cable via pulling head.

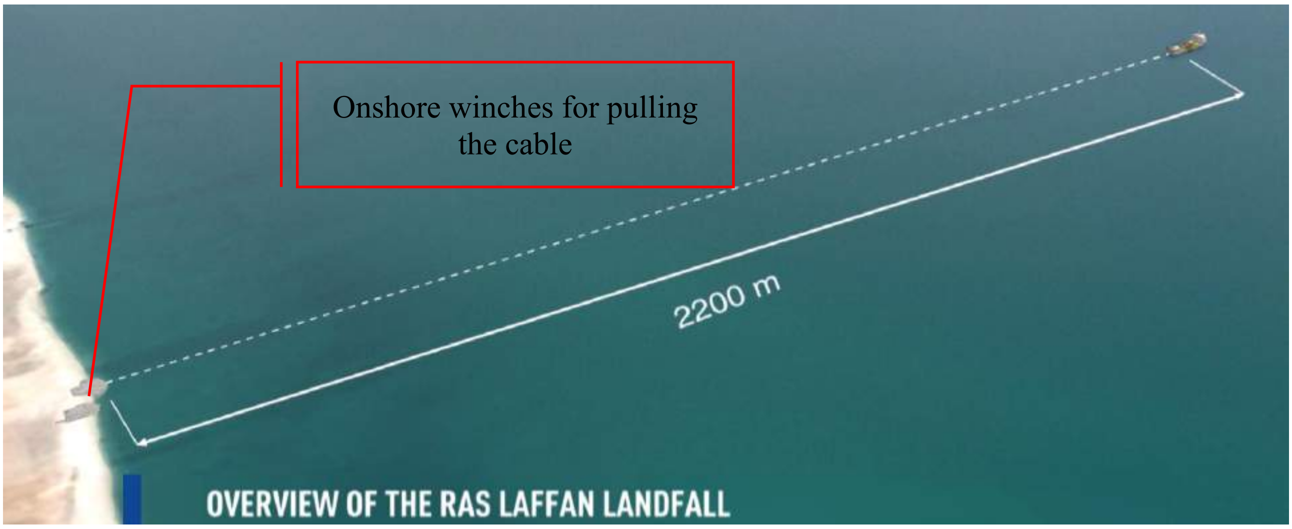


Figure 6-195 Shore Pulling Operation

Figure 6-196 Shore Pulling Operation (Boskalis 2019)

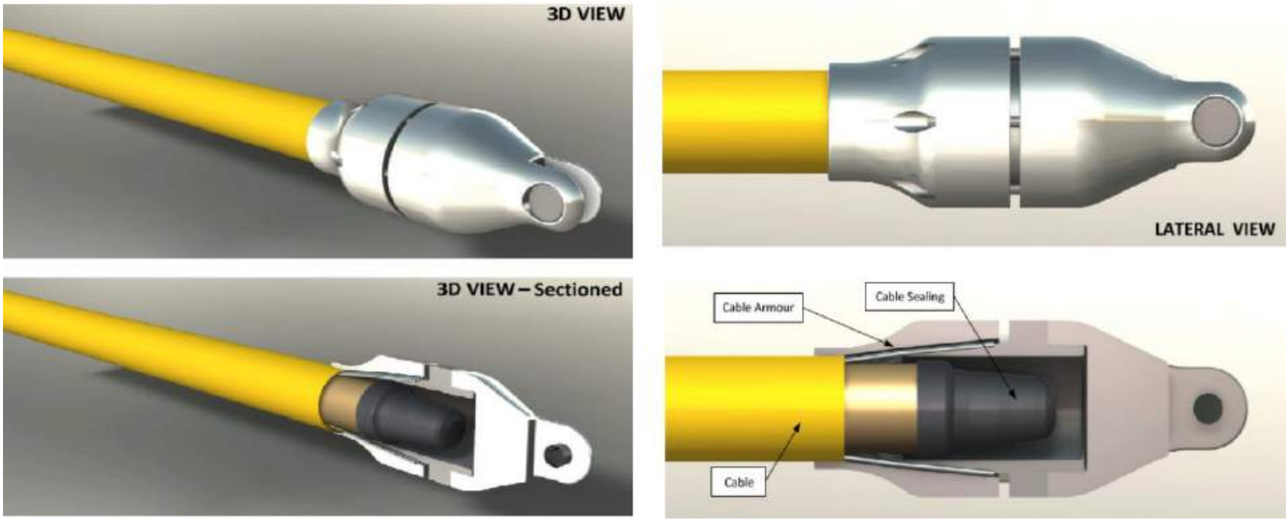


Figure 6-197 Submarine Power Cable Pulling Head (PCS Italiana n.d.)

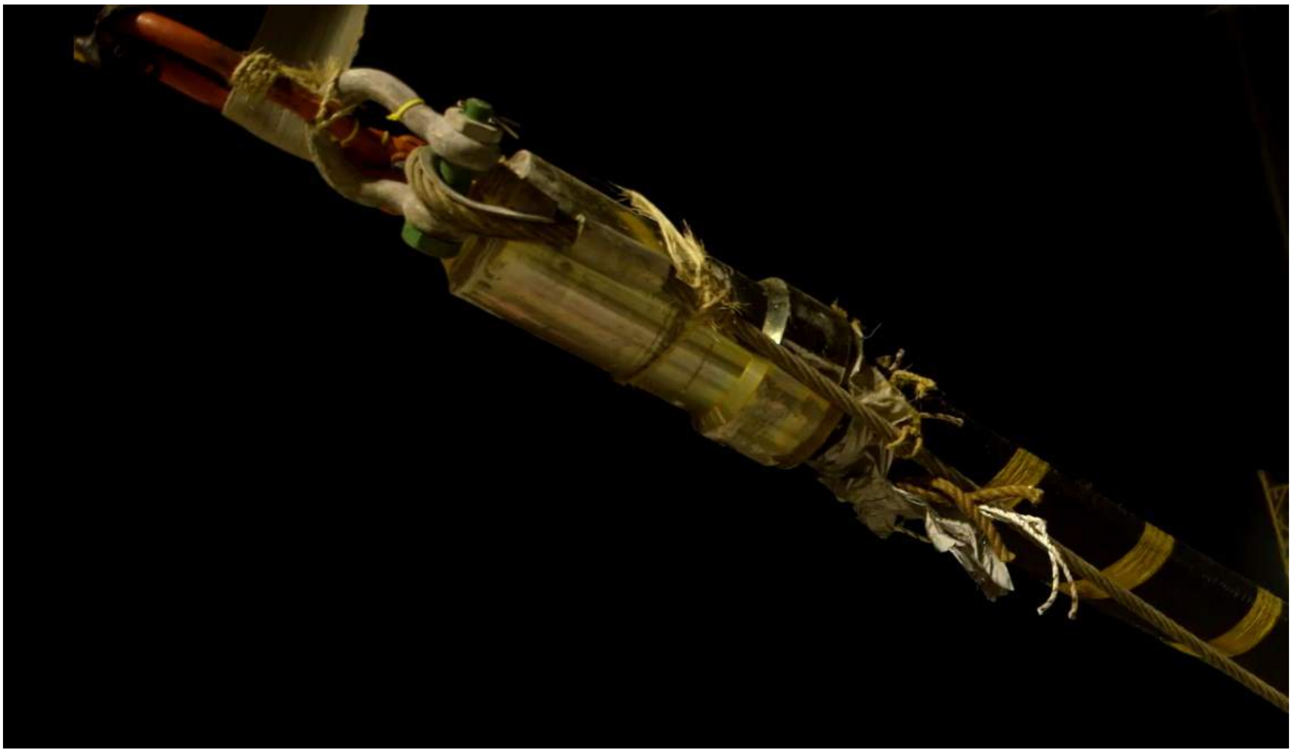


Figure 6-198 Pulling the Cable from Vessel via Pulling Head

Another accessory which can be used for pulling the cable is Chinese finger (also called cable grip). The function of this tools is exactly the same as pulling head. The force that can be exerted to these accessories are different, however, there are various size of these accessories in the market. There are different types of cable grips which Figure 6-199 shows one of these models.

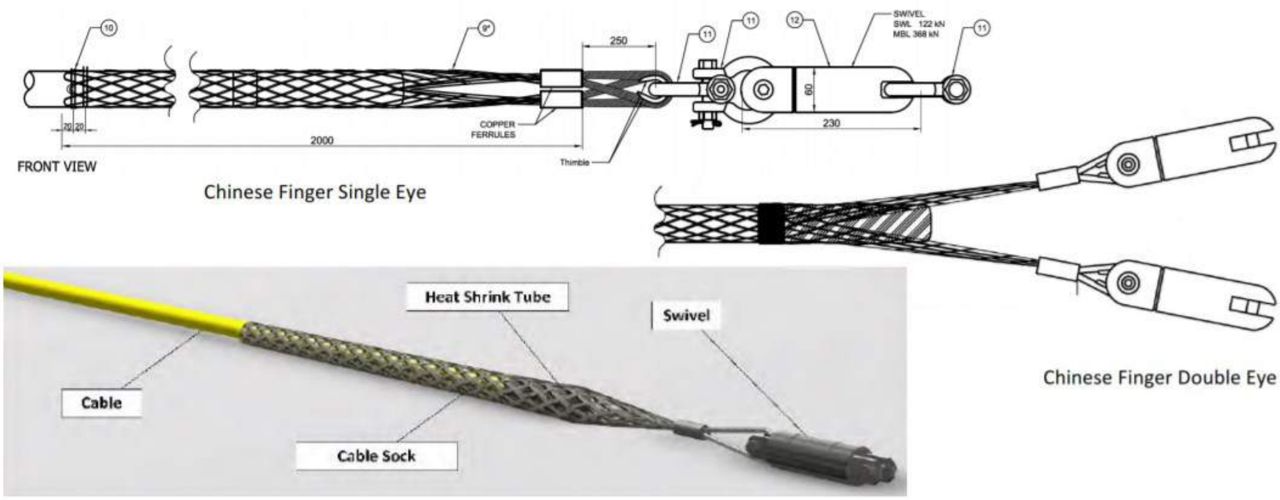


Figure 6-199 Chinese Finger and Drawing of Connection

In order to increase the reliability of the pulling operation and minimize the applied force to the cable, in some cases both types of accessories are used. Figure 6-200 shows that both pulling head and Chinese finger are used for shore pulling operation. Also during recovery of the cables with Decom Tools vessel, it is highly recommended to use both accessories in order to prevent loosing of the cables.

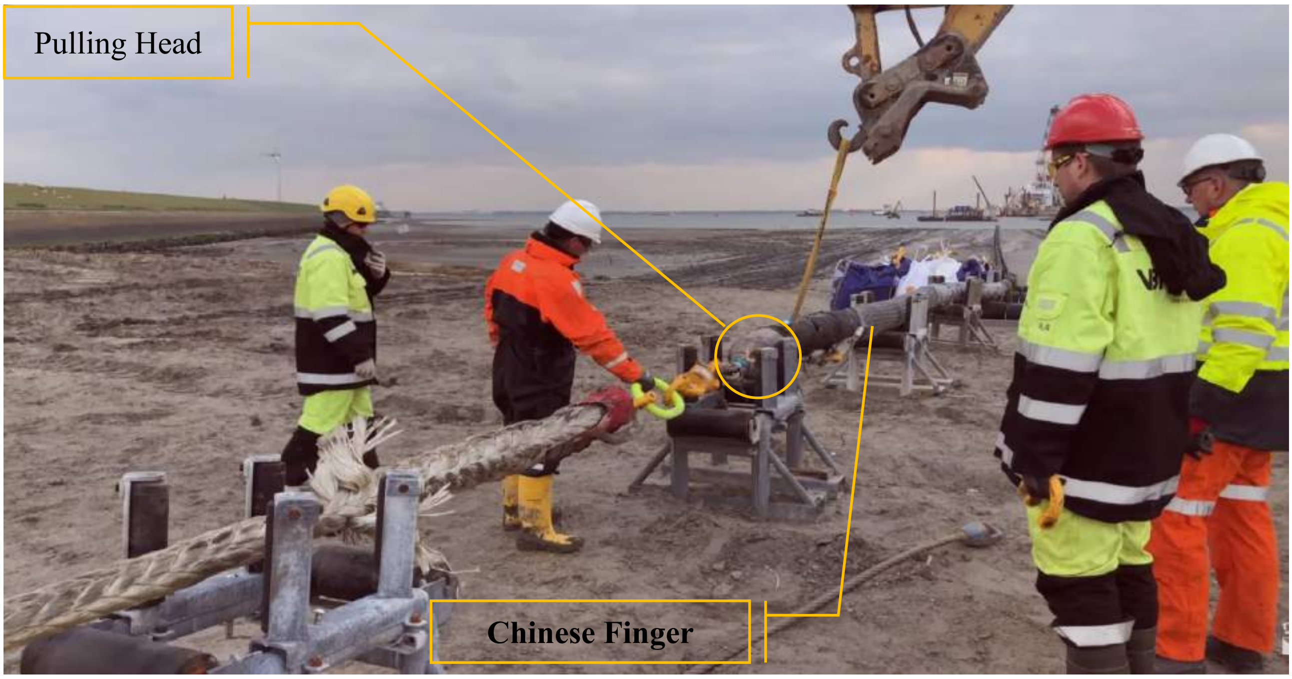


Figure 6-200 Pulling the Cable with onshore winch via both Pulling head and Chinese finger (Boskalis 2019)

6.26 Time-Cost-Consumption-Emission Analysis of Case Study for Cable Retrieval

An algorithm has been designed in order to calculate the cost, emission and duration of cable retrieval operation. In order to evaluate and verify the algorithm, a case study selected based on available information in order to make the calculations.

Anholt wind farm is selected as case study for removal of infield cables. In this wind farm, 111 Siemens SWT 3.6 MW are installed in this wind farm with approximate distance of 600 meter (Orsted 2019). The wind farm is located 20 km from Grenå and 15 km from the island of Anholt. The following figure shows the topology of grid inside the wind farm.

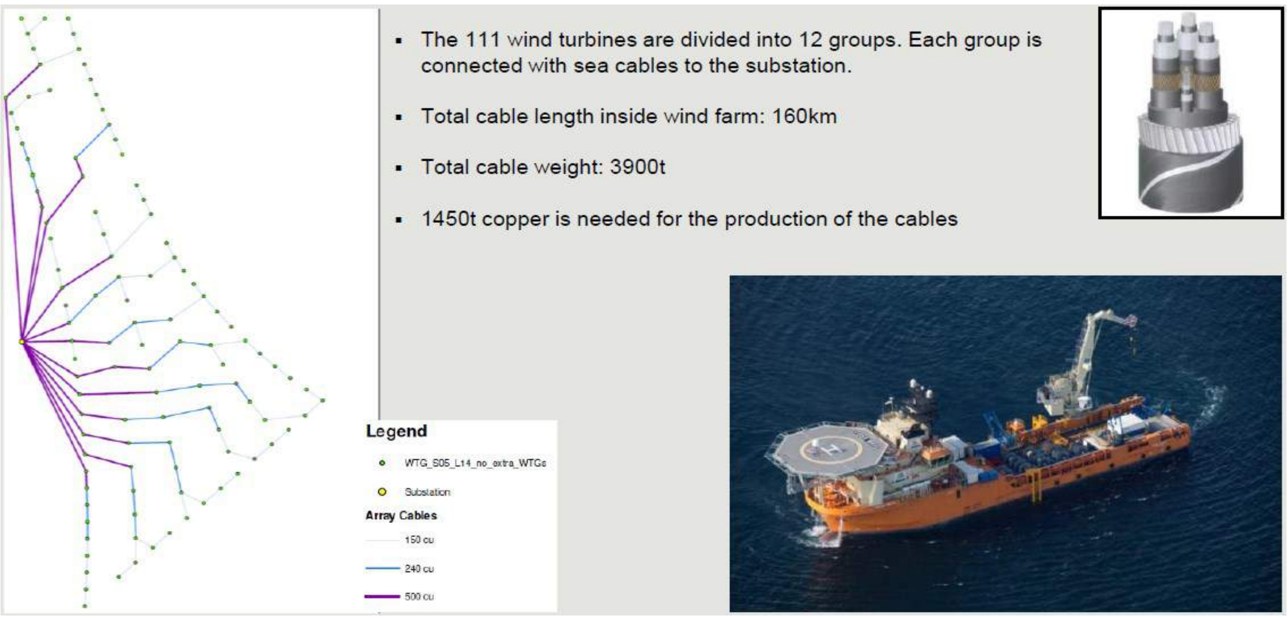


Figure 6-201 Information about Infield Cable of Anholt OWP (Orsted 2019)

6.26.1 Inter Array Cable Installation

Anholts' infield cables have three different cross sections of 150 mm^2, 240 mm^2 and 500 mm^2 which delivered by train on 89 drums.

In this wind farm installation of 111 infield cables with a total length of around 160 km and weight of 3900 tons took 120 days. It means installation of each infield cable took 1.081 day which is equivalent to 25.94 hours.

Boskalis deployed two cable installation spreads to lay cables for the Anholt wind farm.

I. The first cable installation spread which is an anchor barge by the name of Stemat 82, assisted by anchor handling tugs, Lydia D and Nova K.

II. The second installation spread was a DP2 offshore construction vessel by the name of Toisa Wave. This vessel ran into port to load 9 cable drums at a time. This set-up proved to be extremely efficient, resulting in the timely completion of the cable installation scope, ahead of schedule. After each cable was installed, Boskalis used a jetting ROV to trench the cables into the seabed at a target depth of 1.5 meters. The trenching of the cable was done independently of the cable installation, using a DP2 trenching support vessel (Boskalis 2019).

6.26.2 Export Cable Installation

The total length of the three-core subsea export cable is 24 km with the longest delivered cable length of 12.4 km in one length. Outer diameter of cable is 270mm. Cable weight 92 kg/m.

The following vessels are used to install the export cable of this wind farm. The installation of export cable took approximately 60 days. The installation was too lengthy due to malfunction and error of cable construction '(authors would like to select another case study, but easy access to the information was not provided).

I. C/B Henry
II. P. Lading
III. C/S Cable One
IV. T/B Naja
V. T/B Thor
VI. T/B Odin
VII. S/B Victor

Figure 6-202 NKT cables are loaded on the barge on the Rhine at the factory (Kvarts, et al. 2011)

Figure 6-203 Cable Drum on the CLV (Boskalis 2019)

6.26.3 Time-Cost Analysis of Anholt OWP Cable Retrieval Reverse to the Installation

The results of analysis for retrieval of the cable of Anholt wind farm reverse to the installation is shown in the Table 6-15.

The explanation of the above table is as following:

I. **Sailing:** Sailing is the time that the vessel has to sail from the port to the offshore wind park to commence retrieval of the cable. The distance between the farm and then port is considered 24 km. In addition, it is considered that two vessels are used for this decommissioning. One vessel for retrieval of export cable and the other one for removal of inter array cable. The average speed of sailing is assumed 7.2 knots. It takes about 1.45hours to reach the field. The vessel for inter-array cable has to sail 2 times (inward-outward) and export cable just has to sail one time.

Table 6-15 Result of Anholt Cable Retrieval Reverse to the Installation

Results of Recovery of infield and export Cables (Reverse of Installation)			OWP:Anhot
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Overall Charter ($)**
Figures of Sailing	0.22	0.12%	$ 21,373.29
Figures Inter-Array Cable Removal	120.00	64.76%	$ 9,599,990.40
Figures Export Cable Removal	12.00	6.48%	$ 1,200,000.00
Offloading the Cable	4.08	2.20%	$ 408,333.33
Figures of Unplanned Activities	49.00	26.44%	$ 4,655,462.23
Grand Total	**185.31**	**100.0%**	**$ 15,885,159.26**

II. **Inter Array Cable Retrieval:** It is activity which encompass retrieval of infield cables. The installation of all 111 infield cables took 120 day which the same figure is assumed here including cutting the cable, connecting pull head and retrieval.

III. **Export Cable Retrieval:** after installation of the export cable of this project, it was found that the cable is malfunctioned which result in lengthy operation. In this figure, it is considered that de-burial and retrieval of the cable takes 2 km per day. So, for retrieval of 24 km export cable, the duration is 12 days.

IV. **Offloading cable:** after retrieval of the cables, the cable must be stored in the drum. For installation of the cables of this wind farm, approximately 98 drums were used. In case offloading each of them takes 1 hour, it takes 4.08 days to offload all the drums.

V. **Unplanned Activities:** unplanned activities include three different parameters as following:

   I. Waiting on Weather (WOW) which is 35% of the first 3 steps.

   II. Waiting on client (WOC) plus mechanical breakdown which is 2% of the first 4 steps.

According to this assumption, the CLV goes to stand-by mode due to above-mentioned reasons for 49 days which accounts 26.44% of the entire extraction operation.

Conclusion: if two vessels are used for retrieval of the infield and export cable, the time for retrieval takes about **185.31** days and cost about **$ 15,885,159.26**

It should be noted that in this calculation; the daily charter rate of the CLV is considered **$80 000** for recovery of inter array cables (Minns n.d.).

The daily charter rate of CLV for recovery of export cables is considered **$100 000** (Minns n.d.).

6.27 Designed Tools for Cable Retrieval Onboard the Decom Tools Vessel

The first step to minimize the cost and reduce the CO_2 emission caused by cable retrieval is conduction of this operation by a cheaper and greener vessel than conventional and existed cable laying vessel (CLV). Since these CLV has high charter rate and normally, they are not equipped with green technology, therefore, they have high emission. It means by utilizing CLV for cable extraction operation, objectives of Decom Tools project cannot be fulfilled.

More importantly, from an engineering perspective, it can be argued that there is no need for the tensioner, cable carousel and quadrant for decommissioning operation. Therefore, using the CLV from an engineering perspective is not necessary for decommissioning purpose. Thus, cable extraction can be accomplished by designing some basic tools onboard the Decom Tools vessel. Therefore, for retrieval of infield and export cables into the Decom Tools vessel the following equipment are designed:

1. Chute at the aft of the vessel to prevent damage to the cable.
2. Two winches for pulling the cable from seabed.
3. Pulling head or chines finger along with other accessories to connect the cable to the winch.
4. Cutting tools to cut the cable.
5. Rollers to guide the cable through the desired route onboard the vessel.
6. Hydraulic cable clamp to hold the cable firmly to prevent sliding into the sea.
7. A cabin for cutting the cable as well as office for operator to run the hydraulic tool.
8. Launch and recovery structure at the stern of the vessel for the excavation of the soil.

Figure 6-204 shows that during laying the cable, there will be distance between the touchpoint at seabed and the chute of the vessel which is called layback.

There are a number of parameters which during laying or retrieval, these parameters should be maintained including minimum lay angle, maximum lay tension, minimum layback and so forth. Thus, for the excavation of soil cover at touchpoint location, there exist two options as following:

The first option is to excavate the soil cover by another vessel before retrieval of the cable. This method is not sustainable and is costly since another vessel need to be mobilized just for excavation before the cable retrieval.

I. The second option is to mobilize a self-propelled excavation machine. In this case, the propelled trencher needs to move ahead of cable vessel to excavate the soil. The self-propelled trencher is an expensive machine too.

But another method has been devised by the authors to avoid using another vessel or self-propelled trencher. In the further section, the design is explained thoroughly.

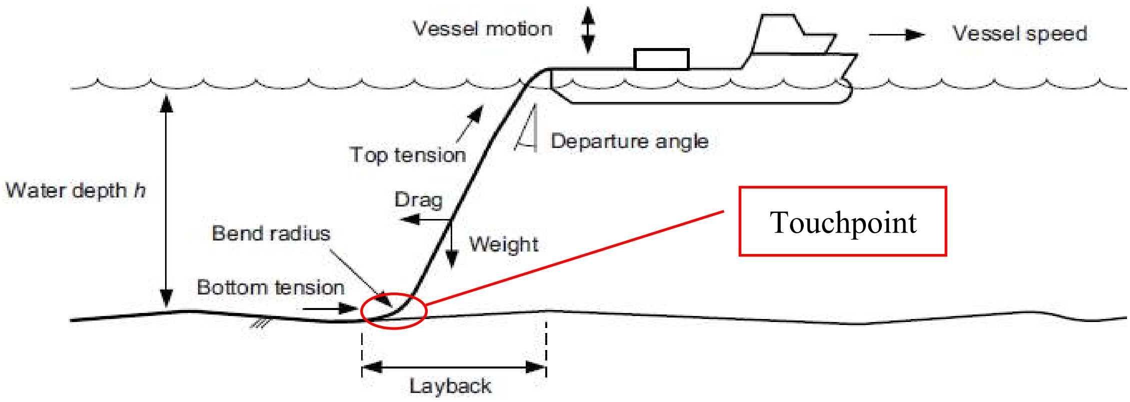


Figure 6-204 Cable Laying Process

With regards to the advantages and disadvantage of soil excavation tools, referring to the section 6.24, the mass flow excavator was the most feasible tool in most of the projects. Therefore, the default tool for excavation of soil cover is mass flow excavator. All the mass flow excavators have launch and recovery system (LARS), but the mass flow excavator can be launched in the distance of maximum 2-3 meter further from the vessel (please refer to the Figure 6-205). The distance of touch point from the chute of the vessel (the location where soil should be excavated) is heavily depending on the water depth, the weight of the cable per meter, the angle of departure and mechanical properties of the cable.

Figure 6-205 LARS of Mass flow excavator (James Fisher and Sons 2014)

The other method of launching the mass flow excavator is using the vessel crane. This method is not sustainable since the crane is energy demanding machine. In addition, all the time the crane operator needs to operate the crane which is not viable if suitable LARS exist.

The proposed method by the authors is to design a LARS structure at the stern of the vessel to launch the non-propelled excavator at touchpoint location in order to excavate the soil cover. This structure should be tiltable, removable and multi-function. The large mass flow excavator has weight of about 5 tones. Therefore, from a structural perspective, the LARS should withstand the weighty machine. This structure has overhead crane to lift and transfer the excavators to the end of the structure. Figure 6-207 shows the designed LARS for deploying the excavator. However, this platform can be used for other application too.

The designed LARS structure for the Decom Tools vessel is something similar to the stinger of pipelaying vessel. The function of stinger is completely different with the designed structure, but from a dimensional perspective, they have similarities. The length of pipelaying vessel's stinger sometimes is about 150 meters. Figure 6-206 shows a stinger of a special purpose vessel. The length of this stinger is about 70 meters.

Figure 6-206 Stinger of the Special Purpose Vessel

The circled pink object in the Figure 6-207 shows the overhead crane of this structure. The overhead crane can move in longitudinal direction in order to lift and transfer the excavator to the desired location. The yellow object is mass flow excavator. By using two mass flow excavators, the excavation time will be reduced considerably which will lead to decrease in the time of cable retrieval. In addition, this structure can be used to lift heavy debris or mattress from the seabed. In case of having any mattress on the cable(s) or any debris, there is no need to use vessel crane to lift them. The objects can be rigged to the winch of LARS of the Decom Tools vessel for the recovery of them. The maximum lifting capacity of this crane/ hoist/ winch is devised to be 10 tones. Therefore, the structure should be designed for 10 tonnes load.

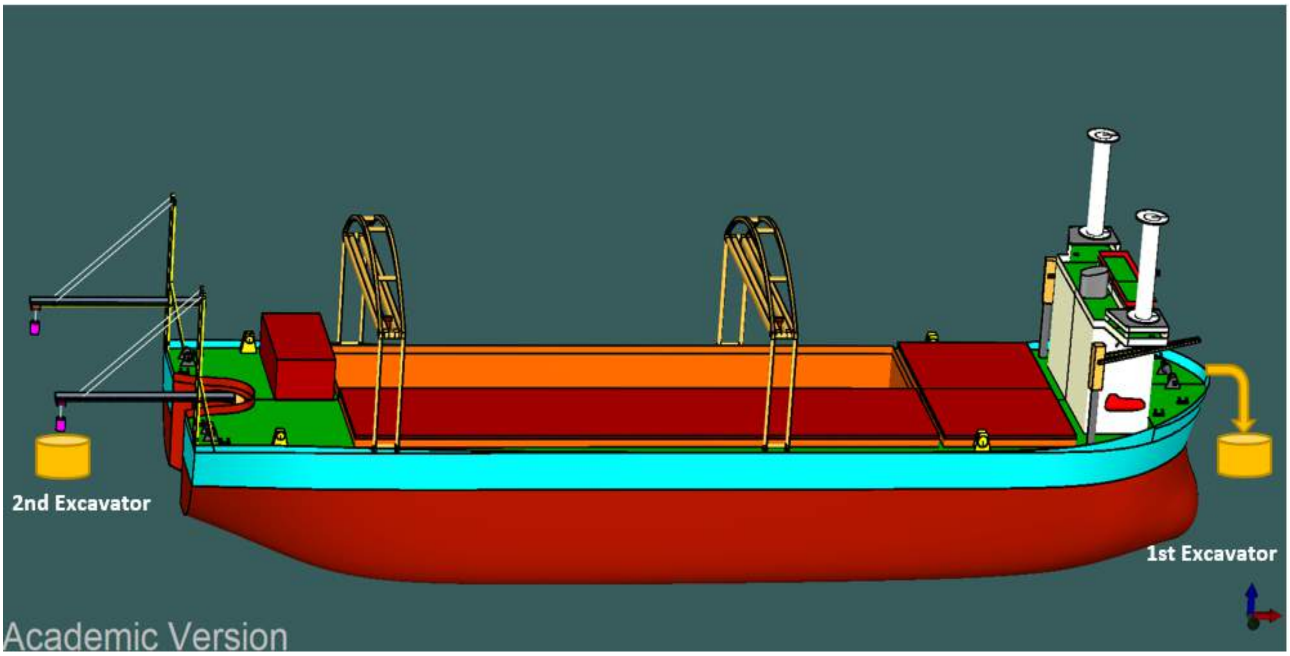


Figure 6-207 Decom Tools LARS Structure (Movable Overhead Crane)

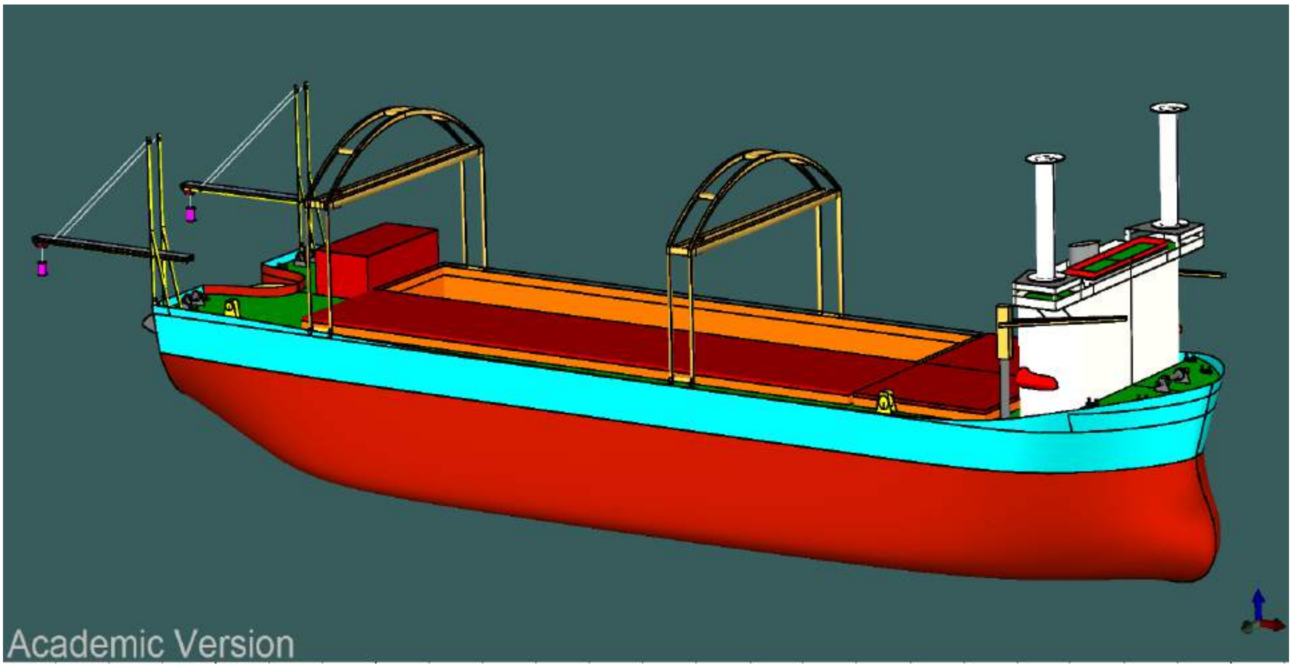


Figure 6-208 Decom Tools LARS Structure (perspective View)

Figure 6-209 shows that the LARS is exactly designed to be on top of the chute. Therefore, there is not necessary to change the location and heading of the vessel for recovery of objects that are placed on the cable or for excavation of soil cover of cables.

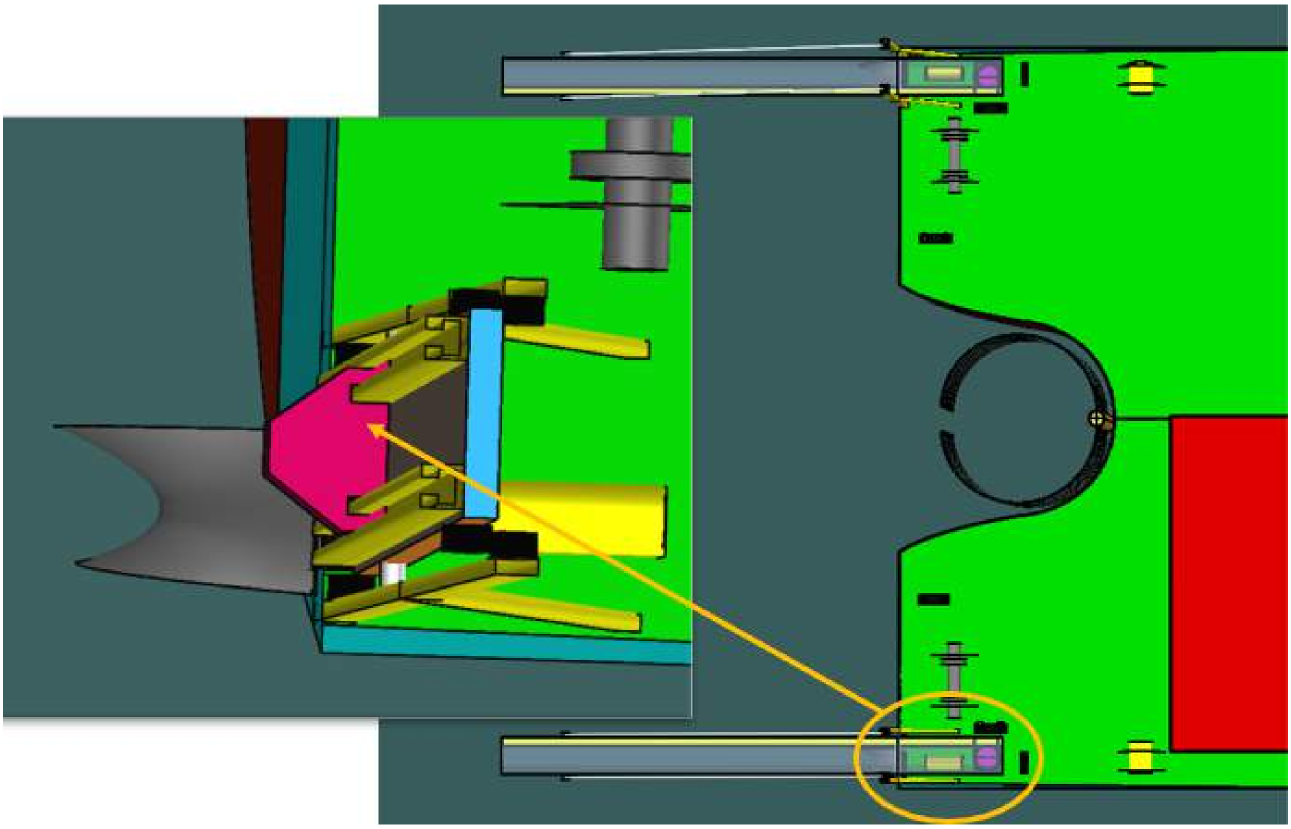


Figure 6-209 Top View of LARS of Decom Tools Vessel

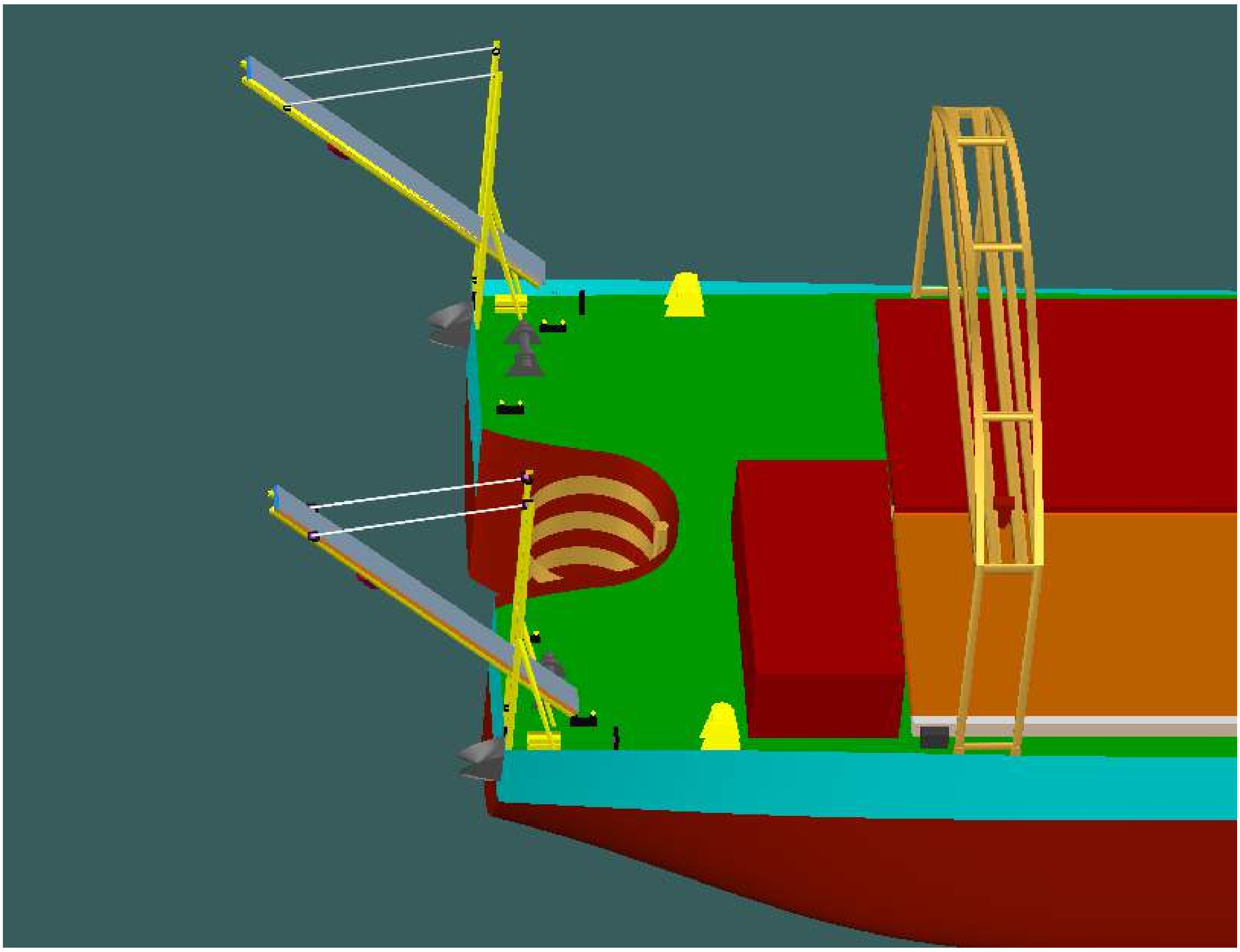


Figure 6-210 Tilting the LARS Structure

The illustrated tiltable LARS of Decom Tools is just a conceptual design. In many cases this structure is not usable such as during sailing, when the vessel is at port or during removal of TP or extraction of MP. In the above-mentioned times, it can be tilted to be protected from probable accident.

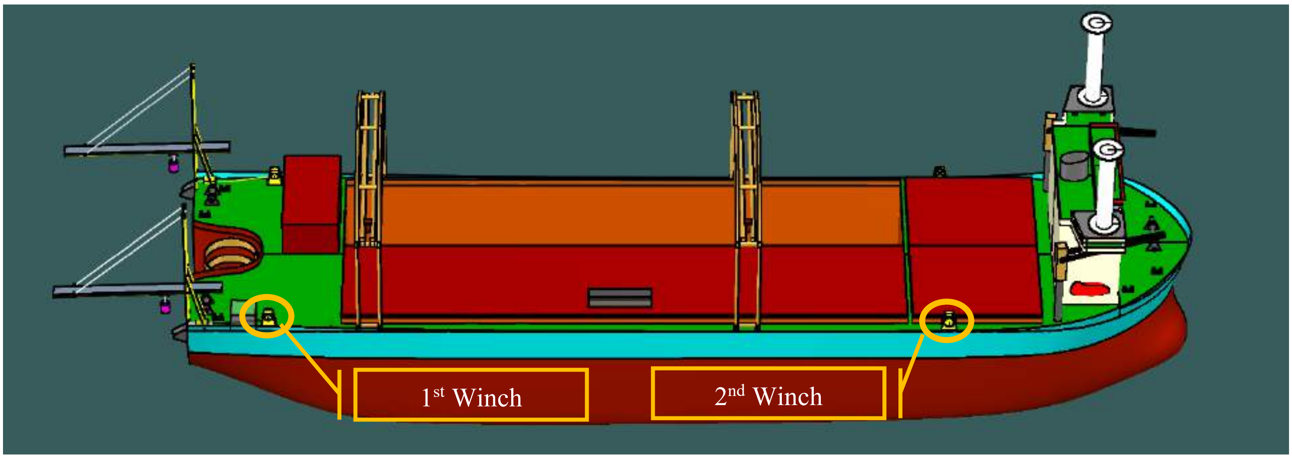


Figure 6-211 Position of LARS after Tilting

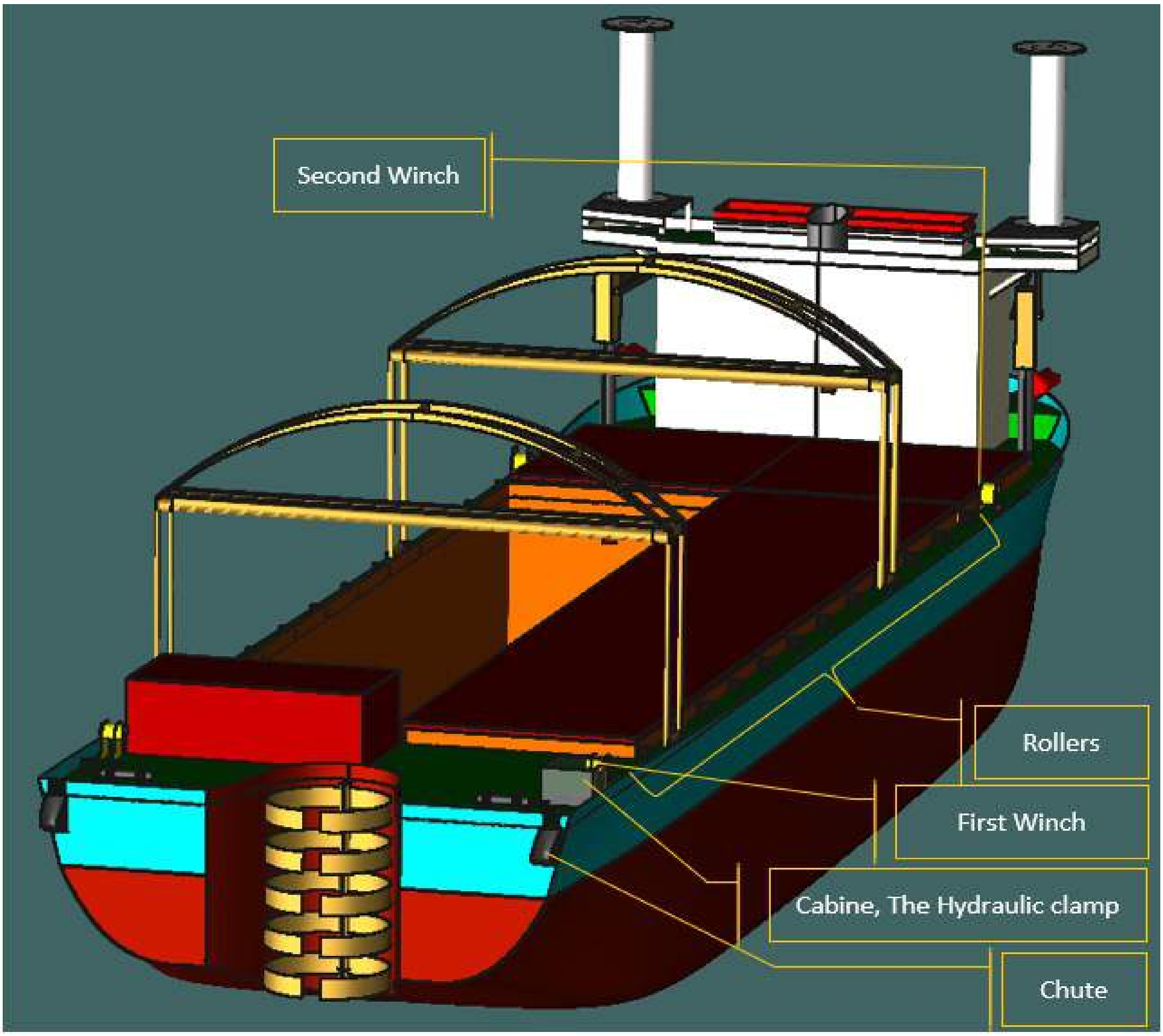


Figure 6-212 Overall View of Decom Tools Vessel & Cable Extraction Tools

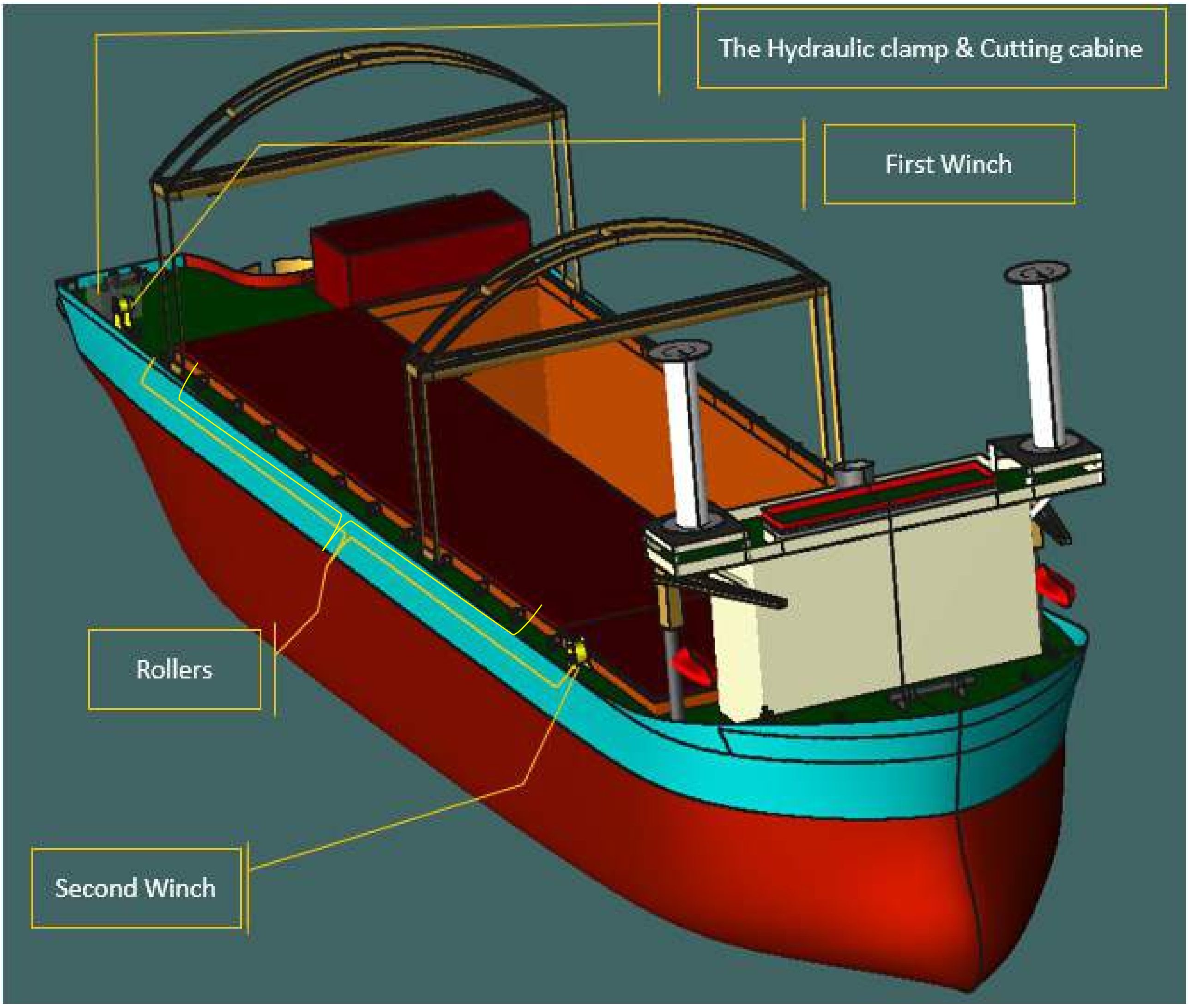


Figure 6-213 Overall View of Decom Tools Vessel & Cable Extraction Tools

Figure 6-214 Guiding Roller onboard CLV (Jan De Nul Group 2016)

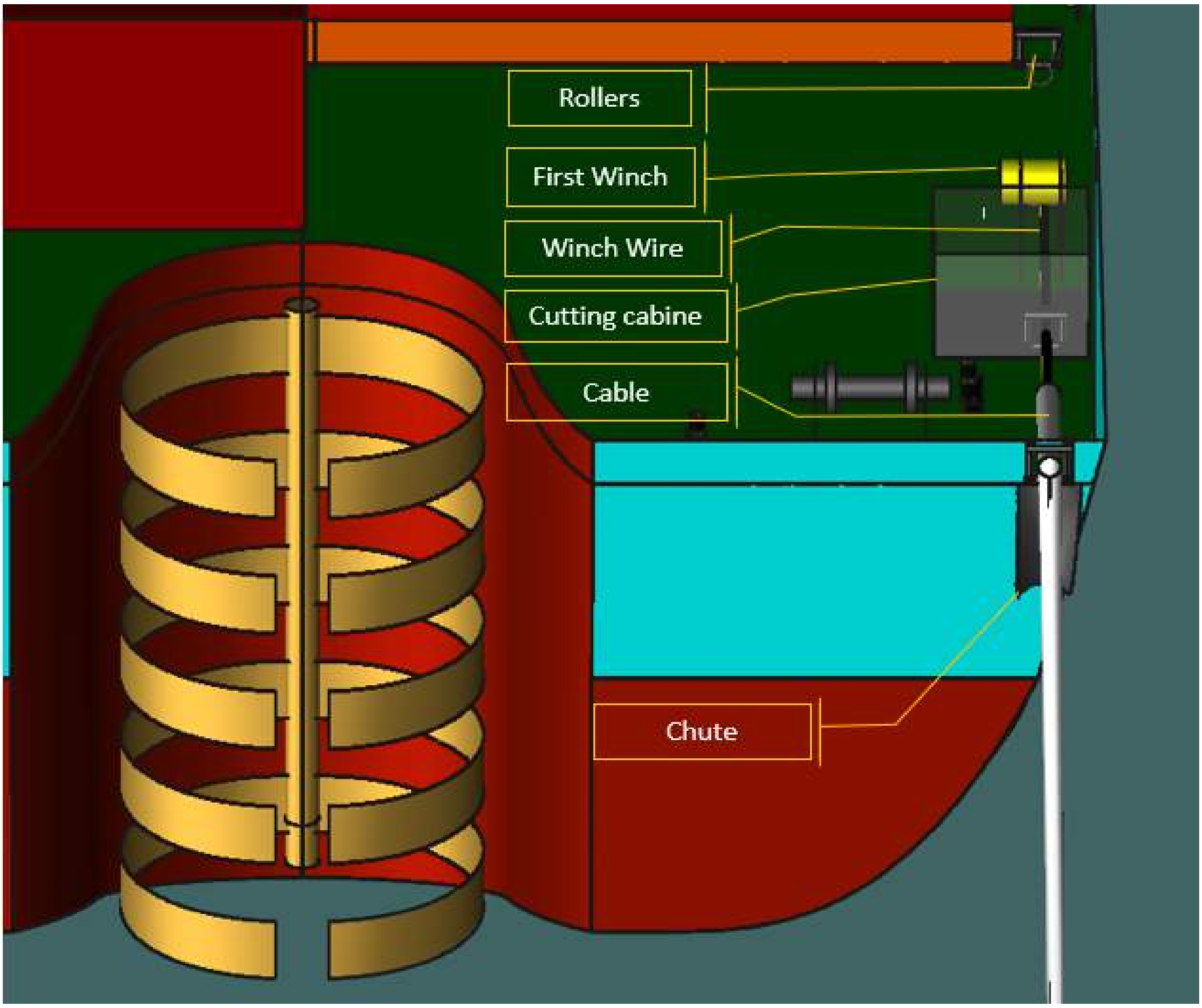


Figure 6-215 Chute, Hydraulic Cable Clamp and 1st Winch

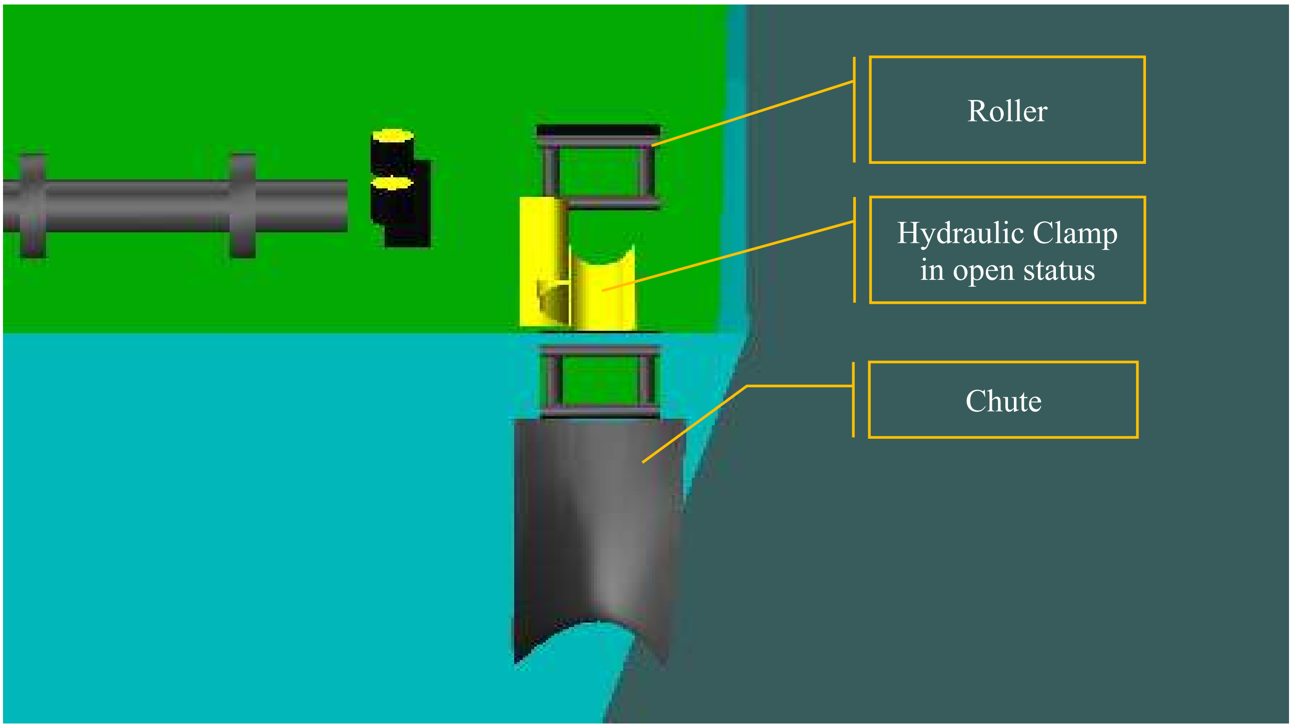


Figure 6-216 Chute, Hydraulic Clamp and Rollers

Figure 6-216 shows the hydraulic clamp for holding the cable tightly. This clamp can be used when the vessel is retrieving the cable or when the cable cutting should take place.

In the next section, the procedure to retrieve the cable is explained with the required drawing in order to make it easy for reader to follow.

6.27.1 Cable Cutting Strategy

The cutting tools which is suitable to cut the cable is shear cutting tools. There are various sizes of shear cutting tools in the market. This tool is suitable since the cutting speed is so high, it is simple to be operated and also does not produce any dust during cutting which means no dust will be spread over the atmosphere. Therefore, it not detrimental for the operator and environment.

Figure 6-219 and Figure 6-220 shows the shear cutting tools during cutting 273mm pipe with 19mm thickness. The cutting took 28 second just. Also, for cutting thinner cable, mobile cutter which is powered by hydraulic is available (please refer to Figure 6-217 and Figure 6-218).

One of the problems of mobile cable cutting tool is that they are designed for the armoured cable with max cutting Ø330mm. Therefore, in the Decom Tools vessel, we proposed the mobile cutting tools for small diameter of cable and shear cutting tool for large diameter of armoured cable.

Figure 6-217 Cutting Cable with Mobile Cable Cutter (Extreme Machine 2017) (Extreme Machine 2017)

Specifications		
article number		100.522.150
model		HCC 150
cutter type		power cable
short description		Cable Cutter
max. working pressure	bar/Mpa	720 / 72
max. jaw opening	mm	145
capacity Ø ground cable	mm	140
capacity Ø telephone cable	mm	145
capacity	kN/t	203.6 / 20.8
required oil content (effective)	cc	452
return type		hydraulic
weight, ready for use	kg	24.9

Figure 6-218 Technical Specification of Mobile Cable Cutter (Holmatro n.d.)

Figure 6-219 Shear Cutting Tool (James Fisher Offshore 2019)

Figure 6-220 Shear Cutting Tool (James Fisher Offshore 2019)

The existing cable recycling facilities can separate the conductor and insulation of 1 meter of the cable. It means that the cable should be cut for every 1 meter in order to peel off the conductor and other layers. The cutting into small pieces (1 meter) should be performed onshore since it not optimum solution to cut the cable to the length of 1 meter offshore. In the Decom Tools vessel, it is designed to cut the cable and place them inside the container in order to be carry them easier both onboard the vessel as well as easier discharging of them. To achieve this, the cables should be cut to the length of the container.

The dimension of 40 feet containers is as following:

- Length 12.031m
- Width: 2.348 m
- Height: 2.69 m

Therefore, the cable should be cut into length of 12 m.

6.28 Cable Extraction Procedure

A procedure for cable extraction/retrieval with Decom Tools has been devised as following:

The sequences of the procedure are explained as following:

1. In the pre-decommissioning phase, the cable should be cut from J/I tube (it can be J/I tube of WT or OHVS). Figure 6-221 shows different types of J/I tubes, and the red line shows the possible points where the cutting can be done. The cutting can be undertaken either by ROV or diver. Figure 6-222 shows a diver close to the bell mouth of a J tube.

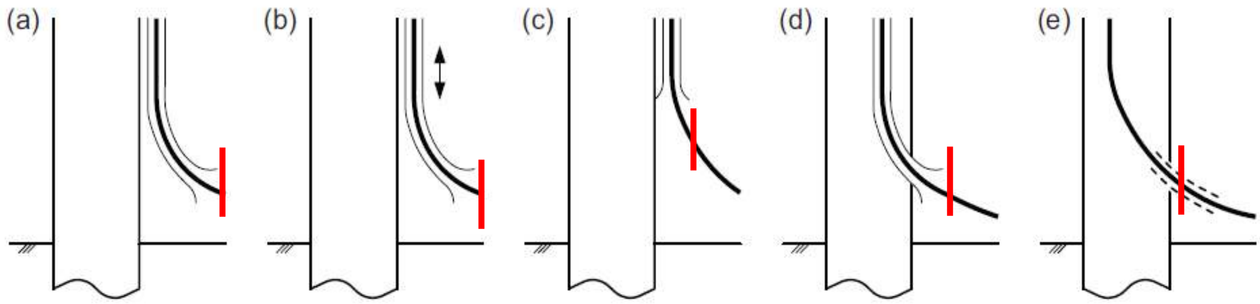


Figure 6-221 Different Types of J/I tube (DNV.GL 2016)

2. If cutting of the cable took place in the pre-decommissioning phase, then buoy should be connected to the end of cable. If the cable cutting undertake during retrieval, no need to install the buoy(s).
3. The cable head plus Chinese finger should be connected to the cable end (this activity can be done during pre-decommissioning phase or during removal phase, both are possible).
4. The load cell should be connected between the winch wire and the cable pull head to monitor the tension on the cable during retrieval.

5. The wire of first winch should be lowered into the seabed for connection to the pull head and Chinese finger which are connected to the cable.
6. The first winch should pull the cable to the deck (this can be performed by vessel too, vessel moves, and the cable is pulled).

Figure 6-222 J-Tube Bellmouth (Kurdve 2016)

7. After pulling of the cable into the deck, the hydraulic clamp should be closed and hold the cable firmly.
8. The pull head should be connected to the second winch.
9. The hydraulic clamp should be opened, then the cable will get released.
10. The second winch should pull the cable for 120 meters (again can be pulled by vessel).
11. The clamp should be tightened again in order to hold the cable.
12. The cutting should be carried out by one of the mentioned cutting tools (now the cable is cut at the length of 120 meter).
13. The cut cable can be shifted by crane to the top of hatch covers for further cutting.
14. The pull head and Chinese finger should be connected again to the cables end.
15. The cable should be pulled again by the first winch.
16. Meanwhile, the cut section of cable (120 meter) should be cut into the section of 12 meter (10 cut per retrieval should be conducted).
17. The 12 meters cable should be loaded inside the racks or strapped.
18. The racks or bundle of cables should be loaded inside container.
19. The above sequences should be repeated until full extraction of the cables.

Figure 6-223 shows that the wire of first winch get ready to be lowered into the sea in order to connect the pull head for the first time to the first winch. Between the pull head and the winch, all the time load cell should be installed in order to prevent breaking of the cable.

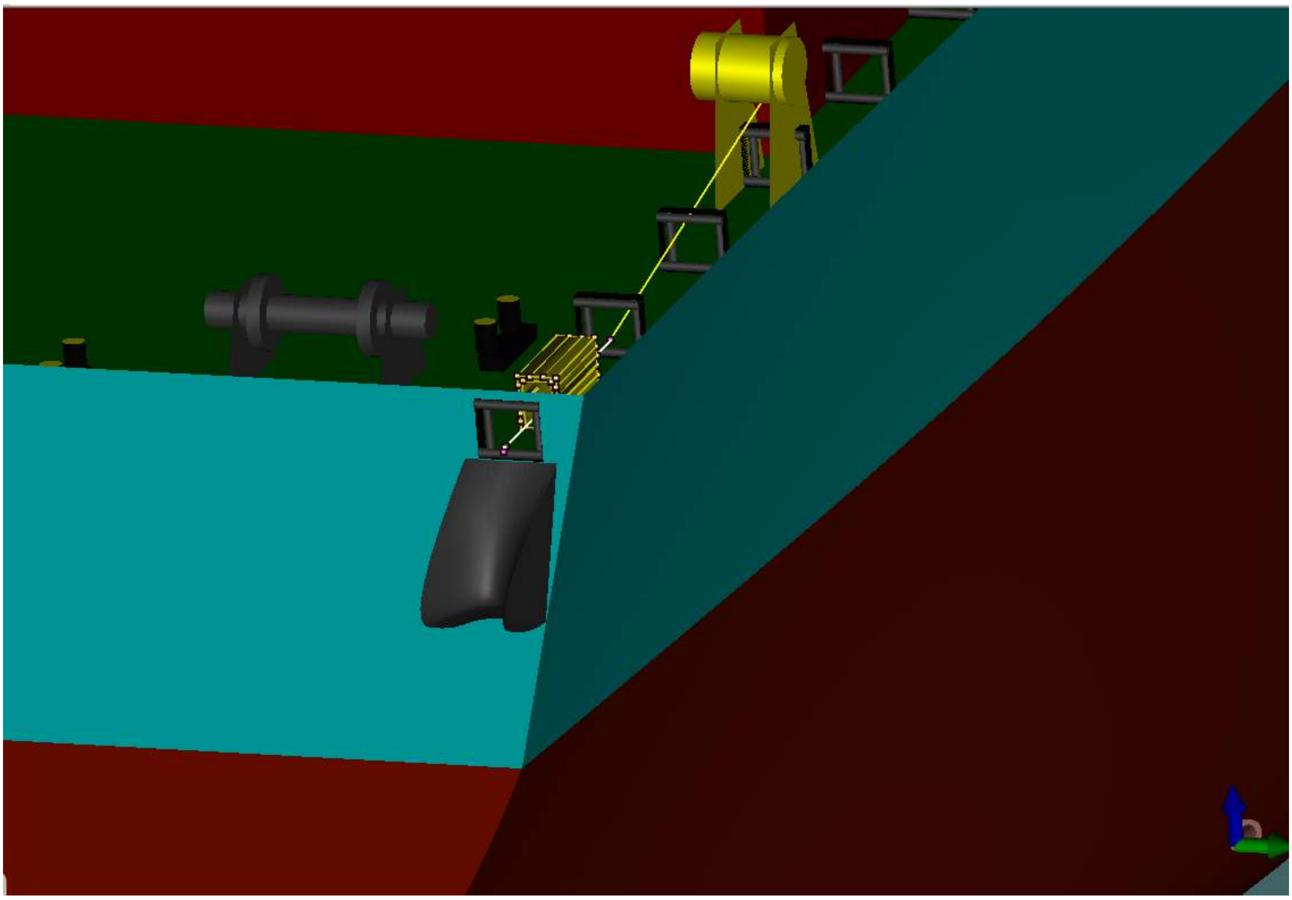


Figure 6-223 Lowering the wire of winch to the seabed

Figure 6-224 to Figure 6-224 show that wire of first winch is connected to the laid cable on the seabed and is pulled to the Decom Tools vessel. This operation may need diver. Depending on the water depth and duration of connection, suitable diving system[77] need to be mobilized.

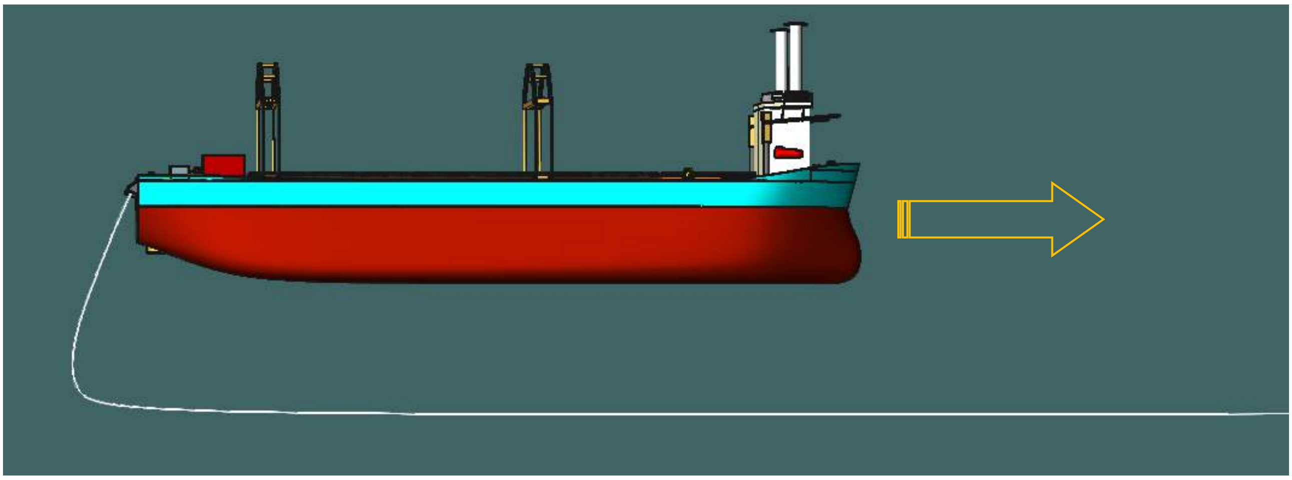


Figure 6-224 Heading of the vessel During Cable Retrieval

[77] Diving can be air diving, mixed diving and saturation diving system.

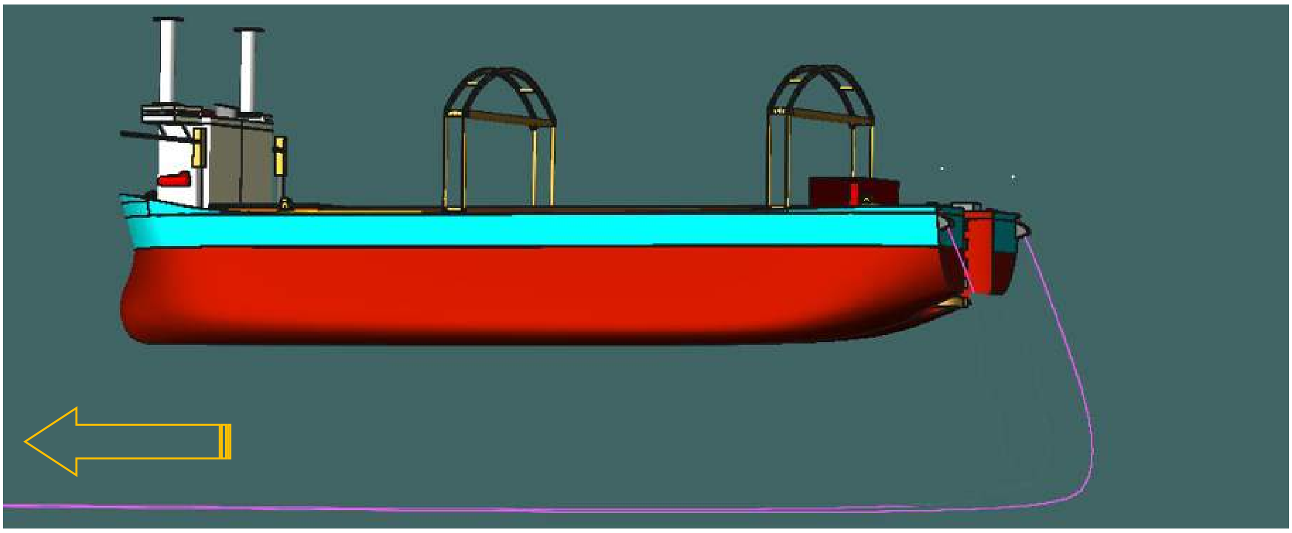


Figure 6-225 Heading of the Vessel with Respect to the Cable

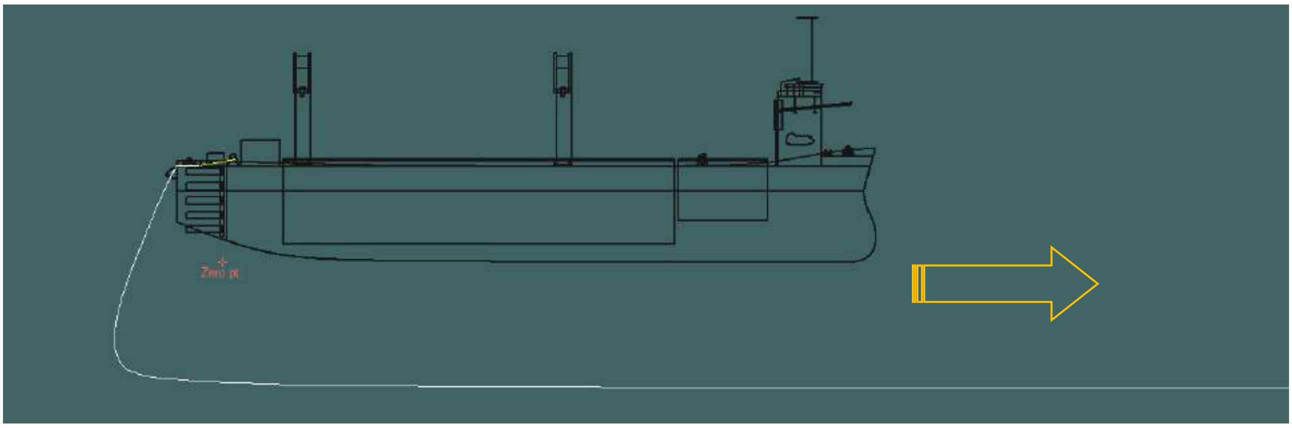


Figure 6-226 Cable is pulled to the deck by first winch

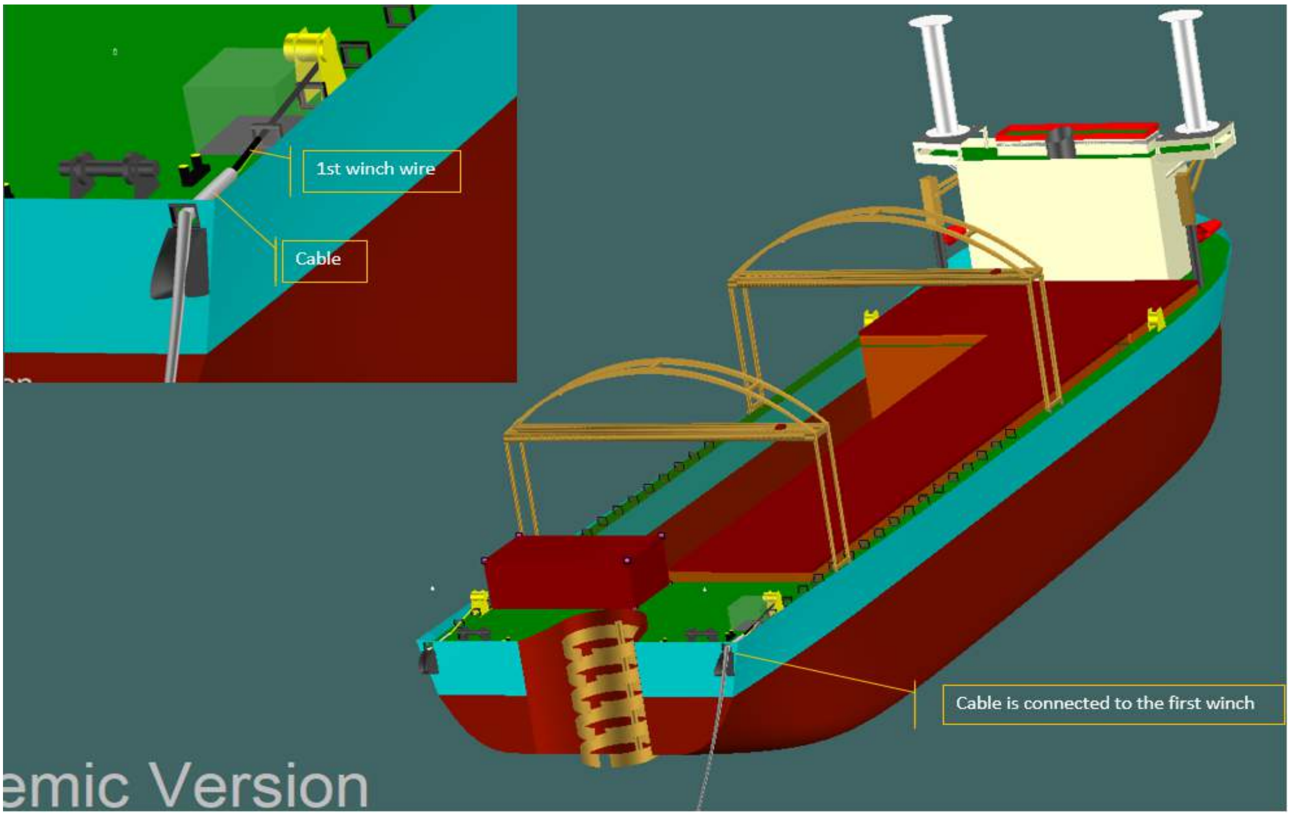


Figure 6-227 Cabled is pulled by first winch onto the deck

As soon as retrieval of the cable onto the deck, the hydraulic clamp should be closed and should hold the cable firmly. Figure 6-228 shows that the hydraulic clamp holds the cable tightly.

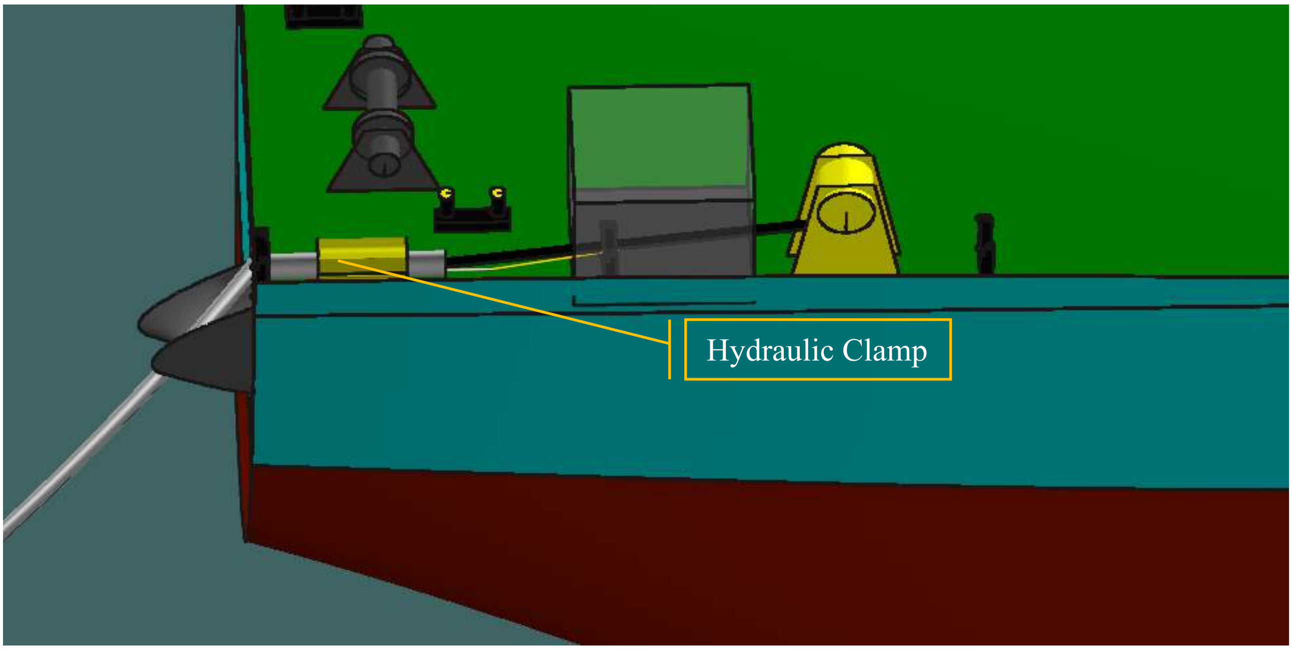


Figure 6-228 Hydraulic Clamp Tightened the Cable Firmly

Figure 6-229 shows that the wire of second winch (the black line is winch wire) is released towards the first winch to take over the pull head along with cable from the first winch.

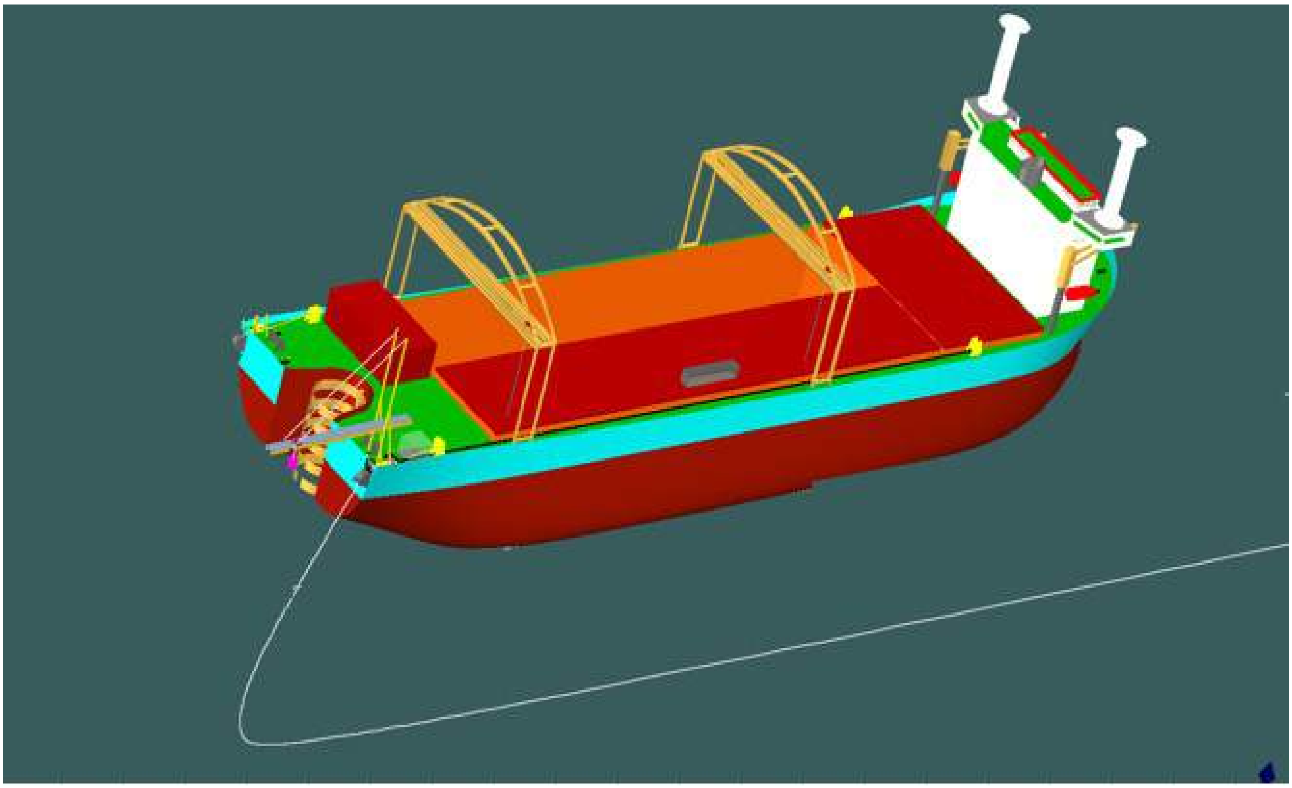


Figure 6-229 The Wire of second winch is released in order to take over the cable head from first winch

Figure 6-231 shows that the cable is pulled by the second winch for the length of 120m.

Figure 6-232 shows that the cable is cut into the length of 120m.

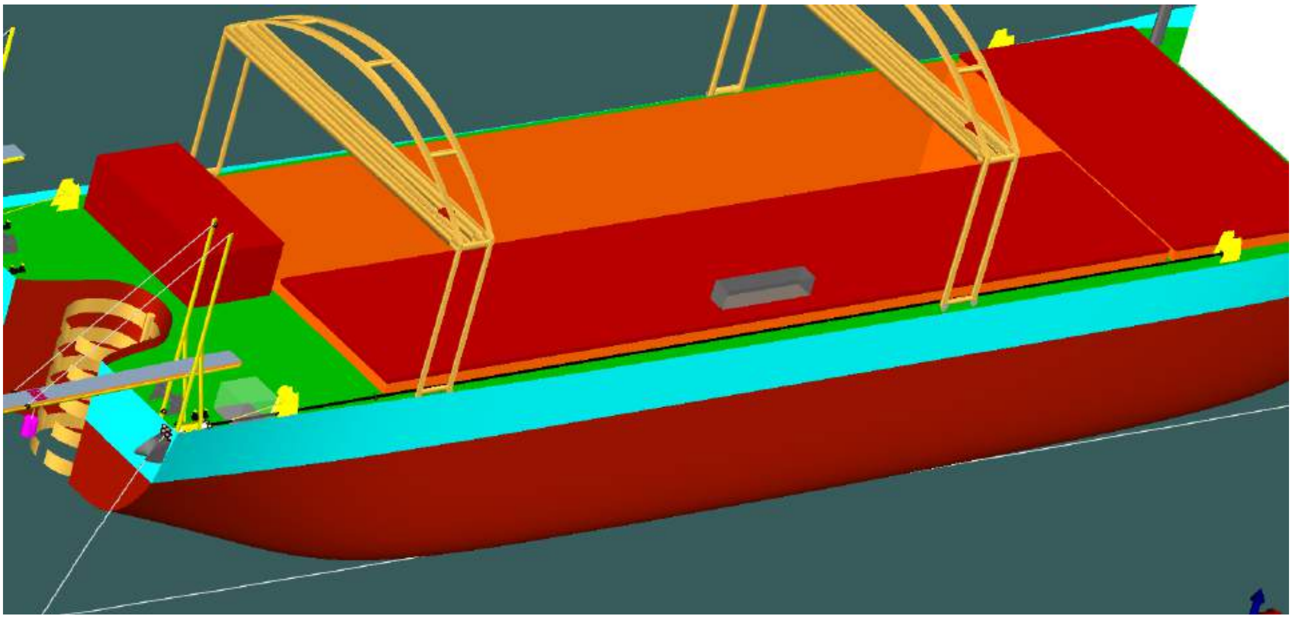


Figure 6-230 The Wire of second winch is released in order to take over the cable head from first winch

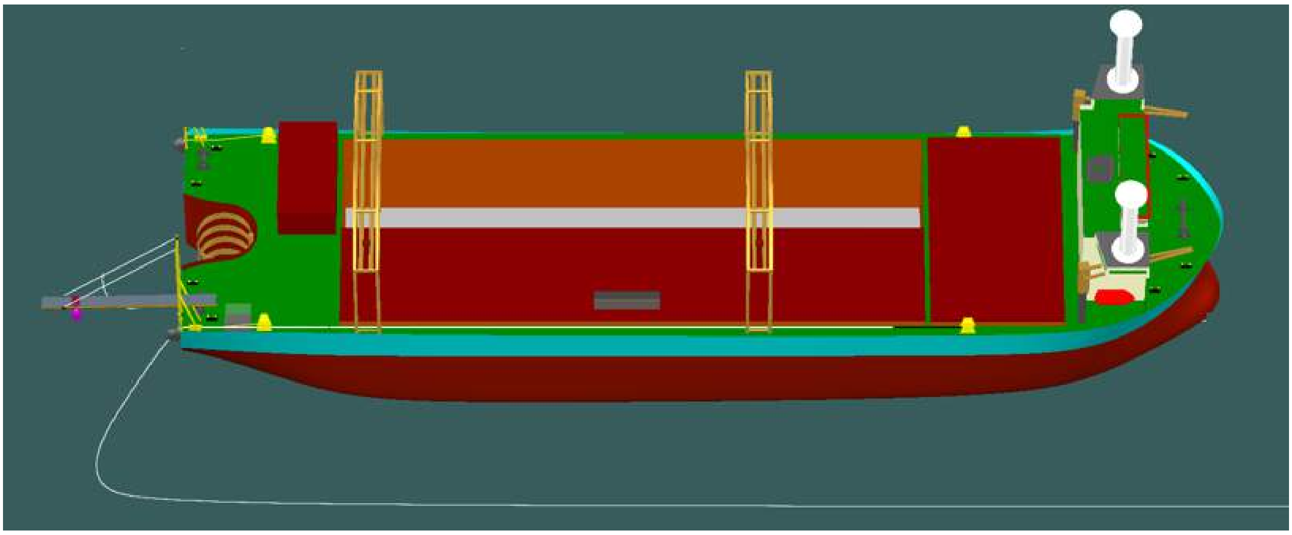


Figure 6-231 The second winch pulled the cable to the final location, ready for cutting

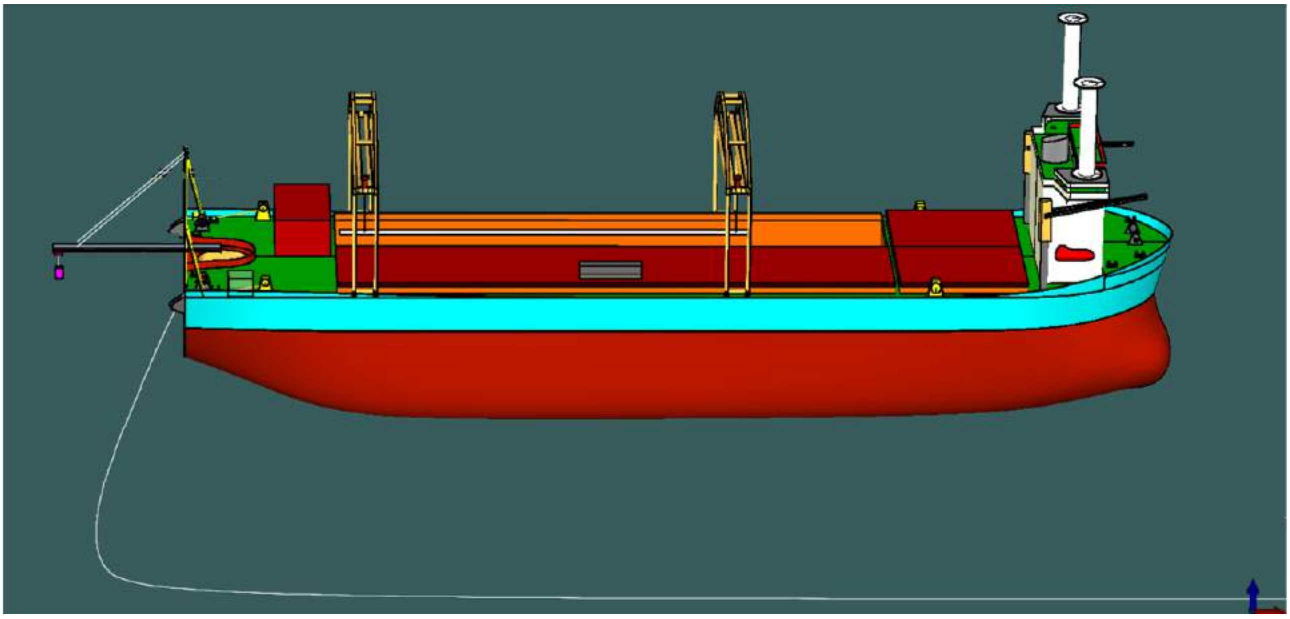


Figure 6-232 The cable is cut to the length of 120m

After cutting the cable to the length of 120m, the cable should be loaded on the adjacent hatch cover in order to be cut into the length of 12 meter. Figure 6-233 and Figure 6-234 show lifting the cut cable and placing them on the hatch cover for further cutting and bundling process.

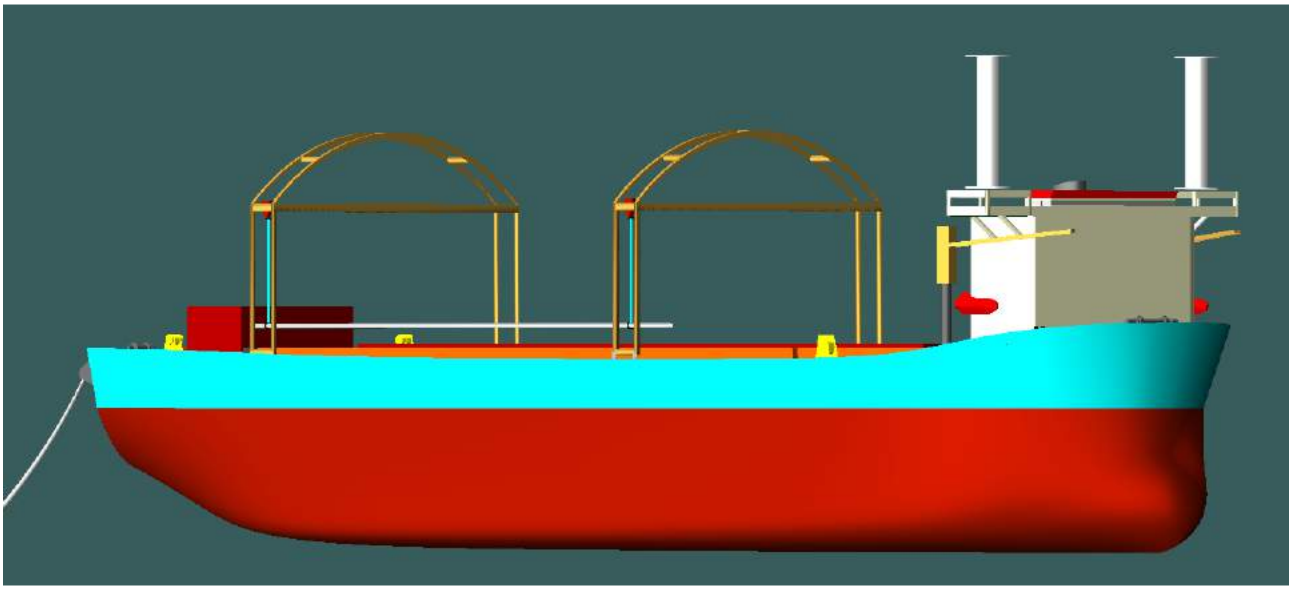


Figure 6-233 The cable is cut and lifted to be loaded on top of the hatch cover

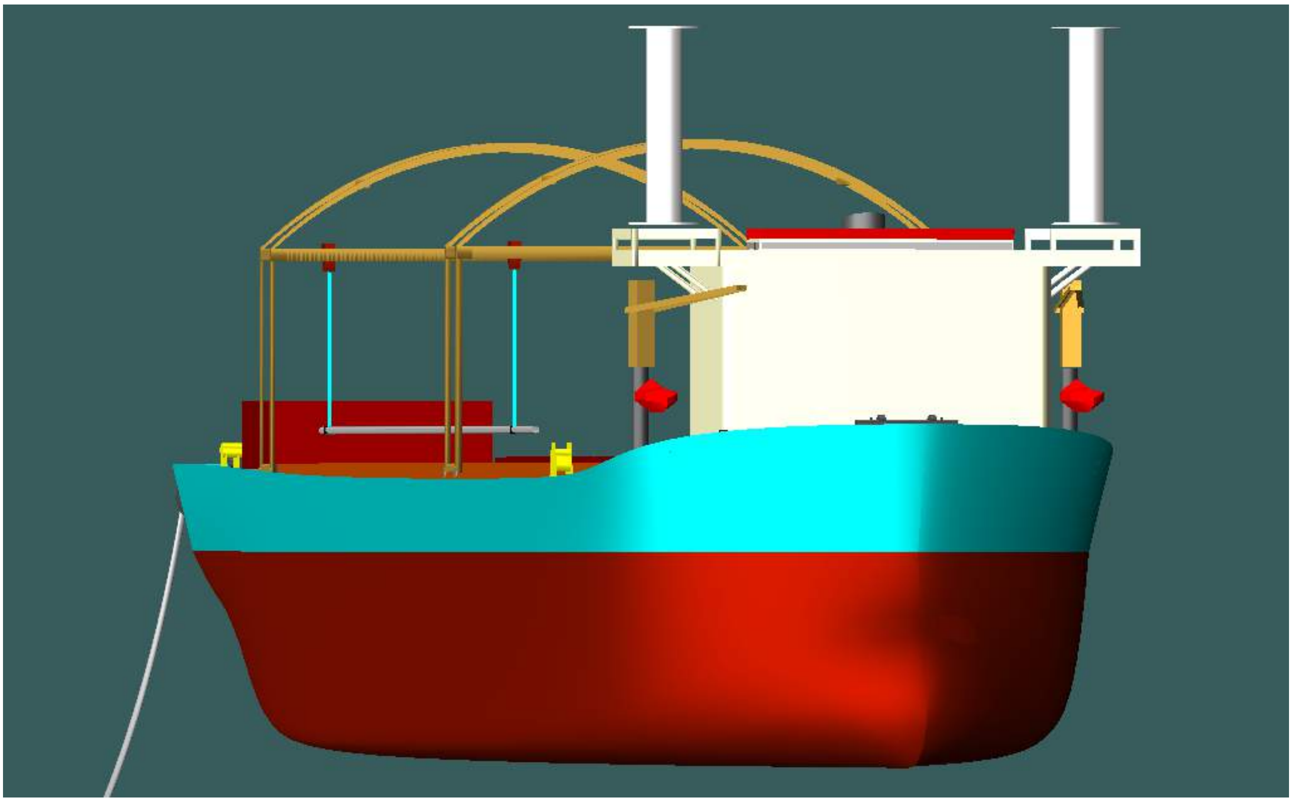


Figure 6-234 The cable is cut and lifted to be loaded on top of the hatch cover

After cutting the cables into the length of 120m, they need to be marshalled inside racks. Strapping the cables instead of rack is another option. Figure 6-236 shows how the drill pipes are marshalled inside the racks. The cables also can be marshalled the same as drill pipes for easier loading and transportations. After this stage, the cables can be loaded inside the container.

Figure 6-235 shows that container which cables need to be loaded inside are placed on top of hatch cover on the port side. The 120 m cable need to be cut into the length of 12 meters in order to be loaded inside the container for easier offloading, transportation and further recycling process.

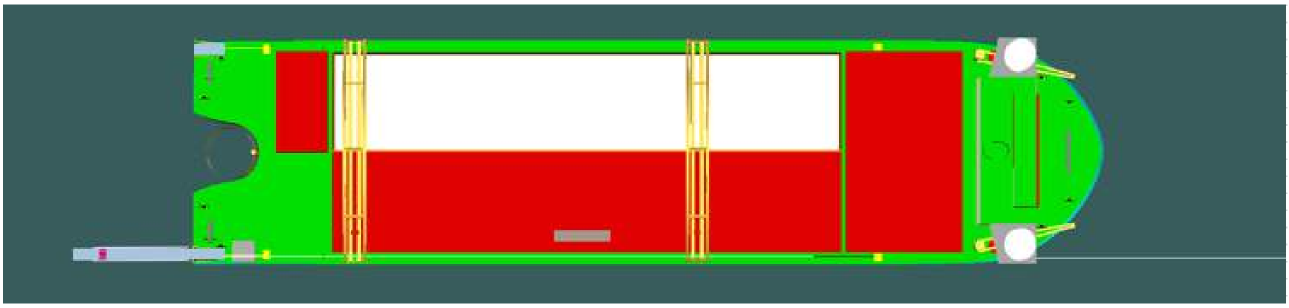


Figure 6-235 Container to Load the Cable on Top of Hatch Cover

Figure 6-236 Marshaling the Drill Pipes

Figure 6-237 Bundle of Pipes

Figure 6-236 shows how the drill pipes are marshalled inside the rack and Figure 6-237 shows how the pipes are bundled by strapping. These two methods seem the best option for marshalling the cable after cutting into the length of 12 m.

Figure 6-238 shows that 90 pieces (10 x 9) of cables with diameter of 25 cm are loaded inside the high cube 40 feet container. Cables with diameter of 25 cm and overall length of 1080 meter can be loaded inside the container. The wight of the cable with this cross section is about 18 kg/m. It means that the overall weight of cable will be 19440 kg. A 40-foot container's empty weight is 3750kg and can be loaded to a maximum overall weight of 29 tons (26300kg) (iContainers 2013). Therefore, the lifting limit does not exist for this cross section. For the rest of cross section, the specification of the cable should be checked.

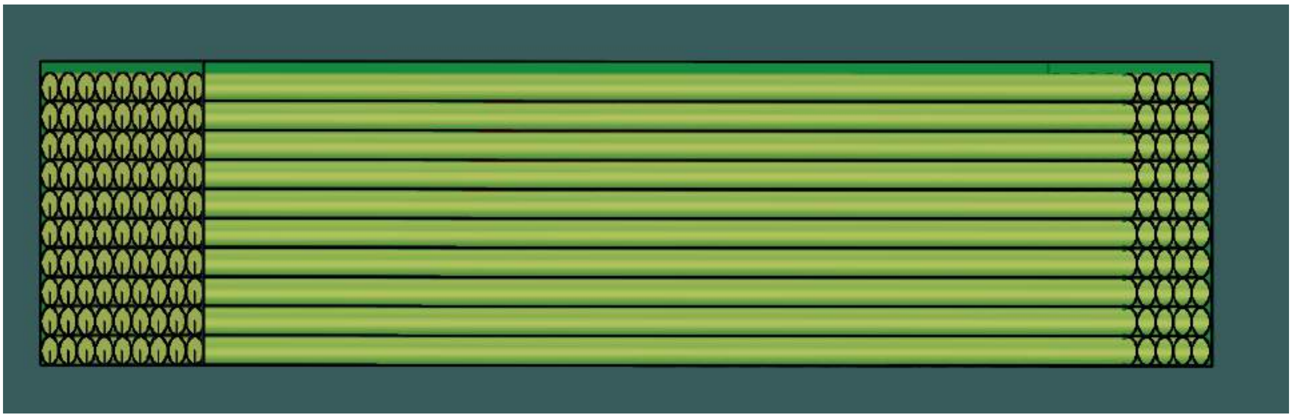


Figure 6-238 Cables are loaded inside the container

In case the diameter of cable is 50 cm, 20 pieces (4 x 5) of 12-meter cable with overall length of 240 meter can be loaded inside the container.

In case the diameter of cable is 70 cm, 9 pieces (3 x 3) of 12-meter cable with overall length of 108 meters can be loaded inside the container.

After loading the cables inside the containers, they can be loaded inside the holds. Figure 6-239 shows one container is loaded inside the hold number 2.

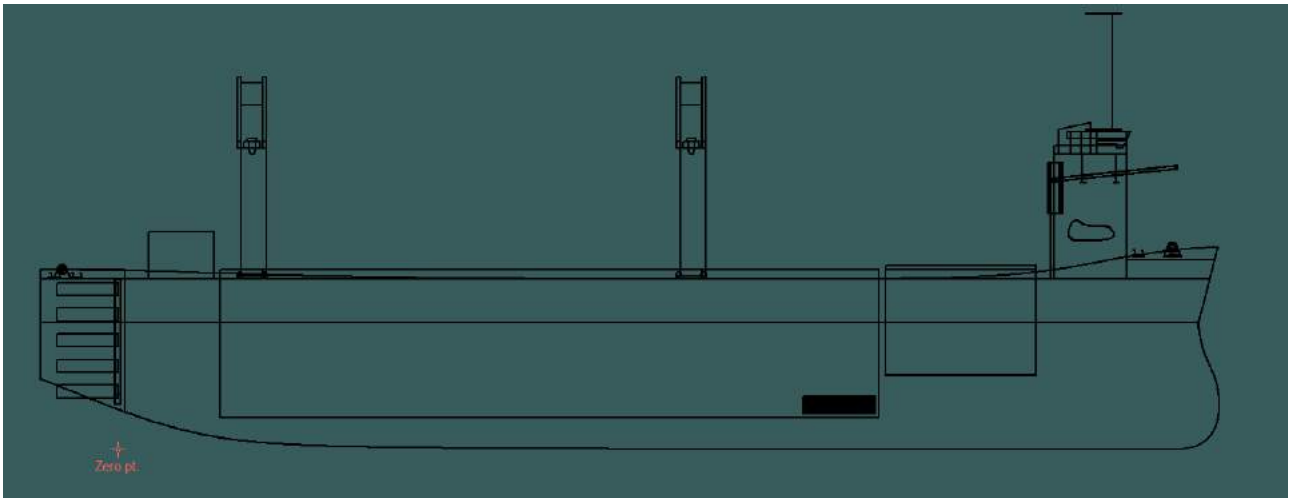


Figure 6-239 Container is Loaded inside the Hold

Based on the dimension of holds and dimension of container, just 1056 numbers of container can be loaded inside the holds. It means 1140 km cable with diameter of 25 cm can be loaded inside the holds. It makes the transportation so cheaper.

Therefore, by execution of the above-mentioned stages, cable can be extracted sustainably, inexpensively and conveniently. Furthermore, it can be cut into small pieces for easier handling, transportation and recycling. It should be noted that riggers can cut the cable into smaller pieces on top of the hatch cover for easier onshore transportation. Given the fact that the cable extraction takes time with respect to cutting operation, so cutting on the top of hatch cover into the length of 12 meter can be undertaken as a meanwhile activity.

Thus, cable extraction can be done easily with some basic machines and simple methods. Therefore, there is no need for tensioner, carousel, special team, cable highway etc.

6.29 Advantage of Cable Retrieval with Decom Tools Vessel

There are many advantages to retrieve the cable with the Decom Tools Vessel which are listed in below:

1. The Decom Tools vessel is green vessel, which is equipped with battery, solar system and Flettner rotor. In addition, the primary fuel is LNG. As a result, the emission in this vessel is much less than existing CLV in the market. In particular, during cable laying operation, the engines are not working in the optimum load, therefore, implementing the vessel with batteries can reduce the fuel consumption as well as mitigate the CO_2 emission significantly (batteries can be charged when the engines do not work in optimum load, then the batteries can feed accommodation around the clock).
2. Despite that the Decom Tools vessel is equipped with DP system, but the authors recommend operating the Decom Tools vessel with mooring system (position anchors) during recover of export cables in order to reduce the fuel consumption and emission. Calling the given load profile under section 5.22.1.35.22.1.3 operating the vessel on the position anchor winches demand over 70% less energy than the DP mode approximately. Regardless of operating the vessel on DP or mooring winches, the retrieval of export cable is a time-consuming operation since one of the bottlenecks is excavation operation. Considering the fuel consumption and emission as well as high wage of DP officers, retrieval of export cable on position anchor winch contribute to achieve the main targets of Decom Tools Project which is cost reduction and emission mitigation. However, due to high manoeuvrability of the vessel on DP, it is recommended to run the vessel on DP for retrieval of the inter array cables.

3. In the previous section it is described that the day rate of CLV is high due to mobilization of DP officers and special equipment onboard the vessel such as tensioner, carousel quadrant etc. Retrieval of the cables can be conducted with basic tools and lower wage crew. The proposed method and procedure of cable retrieval by Decom Tools vessel can lead to attaining the objectives of Decom Tools project during the course of this phase of the project due to low emission and low charter rate.
4. As it was described in previous section, one of the most challenging part of decommissioning of cables is handling of the cables. It was shown that during installation of Anholt OWP cables, approximately, 94 numbers of cable drum were shipped from Germany, Cologne to Grena, Denmark with different vessel and train. Even after removal of the cable, it becomes more challenging since the cables are cut (for example, infield cables) therefore, handing of them is so challenging. By cutting them into small length and stowing them inside the container, the problem of cable handing will be solved. Also cutting them will reduce the time and cost of onshore cutting operation. It was shown that just 1140 km cable with Ø250mm can be stowed inside the holds.
5. One of the major activities is excavation of cover soil which is laid on top of the cable. It was stated that the soil excavation should be done by another vessel or by self-propelled trencher which both scenarios incur extra cost to the project. By designing the LARS structure at the stern of the vessel above the chute, it is possible to deploy the mass flow excavator from that LARS to excavate the soil cover. In this case the soil cover excavation can be done in the same campaign of cable retrieval without any extra cost and any extra emission.

6.30 Time-Cost Analysis of Anholt OWP Cable Retrieval with Decom Tools Vessel

An algorithm has been devised to calculate the retrieval duration, fuel consumption, cost and the emission resulting from cable retrieval with Decom Tools Vessel. In order to verify the results, a case study is selected. To compare the results of cable retrieval, reverse to the installation method with retrieval with Decom Tools vessel, the same wind farm- Anholt wind farm- is selected. The inter array cables in this field has three different cross sections which in this analysis the cross section of 25cm is considered as average cross section. In overall the inert array cables assumed to have length of about 69.74 km. The length of export cable is considered 28.8 km. Authors did not find the accurate information regarding the diameter of export cable and the length of it. However, it is considered that export cable has dimeter of 70 cm and length of 28.8 km.

The results of time-cost analysis are shown in the Table 6-16

Table 6-16 Result of Anholt Cable Retrieval with Decom Tools vessel

Results of Cable Retrieval with Decom Tools Vessel in Decommissioning of				Anholt /Denmark
Summary of Major Activities	**Duration (Day)**	**Portion (%)**	**Daily Charter Rate ($)**	**Overall Charter ($)**
Figures of Sailing	0.07	0.04%	60000.00	$ 4,635.13
Figures Preparation	47.19	28.77%	65000.00	$ 3,067,187.50
Figures Inter-Array Cable Removal (DP)	55.50	33.84%	70000.00	$ 3,885,000.00
Figures Export Cable Removal (PAW)	14.40	8.78%	65000.00	$ 64,000.00
Offloading the Cable	3.46	2.11%	60000.00	$ 07,500.00
Figures of Unplanned Activities	43.39	26.46%	65000.00	$ 2,820,542.91
Grand Total	**164.01**	**100.0%**		**$ 10,848,865.54**

The interpretation of above table is as following:

I. **Sailing:** The time that the vessel has to sail towards the field. In this analysis, it is planned that Decom Tools vessel retrieve the cables both in field and export cables. Therefore, the vessel has just reach to the field. The return is calculated as duration of export cable removal. The maximum speed of the vessel 12.62 knots which here the result is based on 60% of maximum speed which is 7.57 knots. However, in the reserve to the installation method, 10 vessels were used to lay and bury the cables.

II. **Preparation:** As it stated before, the cables are cut into the section of 120 meters. It means after cutting the cable, the pull head plus Chinese finger should be connected to the cable end. The time for cutting the cable as well as installation of pull head and chines finger for each section is considered 1.5 hours. The cutting of each of the infield cable should be performed 5 times since the distance of WT is 600 meters. Also, the export cable has length of 28.8 km which 240 times need to be cut. In overall, the export and all infield cable should be cut 755 times which will account 47.19 days.

III. **Inter Array Cable Retrieval:** as it stated before, it is proposed to run the Decom Tools vessel for retrieval of the infield cables in DP mode. Therefore, in this operation the charter rate of 70000$ has been assumed. It is assumed that for connection of the winch to each infield cable diver should be deployed. The connection of pull head plus Chinese finger to the end of the cable is considered 3 hours. Also. 9 hours is considered just for retrieval of each infield cable. In general, the time of connection of winch to the cable plus cable removal for each infield cable is considered 12 hours excluding cutting operation. Having considered that 111 numbers of infield cable is exited in this wind farm, the overall removal takes about 55.5 days.

IV. **Export Cable Removal:** for removal of export cable by Decom Tools vessel, due to load profile and consumption of the vessel, it is proposed by the authors to run the vessel and maintain its position by deploying position anchor winch (PAW). Furthermore, 2 mass flow excavators are planned to be used for cable retrieval which in this case deburial will not be a bottleneck. Given these facts, the rate of cable removal is considered 2km per day. With this rate, the removal of export cable will be completed in 14.4 days.

V. **Offloading the Cables:** In the proposed procedure of cable removal, after cutting the cable, they should be stowed inside the container for easier discharging and handling. During the installation of this wind farm, 98 numbers of drum were transported to the field by train and different vessels. In this case, the overall length of infield and export cables is about 98.54 km which can be loaded inside 332 numbers of container. Discharging container from vessel to the port is so convenient fast and safe operation. Discharge of each container is assumed to take 15 minutes which normally in reality is less than 10 minutes (here it is supposed the containers are lifted by wires. By using the twist lock it takes less than 5 minutes). Offloading 332 number of containers takes about 3.46 days.

VI. **Unplanned Activities:** unplanned activities here is the bad weather, mechanical failure of equipment and waiting on client. In general, waiting on weather is considered 35% of sailing, the preparation of the cables for removal, cables removals and offloading operation. Since the mechanical failure and waiting on client is 2% of all activities except waiting on weather. During the course of cables retrieval of Anholt wind farm, the Decom Vessel goes to stand-by mode for 43.39 days approximately. This figure is based on assumption and heavily depends on whether condition, readiness of the sites and maintenance of the vessel.

Conclusion: if Decom Tools vessels is used for recovery of the infield and export cables, the time for retrieval takes about **164.01** days and cost about **$ 10,848,865.54.**

It should be noted that in this calculation; the daily charter rate of the Decom Tools vessel is considered **$70 000** for recovery of inter array cables since it works on DP:

The daily charter rate of the Decom Tools vessel for recovery of export cables is considered **$600000** since it works on PAW.

During unplanned activities and preparation activities, the average charter rate of 65000$ is considered in the calculation.

6.31 Comparison of Cable Retrieval with Decom Tools Vessel and Reverse to the Installation

A comparison has been made with the results that were provided in the previous sections. Table 6-17 shows the required time, predict cost, and estimate fuel consumption as well as emission, if the cable retrieval take place with Decom Tools vessel or reverse to the installation. In this calculation, the daily charter rate of CLV for infield cable recovery is considered 80 000 $ and the charter rate of the vessel for recovery of export cable is considered 100000$. The charter rate of the Decom Tools vessel for the retrieval of export cable is 60 000$ per day since the vessel maintain the position on position anchor winches. Besides, for retrieval of infield cable, the vessel is recommended to be maintained on DP mode. Operating the vessel on DP cause more fuel consumption. The charter rate of the Decom Tools vessel on DP is considered 70 000$ per day. The fuel consumption of the Decom Tools vessel on DP is considered 32.77 tons per day and on the PAW is considered 9.4 tons per day.

It is considered that CLV is run on DP, so the daily fuel consumption of CLV is considered 30 tons per day during sailing, 25 tonnes during recovery of infield cables, 20 tonnes during recovery of export cables and 10 tons during unplanned activities.

With regards to all above facts and figures the result of comparison is as following table.

Table 6-17 Comparison of Cable Retrieval Reverse to the Installation and with Decom Tools Vessel

Parameters	Comparison of Cable Retrieval	
Configuration	Reverse of Installation	Decom Tools Vessel
Parameters	Mixed Fleets	Decom Tools Vessel
Time (Day)	185.31	164.01
	Base Scenario	-21
		11%
Cost ($)	$ 15,885,159.3	$ 10,848,865.5
	Base Scenario	$ (5,036,293.7)
		31.70%
Fuel (Tones)	3761.30	3112.61
	Base Scenario	-648.69
		17%
CO2 Emission (Tones)	12058.71	8559.67
	Base Scenario	-3499.05
		29%

1. According to above comparison table, the retrieval of the cable with Decom Tools vessel takes 11% less time than reverse to the installation vessel.
2. From a cost perspective, the cost of decommission of the cables including both infield and export cable removal is about 31.70% less cost than reverse to the installation.
3. From a consumption point of view, the consumption of the cable retrieval operation by Decom Tools vessel is about 17% less than the conventional cable laying vessel due to utilization of solar system, batteries and Flettner rotor.
4. And finally, from an environmental stance, the emission of cable retrieval with Decom tools vessel is about 29% less than removal of cable with the CLV due to the fact the Decom Tools vessel is equipped with LNG powered engines.

7 Stability Analysis of the Decom Tools Vessel

7.1 Introduction to the Stability of Decom Tools Vessel

"Safety First" is the most common, and famous phrase in the maritime industry as well as other industries. It is therefore for every seafarer essential to understand what safety means and how safety is defined. The term of "Safety" in the military standards of the United States is defined as following: "*Freedom from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment.*" (Department Of Defense Standard Practice 2012).

The absence of safety can lead to unpredictable and calamitous accidents. There are many factors that influence the ship's safety, where the major contributor is any element can touch the ship's stability. Herby, the intact stability of vessels, is a significant factor which can contribute if not accurately applied or maintained to loss of life as well as to the loss of a vessel and its cargos. That is why stability-related problems must be carefully dealt with, if not taken care, they can predominantly lead to catastrophic consequences. (Tupper 2013, 370-371)

Therefore, to demonstrate whether the vessel is safe to carry wind turbines components as per prescribed stowage plans which are explained under section 6.8 of this document, a comprehensive stability assessment has been executed. Stability assessment should verify that the vessel has sufficient longitudinal and transverse stability, and it can meet the minimum intact stability criteria during the whole journey. Therefore, we can define the transverse stability as it is the vessel ability to return to un upright position after being heeled by an external force.

Stability assessment will be conducted for several examples of loading conditions, they are as following:

1. The 12 MW stowage plan (8 complete sets)
2. The 12 MW – 24 Towers
3. The 12 MW – 26 Nacelles
4. The 12 MW – 48 Blades
5. The 5 MW stowage plan (24 complete sets)
6. The 3.6 MW stowage plan (33 complete sets)

Accordingly, to proceed with the analysis, missing stability information must be collected. For instance, in order to calculate the stability and trim for the designed vessel, we must first of all find out the location of the centre of gravity, as well as the lightweight of the Decom Tools Vessel.

Note: Not only the geometry and sections of the vessel are designed in the MAXSURF software, but also does the stability is calculated and analysed in the MAXSURF.

Therefore, the following stability assessments has been conducted by the MAXSURF Stability software to ensure that the ship is seaworthy. Accordingly, all stability parameters will be generated by importing the hull geometry from MAXSURF Modular to MAXSURF Stability. Therefore, the basic points such as the centre of buoyancy (B), as well as the metacentre (M), and all related parameters, will be gathered automatically from the MAXSURF Stability software. Manual calculation is carried out for calculating the centre of gravity (G) for the designed ship, as well as for the proposed stowage plans.

For better understanding the values, first we should define the coordinate system of the Decom Tools Vessel. The aft perpendicular (AP) is situated exactly at the reference point where the fore perpendicular (FP) is situated 177 meters away, which resulting a 177 meters length between perpendicular (LPP). Figure 7-1 shows the reference point, the zero point, AP, FP, DWL, MS and baseline.

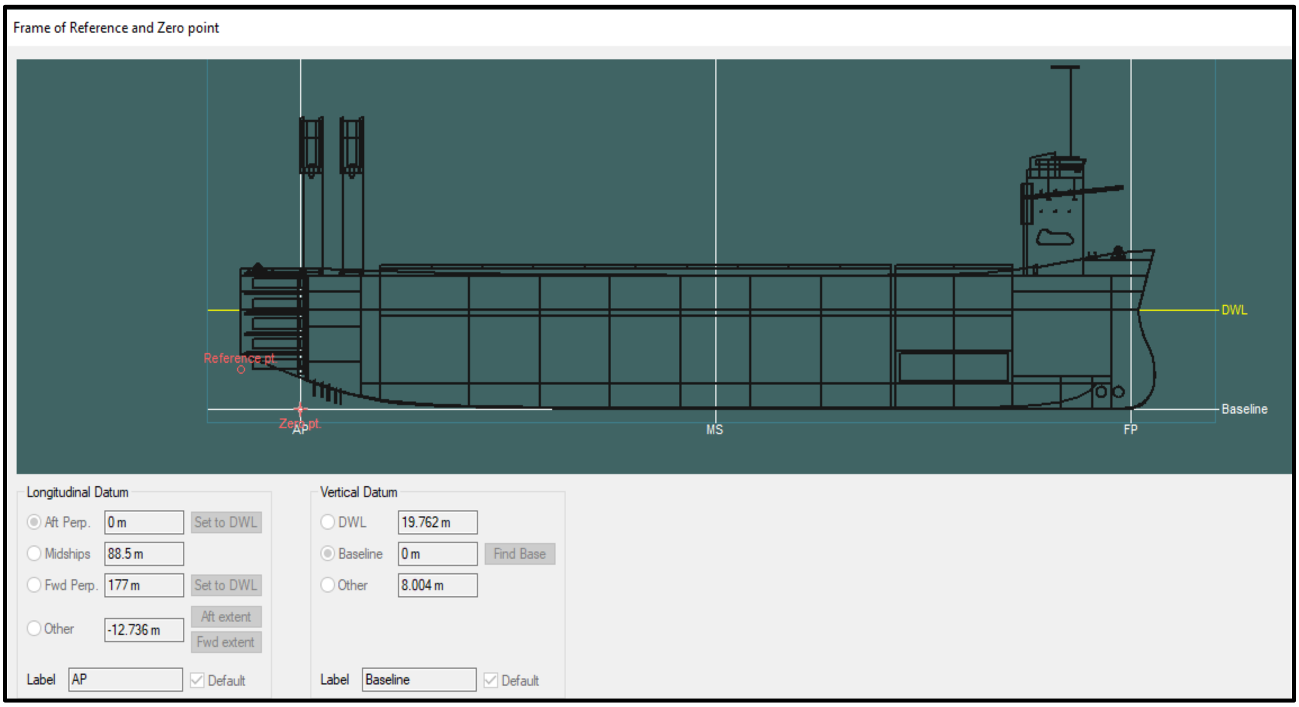


Figure 7-1 Decom Tools Vessel Coordinates

All reference points have to be measured from the Aft perpendicular, positively in the forward direction and negatively in the aft direction. In other words, longitudinal centre of gravity (LCG), longitudinal centre of floating (LCF), as well as longitudinal centre of Buoyancy (LCB)) are measured from the Aft perpendicular. Similarly, in the transvers direction, the transverse centre of gravity (TCG), transverse centre of floating (TCF) are transverse centre of buoyancy (TCB) are positive if they are in starboard side from the centre line and negative if they are in the port side. But for the vertical direction all values must be positive, because the reference point (zero point) exactly at the lowest possible point of the keel.

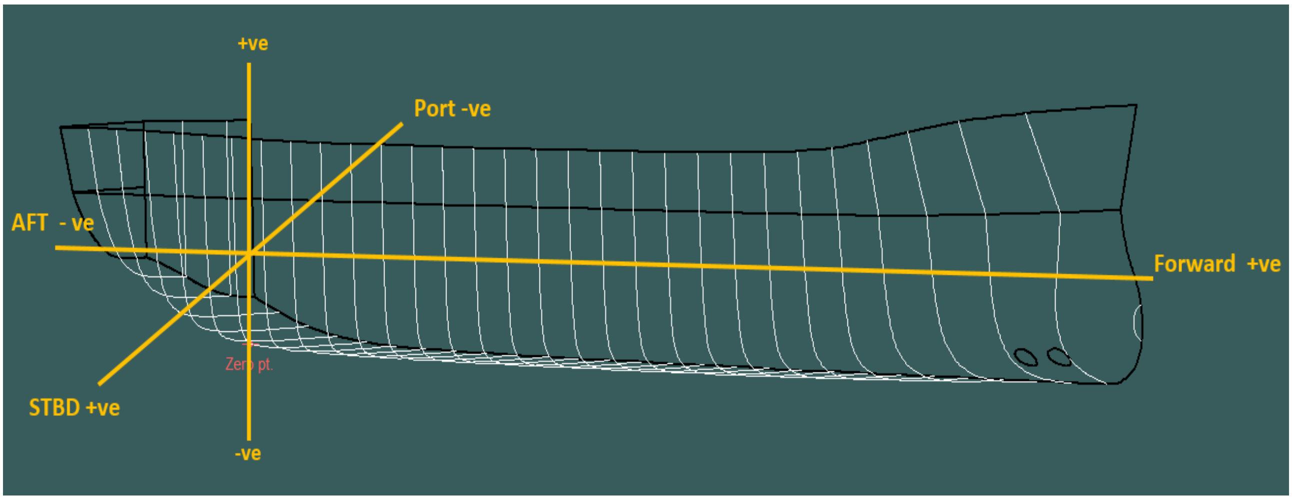


Figure 7-2 Direction and Coordinate of the Vessel

The transverse distances are measured from the centreline of the ship, positive on starboard and negative on port. The trim is measured as the difference between draft at AP and draft at FP; the trim with the stern down is defined as positive. The heel to starboard is positive, to port is negative, See Figure 7-2. To be more exhaustive, this chapter will cover the following points:

- Lightweight and COG estimation
- Calculating freeboard height and maximum draft
- Intact stability criteria
- Watertight hull and Subdivision arrangement
- Stability terms definition
- Tanks of the Vessel
- Equilibrium status for the lightweight, and for full ballast condition.
- Ship hydrostatic for several drafts
- KG limit & KN values
- Position of progressive flooding points
- Rolling period
- Heeling tanks
- Stability assessment for 12 MW wind turbine (8 complete sets: Nacelle, blades, towers)
- Stability assessment for 12 MW – 24 towers
- Stability assessment for 12 MW – 26 Nacelles
- Stability assessment for 12 MW – 48 Blades
- Stability assessment for 5 MW wind turbine (24 complete sets: Nacelle, blades, towers)
- Stability assessment for 3.6 MW wind turbine (33 complete sets: Nacelle, blades, towers)

7.2 Decom Tools Vessel Light Weight Estimation

Lightweight is the overall weight of structure, superstructure, hull weight, engines, pumps, accommodation, and so forth, excluding liquids, spare parts, provision, and all consumable material. The ship's lightweight is constant in all the time. In case huge amount of steel have been changed, lightweight check has to be carried out. According to IS code 2008 the definition of lightweight is as following: "Lightship condition is a ship complete in all respects, but without consumables, stores, cargo, crew and effects, and without any liquids on board, except that machinery and piping fluids, such as lubricants and hydraulics are at operating levels."

Generally, the final determination of ship's light weight carries out by naval architect after completion of ship construction. After conduction of stability test, with using the observed results and data, the engineering team including naval architects can calculate the lightship very accurately. The theory behind the stability test requires the naval architect to measure heel angles as they intentionally apply a heeling moment. Heeling angles can go from one to three degrees. Stability test is a combination of lightweight survey and inclining experiments. Having considered that basic design of the Decom Tools vessel is not conducted so far, calculating lightweight and centre of gravity can be only estimated mathematically.

The plan is to choose an existing vessel as a reference vessel and conduct a proportional estimation. The methodology which will be followed to estimate the lightship weight is the "method of difference". Where the dimensional correction is done for the designed length, depth and beam after comparisons have been created between the designed vessel and a reference vessel. In this case the selected reference vessel is "MV SVENJA". MV SVENJA has been chosen as a reference vessel because firstly she has one long hold which is similar to the designed vessel, and secondly, she is a heavy lift cargo vessel, and thirdly she can sail also with open hatch (SAL Heavy lift kein Datum). Figure 7-3 shows the photo of this ship. The dimension and information of this vessel are as following):

MV SVENJA ship's particulars (Figure 7-4):

- Length over all: 160.50 m
- Breadth moulded: 27.50 m
- Depth moulded: 13.80 m
- Deadweight: 12 501 t
- Displacement: 23 600 t

According to the method of difference the majority of ships which have been built has indicated that the steel weight in tons/m run for length, breadth and depth which they are: 85% is affected by length, 55% is affected by breadth, and 30% is affected by depth of a ship

Table 7-1 Lightweight estimation with Method of difference

Dimension	Weight	Length	Beam	Draft
"MV SVENJA" Lightweight (t)	11099			
Reference ship "MV SVENJA"		160.5	27.5	13.8
Decom Tools Vessel		195	48	26.5
Differences in meters		34.5	20.5	12.7
Affection rate		85%	55%	30%
Rate in tonnes /m run along the (length, breadth, depth)		58.779751	221.98	241.28261
Modifications (t)		2027.9014	4550.59	3064.2891
Total Modifications (t)	9642.7805			
Estimated Final Light weight for New Design (T)	**20741.781**			

According to the Table 7-1, the calculation estimates that the lightweight is 20741.781 tons. This value will be used in the stability calculation, as well as to determine the centre of gravity.

In the next step, in order to calculate the stability of the designed ship, we have to estimate its centre of gravity. The estimation will be carried out by calculating and estimating the weight for each part on the vessel. The method which will be used in the next sections is using the area of each part and give each square meter of the selected part an estimated weight in tons.

Figure 7-3 MV Svenja

MV SVENJA SHIP'S PARTICULARS

TYPE 183 / DP 1

Flag of Registry:	German
Port of Registry:	Hamburg
Owner:	SAL Heavy Lift GmbH
Operator:	SAL Heavy Lift GmbH
Technical Manager:	SAL Ship Management UG (haftungsbeschränkt) & Co. KG
HSE Manager:	SAL Ship Management UG (haftungsbeschränkt) & Co. KG
Classification:	Germ. Lloyd +100 A5 "Multi-Purpose Dry Cargo Ship", "HEAVY LIFT SHIP", "EP", "BWM-S", "Hatchcoverless", "DP-1", "DG", + MC AUT
Keel Laying:	2007/12
Commissioning date:	2010/12
Shipyard:	J.J. Sietas KG
Newbuilding No.:	1279

Length over all:	160.50 m	**Speed @ 85% MCR:**	18 kn
Length between perps.:	149.38 m	**Air draught (jibs in rest.):**	41.09 m
Breadth moulded:	27.50 m	**Air draught (jibs upright):**	66.47 m
Breadth over all:	27.91 m		
Depth moulded:	13.80 m		
GT (int'l 69):	15 199 t		
NT (int'l 69):	4 559 t		
GT (Suez):	15 670.10 t		
NT (Suez):	14 894.01 t		
NT (Panama):	12 925 t		
(Summer)		*(Summer – Open Top)*	
Draught:	9.01 m	**Draught:**	7.50 m
Deadweight:	12 501 t	**Deadweight:**	7 396 t
Freshwater Allowance:	165 mm	**Freshwater Allowance:**	145 mm
Freeboard:	1.809 m	**Freeboard:**	3.309 m
Displacement:	23 600 t	**Displacement:**	18 500 t

Capacity BW:	10 493 m³
Capacity GO:	227 m³
Capacity HFO:	1686 m³
Capacity FW:	261 m³
Cargo gear:	2 cranes, each 1000 t SWL (in combination 2000 t); Auxiliary hoist 2 x 60 t; Sling hoist 2 x 10 t. Auxiliary hoist proved for man riding
Hatch cover:	MacGREGOR hydraulic operated combined folding type and lift and roll type
Number of holds:	1
Number of hatches:	1
Dimension of hold:	107.1 x 17.0 x 13.5 m
Volume of hold:	18 470 m³ (with tweendeck)
Bale capacity:	626 310 cuft
Free deckspace:	3427 m²
Main Engine:	MAN 9L 58/64; 12 610 kW @ 428 min-1
Rudder:	Flap type spade rudder (high efficiency rudder)
Bow Thruster:	Brunvoll 1200 kW
Aft Tunnel:	Brunvoll 745 kW
Certifications:	

SAL Heavy Lift GmbH • Brooktorkai 20 • 20457 Hamburg/Germany • Phone: +49 40 380380-0 • www.sal-heavylift.com
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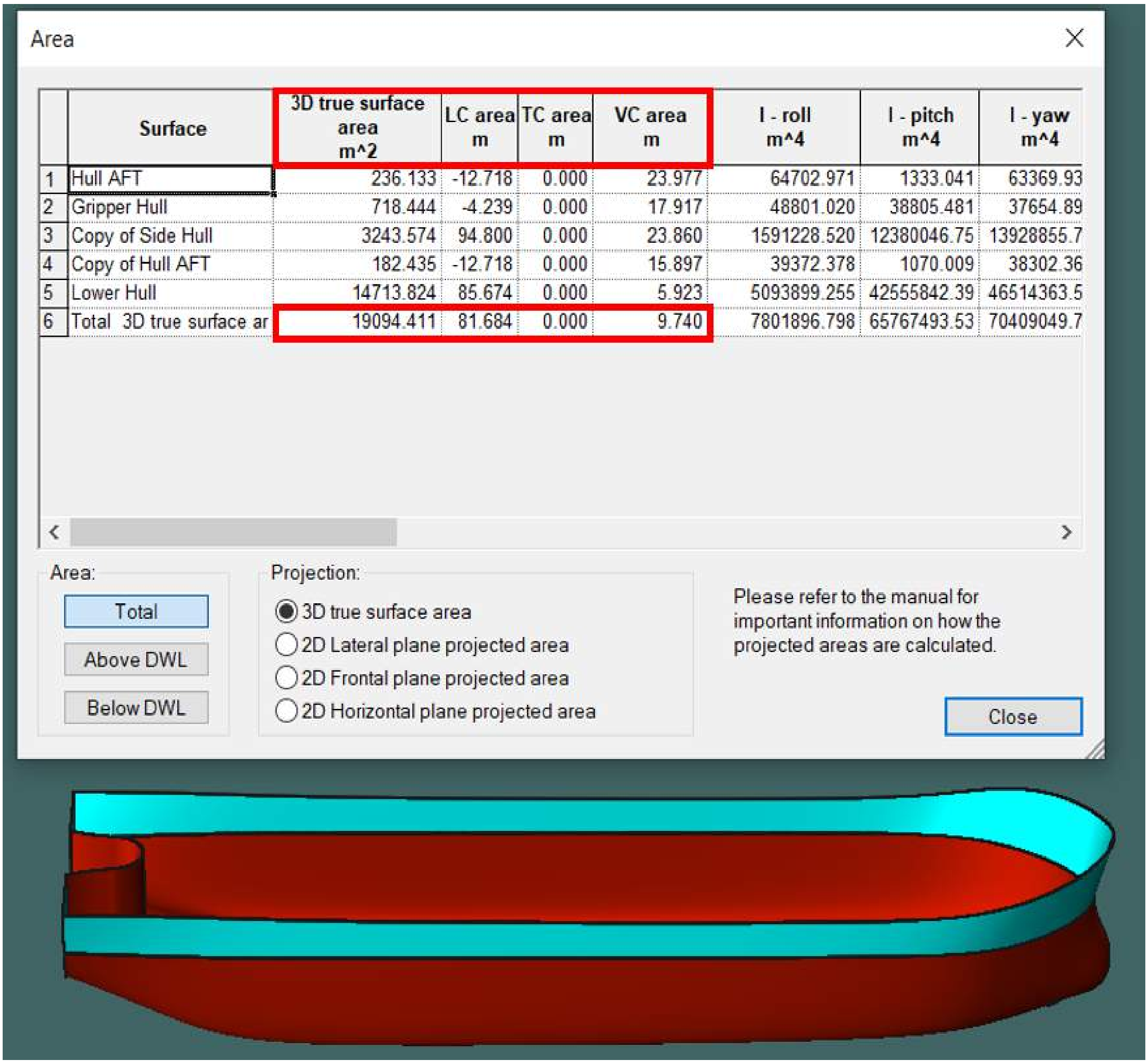
Figure 7-4 MV SVENJA Particular

7.3 Decom Tools Vessel Centre of Gravity Estimation

As mentioned earlier, finding the final centre of gravity COG for a ship could be done by a naval architect after construction of the ship, by doing the stability test and making the necessary analysis and calculation. However, here in this document, the COG is estimated theoretically based on numerical methods.

The estimation method is to give each designed part of the ship a specific estimated weight in tons, and then by using the MAXSURF modeler, it is possible to define the COG for each single part. By summarizing all parts' COGs and weights, a final COG of the designed vessel can be estimated. For instance, to calculate the COG of the designed ship's hull, we need to find the overall hull area. The hull's area can be generated directly from the MAXSURF modeler software.

Figure 7-5 illustrates the hull shape and the 3D true surface area and centre of gravity.



	Surface	3D true surface area m^2	LC area m	TC area m	VC area m	I - roll m^4	I - pitch m^4	I - yaw m^4
1	Hull AFT	236.133	-12.718	0.000	23.977	64702.971	1333.041	63369.93
2	Gripper Hull	718.444	-4.239	0.000	17.917	48801.020	38805.481	37654.89
3	Copy of Side Hull	3243.574	94.800	0.000	23.860	1591228.520	12380046.75	13928855.7
4	Copy of Hull AFT	182.435	-12.718	0.000	15.897	39372.378	1070.009	38302.36
5	Lower Hull	14713.824	85.674	0.000	5.923	5093899.255	42555842.39	46514363.5
6	Total 3D true surface ar	19094.411	81.684	0.000	9.740	7801896.798	65767493.53	70409049.7

Figure 7-5 Calculating the Surface of Decom Tools Hull

For the simplicity in finding the final COG the hull thickness will be considered homogeneously distributed across the entire hull. Accordingly, the longitudinal centre of gravity, transverse centre of gravity and vertical centre of gravity will be as following:

- Hull area: **19094.411 m^2**
- LCG stated for longitudinal centre of gravity: **81.684 m**
- TCG stated for Transverse centre of gravity: **0 m**
- VCG stated for Vertical centre of gravity: **9.74 m**

Similarly, this method will be applied for the whole ship in order to find the final centre of gravity. After acquiring the areas for all designed parts and their COG, we need to give a weight for each selected part. Weight will be giving in different values for different parts.

Table 7-2 shows the estimation of weight in ton for the different part and sections of the Decom Tools Vessel. The hull area is taken from MAXSUR0F Modeler, and by giving a specific weight for each square meter we can calculate the hull weight. Weight per square meter run is including the steel sheet and associated frames.

If we assume that each 1m^2 of the hull area can weigh 400 kg, then the overall weight in this case will be 7637.7644 tons. This strategy will be followed for all parts

Note: the overall distribution of weight should be in average the same value of the pre-calculated lightship 20741.781 ton.

Table 7-2 Weight Distribution Calculation and Estimation

Name	Area m^2	Estimated Weight Per m^2 (ton)	Weight in Tons
Hull	19094.411	0.4	7637.7644
Transverse Bulkheads	4948.762	0.3	1484.6286
Weather deck	2978.452	0.15	446.7678
Longitudinal Bulkhead	5039.8165	0.3	1511.94495
Ballast Tanks sections	19492.032	0.275	5360.3088
Gripper	381.372	0.1	38.1372
LNG Tanks	1526	0.075	114.45
Hold No 1 - Hatch cover	1075	0.15	161.25
Hold No 2 - Hatch cover	4687	0.15	703.05
Accommodation	4012.601	0.05	200.63005
STBD Crane	176.216	0.25	44.054
Port Crane	176.216	0.25	44.054
Gantry Cranes	4230.623	0.25	1057.65575

Calling the strategy of calculation based on "method of difference" which is summarized in Table 7-1, the calculated estimated lightship is 20741.781 tons, and by distributing the weight through all parts which is based on

Table 7-2, the final lightweight has been estimated as 20744.7 tons. Table 7-3 shows the summary of components weight, components' COG, lightweight, and the final centre of gravity of the entire design.

Table 7-3 Final Centre of Gravity and Lightweight of Decom Tools Vessel

No	Compartments	Weight	LCG	TCG	VCG	Longitudinal moment	Transverse moment	Vertical moment	Sources
		t	m	m	m	t.m	t.m	t.m	
1	Hull	7637.7	81.68	0	9.740	623883.14	0	74391.82	MAXSURF
2	FWD Engine room and Associated tanks	750	163	0	13	122250	0	9750	Estimated
3	Accommodation	200.6	161.4	0	42	32396.9	0	8486.6	MAXSURF
4	FWD Store and machineries	50	176.5	0	28.9	8825	0	1445	Estimated
5	FWD Mooring and related winches and both anchors- 4 winches+ 2windlass	150	176.5	0	32	26475	0	4725	link
6	Ballast Tanks sections	5360.3	87.54	0	10.00	469268.2	0	53603.08	MAXSURF
7	Weather deck	446.7	78.32	0	26.50	34991.30	0	11839.34	MAXSURF
8	Hatch cover 1	161.2	139.5	0	28.3	22494.37	0	4563.37	MAXSURF
9	Hatch cover 2	703.0	71.5	0	28.3	50268.07	0	19896.31	MAXSURF
10	Provision crane STBD	44.05	158.7	19.55	41.0	6991.36	861.52	1806.21	MAXSURF
11	Provision crane Port	44.05	158.7	19.55	41.0	6991.36	-861.52	1806.21	MAXSURF
12	Flettner Rotor STBD	40	162.9	20	60	6519.8	800	2400	link
13	Flettner Rotor Port	40	162.9	-20	60	6519.8	-800	2400	link
14	Aft Store and machineries + mooring	100	-5.636	0	30	-563.6	0	2950	Estimated
15	Gantry cranes	1057.6	6.487	0	48.0	6861.01	0	50767.47	link
16	Transvers Bulkheads	1484.6	90.02	0	14.520	133658.1436	0	21556.80	Maxsurf
17	Gripper	38.13	-3.927	0	16.690	-149.7647844	0	636.50	Maxsurf
18	Longitudinal Bulkhead	1511.9	91.18	0	14.597	137860.6525	0	22069.86	Maxsurf
19	Aft machineries + propulsion	750	8	0	15.000	6000	0	11250	Estimated
20	LNG Tanks (Steel)	114.45	139.5	0	9.493	15965.775	0	1086.47	MAXSURF
21	Lifeboats + davit	60	160.7	0	35	9645	0	2100	Estimated
Final Estimated Lightweight		**20744.69**	**83.25**	**0**	**14.920**	**1727151.62**	**0**	**309530.15**	

Accordingly, the Decom tools vessel lightweight and COG are summarised in Table 7-4

Table 7-4 Lightweight, LCG, TCG & VCG of the Decom Tools Vessel

Lightship (t)	LCG (m)	TCG (m)	VCG (m)
20744.7	83.26	0	14.921

The above lightship does not include the following items (Table 7-5) which are to be included in the loading condition as deadweight items.

Table 7-5 Components that impact Deadweight and Stability

Item	Weight (t)	LCG (m)	TCG (m)	VCG (m)
Tween deck				
Cable Retrieval Equipment's				
Monopile cutting Tool				
Whatsoever is not mentioned in the Table 7-2 Table 7-2				

Weight and COG for the above-mentioned items has to be gathered from their specification sheets.

7.4 Decom Tools Vessel Freeboard and Draft

According to the International Convention on Load Lines (IMO 2005), ships are classified into two essential types:

- **Type A ships:** They are designed to carry liquid cargos; they have lower freeboards than type B ships. Type A ships have higher safety principles, and well-subdivided to limit the unsymmetrical flooding.
- **Type B ships:** They are those carrying dry cargoes, they have relatively larger freeboards, and they are less subdivided.

Based on the regulation No.28 table B of the above-mentioned convention, the freeboard for a 195 m length overall vessel should be at least 3185 mm. Freeboard is also subjected to two different corrections, correction for block coefficient, and correction for depth.

Firstly, based on regulation 30 of the International Convention on Load Lines, the tabular free board shall be multiplied by a factor of $\frac{C_b+0.68}{1.36}$ in case the block coefficient (C_b) exceeds 0.68.

Secondly, based on regulation 31 of the International Convention on Load Lines, free board have to be corrected for the depth as well. According to section (1) of the rule, if the depth of the vessel (D) exceeds $\frac{L}{15}$ the free board have to be increased by $\left(D-\frac{L}{15}\right)R \quad mm.$

Where:

- R is 250, and
- L is the length of overall.

Table 7-6 illustrates the freeboard calculation as well as the maximum draft.

Table 7-6 Decom Tools Vessel Freeboard Calculation

Freeboard Calculation		
Freeboard tables - Reg 28 - table B		
Ship LOA	195	m
Freeboard >> table B	3185	mm
Correction of Block coefficient - Reg 30		
Vessel C_b @ draft 10.5 m	0.756	
correction factor	$\frac{C_b + 0.68}{1.36}$	
correction factor	1.055882353	
Correction for depth - Reg 31 (1)		
Ship's depth	26.5	m
correction	$\left(D - \frac{L}{15}\right)R$	mm
R	250	
correction	3375	mm
Final Freeboard	6737.985294	mm
Final Freeboard	6.738	m
Maximum Draft	19.762	m

7.5 Decom Tools Vessel Intact Stability Criteria

The term of intact stability refers to a ship that is stable in the water and is not damaged. The stability of the ships is subject to several national and international regulation. The primary basis is the SOLAS 74 convention. This convention itself only contains general rules regarding intact stability. These rules are implemented by the International Code on Intact Stability for all ships covered by SOLAS 74 (IS-Code). Among others, this code contains criteria for the safe intact stability as well as design rules for particular ship types. Besides this code, rules on intact stability can be found in some other international regimes that deal with particular types of ships or cargoes. In addition to these international regimes, some flag states implemented their own, national legal sources that go beyond the international minimum standards of IMO.

There are different parameters used to measure a ship's stability against the IMO's intact stability rules. The typical parameters are:

1- The area under GZ curve from the equilibrium up to 30° shall not be less than 0.055 m.rad.
2- The area under GZ curve from the equilibrium up to 40° angle of heel, or the angle of down flooding if this is less than 40° shall not be less than 0.09 m.rad.

3- The area under the GZ curve between angles of heel 30° - 40° or between 30° and the down flooding angle (if it is less than 40°) shall not be less than 0.03 m.rad.
4- The value of GZ has to be at least 20 cm at angle of heel 30°.
5- The maximum GZ has to occur at an angle of heel preferably exceeding 30° but not less than 25°
6- The initial metacentric height GM has to be at least 15 Cm

Table 7-7 summarizes the ship stability criteria for a merchant vessel, which will be the bases for the upcoming stability calculation.

Table 7-7 Stability criteria as per Intact Stability Code Part A 2.2

Dynamic Stability	$A_{30°} \geqslant 0.055$ m. rad $A_{40°}$ or $A_{\varnothing f} \geqslant 0.090$ m. rad $A_{30°\text{-}40°}$ or $A_{30°\text{-}\varnothing f} \geqslant 0.030$ m. rad
Angle of maximum righting lever	$\varnothing_s \geqslant 25°$
Righting levers	GZ $\geqslant$ 0.20m at o $\geqslant$ 30°
Initial stability	$GM_c \geqslant 0.15$m

7.6 Decom Tools Vessel Watertight Hull and Subdivision Arrangement

Watertight hull and bulkheads are used to maintain the ship's integrity and stability. The watertight hull is defined up to the bulkhead deck and it should cover all the watertight compartments. The ship is designed with longitudinal and transverse subdivisions to limit possible progressive flooding and increase survivability after hull damage. Subdivision is the term used to describe watertight integrity below the bulkhead deck (freeboard deck). The ship and the watertight subdivision (watertight compartment arrangement) are designed to meet the required safety level with respect to flooding. 'Subdivision' refers to the transverse bulkhead, longitudinal bulkheads, and horizontal decks below the bulkhead deck. According to DNV.GL All ships shall have at least one collision bulkhead, one aft peak bulkhead, and one bulkhead at each end of the engine room. The number of transverse bulkheads shall be arranged to suit the requirements for transverse strength, subdivision, floodability and damage stability, and shall be in accordance with the requirements of national regulations. For vessels where no damage stability has been carried out, a fulfilment of the international standard is mandatory, for instance SOLAS. However, DNV.GL advised to have 10 number of transvers bulkheads for the range of ships which has length between 190 to 225 m (DNV GL 2015). However, the Decom Tools vessel has only 5 transverse bulkheads, and one longitudinal bulkhead. The longitudinal bulkhead is exactly at the centreline along the entire length of the ship. Accordingly, a damage stability calculation has to be proved in a separate study. Furthermore, the arrangements of the bulkheads have to be considered, for instance, they have to be extended to the freeboard deck, and should also have minimum opening. Not only the vertical extant is necessary, but also the longitudinal positioning of the transverse bulkheads is highly important. For example, the collision bulkhead has to be located at a certain distance from the forward perpendicular FP. According to DNV.GL standards (DNV GL 2015), the distance X_c in m, from the perpendicular FP to the collision bulkhead for vessels which are less than 200 m shall be taken as following:

$$X_{c-min} = 0.05L_{LL} - X_f$$

Where the value of X_f is not less than the following:

$$X_f = \min(0.5\,X_{be}; 0.015\,L_{LL};\ 3.0)$$

Where: X_{be} = the distance in m from forward perpendicular FP to the extreme forward end of the bulb extension, See Figure 7-6 and Figure 7-7.

Furthermore, all tanks and compartment located forward of the collision bulkhead shall not be arranged for the carriage of fuel oil or other flammable products.

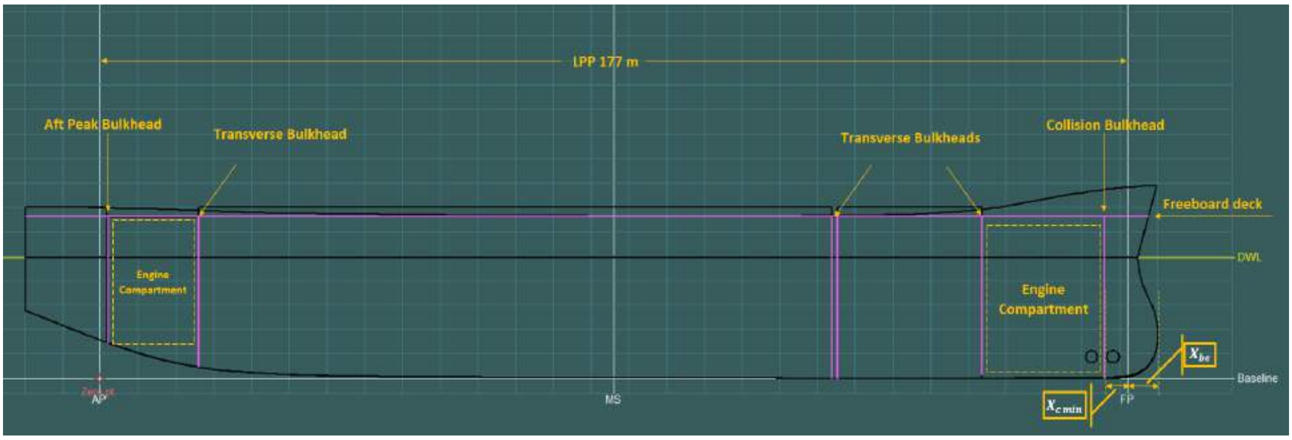


Figure 7-6 Watertight Hull and Subdivision of Decom Tools Vessel

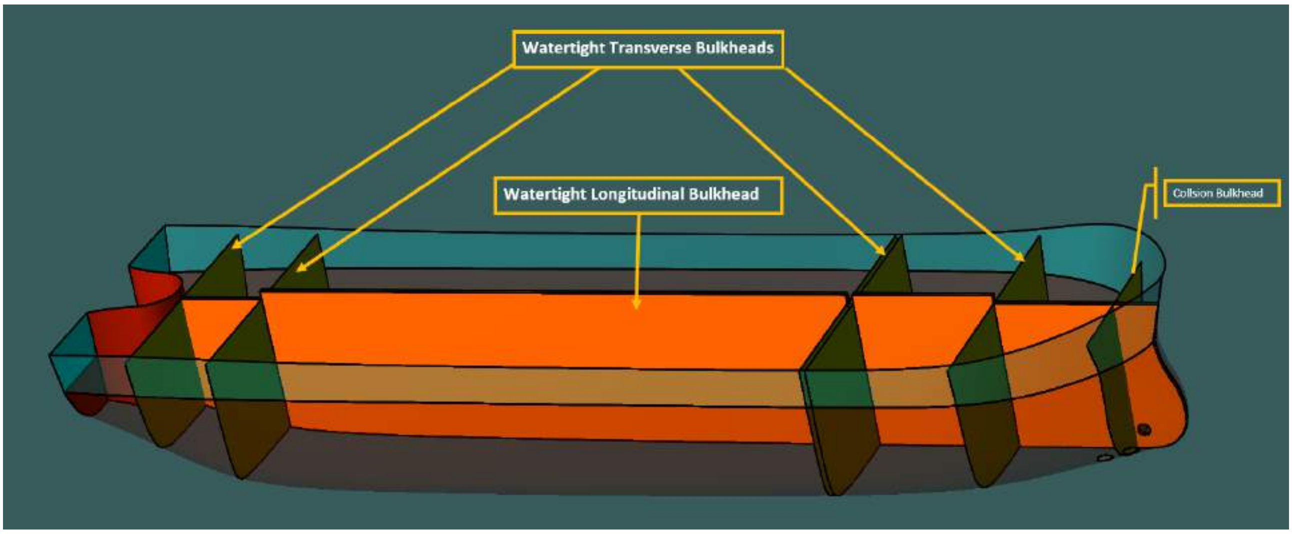


Figure 7-7 Watertight Hull and Subdivision of Decom Tools Vessel

7.7 Definition of Stability Term

The Information mentioned in this section has been collected from the Maxsurf stability manual and the following book “Introduction to naval architecture” (Tupper 2013).

Keel (K): Keel is the longitudinal structure at the lowest point of the ship’s hull, on which the rest of the hull is built. Several reference points use the keel (K) as a datum point.

Centre of Gravity (CoG): the centre of gravity is the single point where the force of weight, due to gravity, acts downwards and is dependent on total mass of the ship. The position of CoG is defined as a longitudinal centre of gravity LCG, transverse Centre of Gravity TCG, and vertical centre of gravity VCG. The centre of gravity is affected by a change in the weight distribution onboard the ship in the following ways:

- CoG moves towards added weight
- CoG moves away from any removed weight
- CoG moves in the same direction as any shift in the weight

Centre of Buoyancy (B): is the geometric centre of the underwater volume. A single point where the upward force of buoyancy acts. The position of B is defined in a similar way to G with a longitudinal centre of buoyancy LCB, transverse centre of buoyancy TCB, and vertical centre of buoyancy VCB. The location of B is dependent upon the underwater hull form. Unlike the centre of gravity, the centre of buoyancy is constantly shifting, relative to the ship, as the ship moves. This is due to the changes in the geometry of the submerged hull volume

Buoyancy: gravity is a force acts downwards through CoG. What keeps the ship afloat is the force of buoyancy acting upwards, through centre of buoyancy and the force is equal to the weight of displaced water. In other words, the force of gravity is opposed by buoyancy.

The Metacentre (M): it is the point at which, when the ship is inclined, the vertical line through the centre of buoyancy will intersect the vertical line on which the centre of gravity acts when in equilibrium. The location of this point depends much on the underwater geometry of the ship. The Metacentre M can only be influenced by changing the floating position as it is dependent on the underwater volume (displacement) and waterplane area.

Waterplane: it is the horizontal slice of the ship taken at the waterline. This area changes with changing of displacement and or motion

Transverse stability largely determines the ship’s seaworthiness. Among others, the initial locations of B, G and M can determine if a ship will experience challenges in any given moment of operation. The ship draft directly influences the position of B and M on every ship. The position of G is the only position we can control. The significant measures for transverse stability are KM, KB, BM, and KG. Where the most important measure and resultant is GM

GM: the resultant of the relationship between KB, BM, and KG is the Metacentric height GM. GM is the distance measured from the metacentre (M) to the Centre of gravity G. GM is calculated based on the weights and vertical moments of all crew, cargo, liquids and other weight. GM can be calculated by using the following formula:

$$GM = KB + BM - KG$$

The ship is said to be in stable equilibrium if it has positive initial metacentric height. This means that the centre of Gravity G is below the metacentre M. This is the desired state.

If the G coincides with M the ship is said to be in Neutral equilibrium. The ship floats upright but there is no stability to resist an external force.

If the G is located below the M this means the ship has negative initial stability and it is said to be in unstable equilibrium. In this case the ship will tend to tip over when external force is introduced. This condition will lead to the angle of Loll.

KB: this is the vertical distance from the keel to the centre of Buoyancy. It is determined by the shape and volume of the underwater hull, and it can be calculated for different hull shapes.

BM: it is the distance between the centre of buoyancy and the Metacentre. BM is dependent on waterplane and the volume of displacement, and it can be calculated by using the formula:

$$BM = (\frac{I}{V})$$

Where:

I = the second moment of the waterplane area about the centreline

V= the ship's volume of displacement

KG: this is the vertical position of the centre of gravity above the keel. It is defined by the vertical distribution of the weight throughout the ship. The distance KG can be varied by shifting weight up or down in the ship. KG can be calculated using the total moment of all weights about the keel and the total displacement of the loaded ship.

Angle of Loll: the term that describes the ship that is not stable when in the upright position, this resulting in the ship floating at an angle to one side. Loll tends to happen when G is located above M, in other words, GM equal zero.

Angle of List: Occurs as a result of a ship that is not upright due to and internal force, such as non-symmetrical weight distribution or flooding.

Angle of Heel: when the ship is not upright due to an external force, such as wind or waves.

In order to determine whether a vessel has a good stability we have to assess static and dynamic stability. Whereas static stability is defined as the ship's ability to maintain its upright position in calm conditions, dynamic stability is the ship's ability to resist external heeling forces such as wind, waves, turning, or a shift of cargo. Dynamic stability is measured by GZ curve.

GZ (righting lever): the moment arm which the forces of gravity and buoyancy use when they try to return the ship to its original floating positions. In any stability analysis, the value of GZ is plotted over the entire range of heeling angles for which it is positive to form the GZ curve. Where the GZ curve is the stability curve for the ship. GM the metacentric height

Deadweight: the deadweight is the difference of the total weight (displacement) and lightweight of the ship and includes all the loaded liquid substances (cargo and bunker), solid mass loads and passenger weight.

Displacement: the displacement of a ship is the weight of water displaced by the ship's hull when floating. As the ship floats, the submerged body occupies the volume which would otherwise be occupied by water. The weight of the volume of water displaced by the ship is always equal to the ship's weight. Displacement is comprised of the lightweight and deadweight of the ship.

Free surface effects: it is the virtual rise of the centre of gravity related to the movement of the water inside the slacked tank, affecting the stability and causing a reduction of the metacentric height. (Georage 2005) "FSE has been the primary cause of numerous losses of ships." (Patterson und Ridley 2014)

Bulkhead: "Vertical partitions in a ship arranged transversely or fore and aft are referred to as "bulkheads". Those bulkheads that are of greatest importance are the main hull transverse and longitudinal bulkheads, dividing the ship into a number of watertight compartments." (Eyres 2009)

Freeboard deck: "the freeboard deck is normally the uppermost complete deck exposed to weather and sea, which has permanent means of closing all exposed openings in a ship having a discontinuous freeboard deck, the lowest line of the exposed deck and the continuation of that line parallel to the upper part of the deck is taken as the freeboard deck. At the option of the owner and subject to the approval of the flag administration, a lower deck may be designated as the freeboard deck provided it is a complete and permanent deck continuous in a fore and aft direction at least between the machinery space and peak bulkheads and continuous athwart ships. When this lower deck is stepped the lowest line of the deck and the continuation of that line parallel to the upper part of the deck is taken as the freeboard deck. When a lower deck is designated as the freeboard deck, that part of the hull which extends above the freeboard deck is treated as a superstructure so far as concerns the application of the conditions of assignment and the calculation of freeboard. It is from this deck that the freeboard is calculated" (IMO 2005)

Watertight: "watertight means capable of preventing the passage of water in any direction under a head of water calculated from the most critical situation of damaged condition at equilibrium, including intermediate stages of flooding" (DNV GL 2018). Also, watertight means that in any sea conditions sea water will not enter the ship.

Figure 7-8 illustrates the location of M Metacentre, G centre of gravity, B centre of Buoyancy, and K Keel for a stable upright ship.

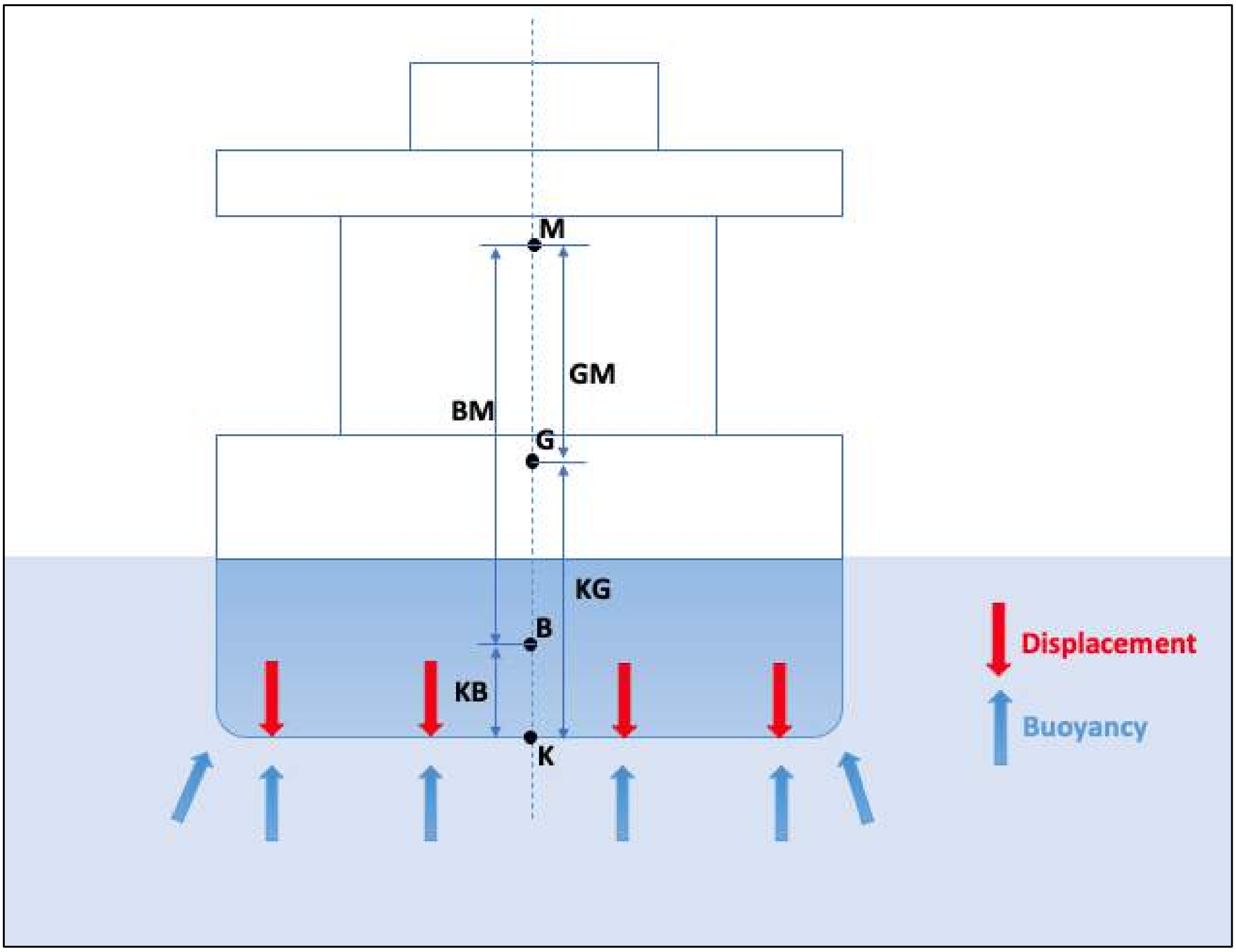


Figure 7-8 Displaying the M, GM, BM, B, KB & K

7.8 Decom Tools Vessel Fuel, Lube oil and Ballast Tanks

Figure 7-9 and Figure 7-10 represent the location in the designed ship for all tanks on board. There are 86 ballast tanks which includes 42 double bottom tanks, 22 side tanks, 18 topside tanks as well as 2 fore peak tanks and 2 Aft peak tanks.

In addition to ballast tank, there are two heeling tanks and two freshwater tanks. Besides, there are also two LNG tanks, four diesel tanks, and two lube oil tanks.

According to the DNV.GL standards the minimum vertical distance h_{DB} of the double bottom tanks from the Keel should be calculated as per following formula (DNV GL 2018):

$$h_{DB} = 1000 \cdot {}^{B}/_{20}$$

Where:

B is the ship's width in meters

h_{DB} vertical distance measured from the keel line, in mm.

Accordingly, the required h_{DB} for the designed vessel shall not be less than 2.4 m. However, the designed vessel has considered the double bottom height is at 5 meters form the keel line, in order to give the vessel, the freedom to sink few meters to use the gripper for extracting the monopile.

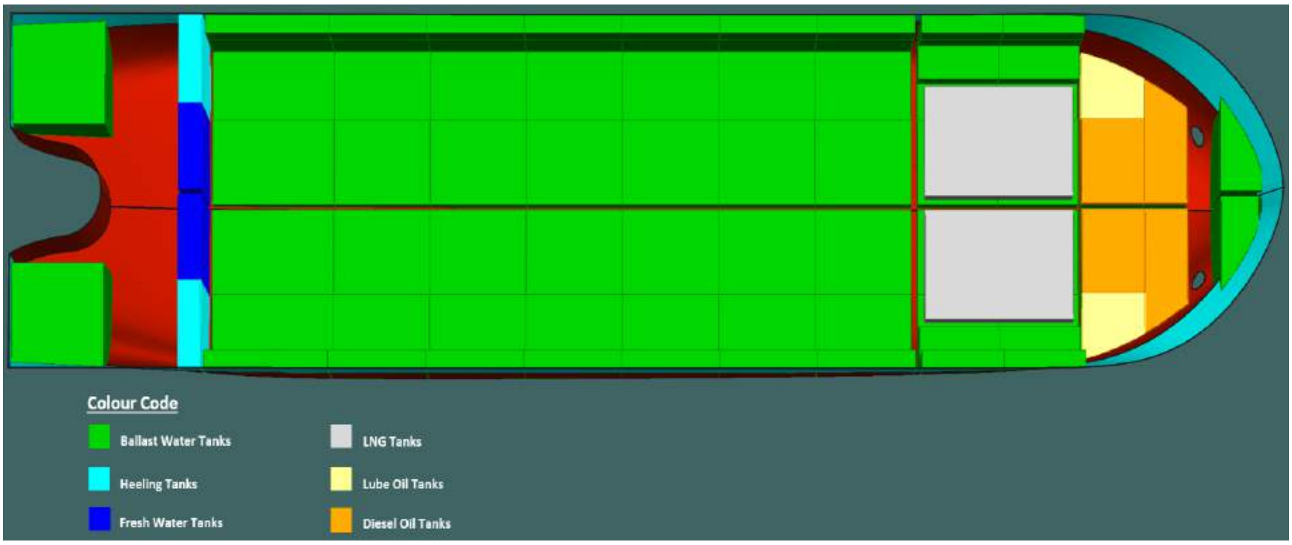


Figure 7-9 Plan of Tanks of Decom Tools Vessel

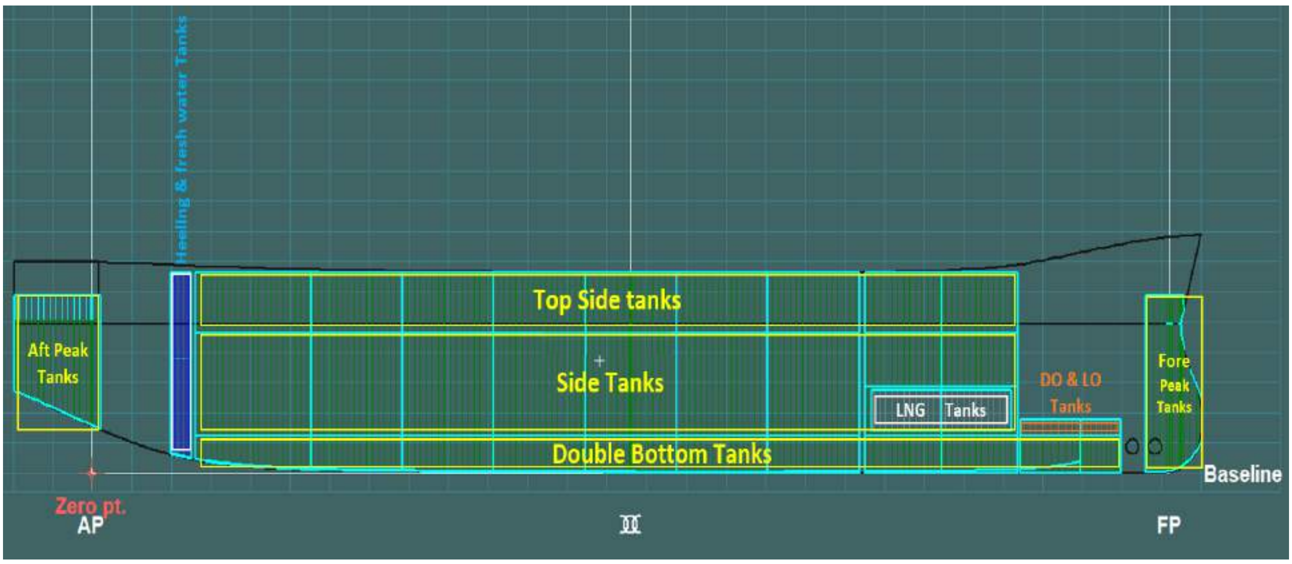


Figure 7-10 Side View of Decom Tools Vessel

7.9 Decom Tools Vessel Status at Lightweight Equilibrium

The output of the equilibrium analysis is to determine the draft, heel and trim of a vessel as a result of the loads applied on it. Therefore, MAXSURF stability software will be in charge of conducting this calculation in order to acquire the lightweight's equilibrium status of the designed vessel. During this analysis, all tanks are considered empty. Accordingly, the lightweight's equilibrium analysis the shows that the vessel is floating on a draft of 3.516 m and, on the trim of 2.068 m, to stern. The GM is 44.973 m which is reflecting a very stable vessel, See Figure 7-11.

LShip - Intact

1	Draft Amidships m	3.516
2	Displacement t	20744
3	Heel deg	0.0
4	Draft at FP m	2.481
5	Draft at AP m	4.550
6	Draft at LCF m	3.546
7	Trim (+ve by stern) m	2.068
8	WL Length m	175.635
9	Beam max extents on WL m	47.062
10	Wetted Area m^2	7594.228
11	Waterpl. Area m^2	7254.830
12	Prismatic coeff. (Cp)	0.721
13	Block coeff. (Cb)	0.653
14	Max Sect. area coeff. (Cm)	0.906
15	Waterpl. area coeff. (Cwp)	0.878
16	LCB from zero pt. (+ve fwd) m	83.110
17	LCF from zero pt. (+ve fwd) m	85.936
18	KB m	2.055
19	KG fluid m	14.983
20	BMt m	57.902
21	BML m	768.021
22	GMt corrected m	44.973
23	GML m	755.092
24	KMt m	59.953
25	KML m	770.024
26	Immersion (TPc) tonne/cm	74.362
27	MTc tonne.m	884.958
28	RM at 1deg = GMt.Disp.sin(1) tonne.m	16281.864
29	Max deck inclination deg	0.6695
30	Trim angle (+ve by stern) deg	0.6695

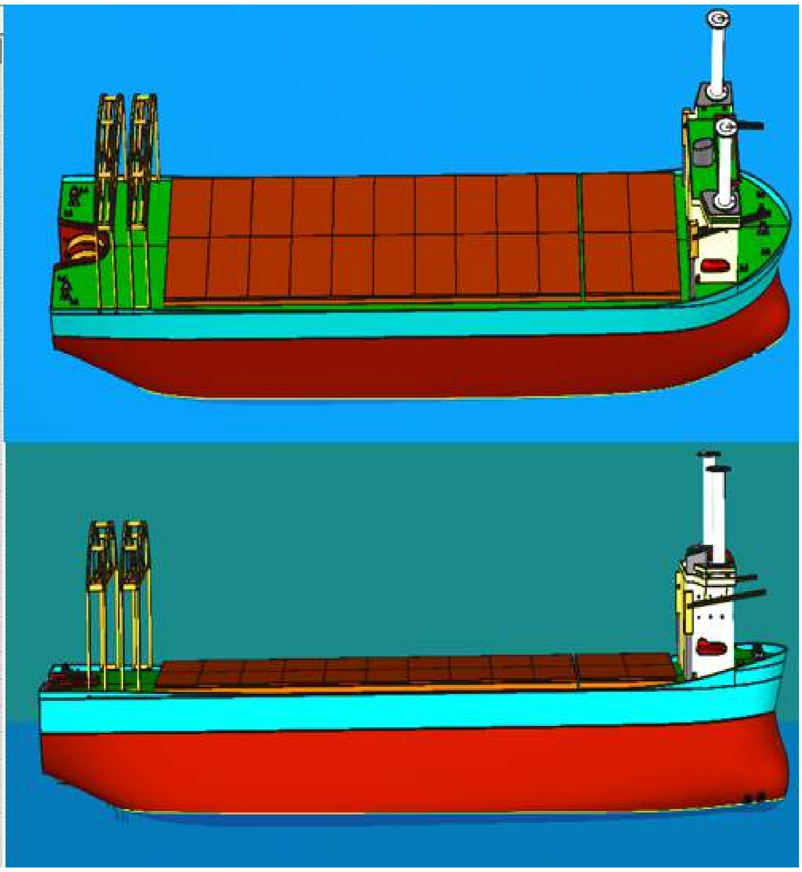
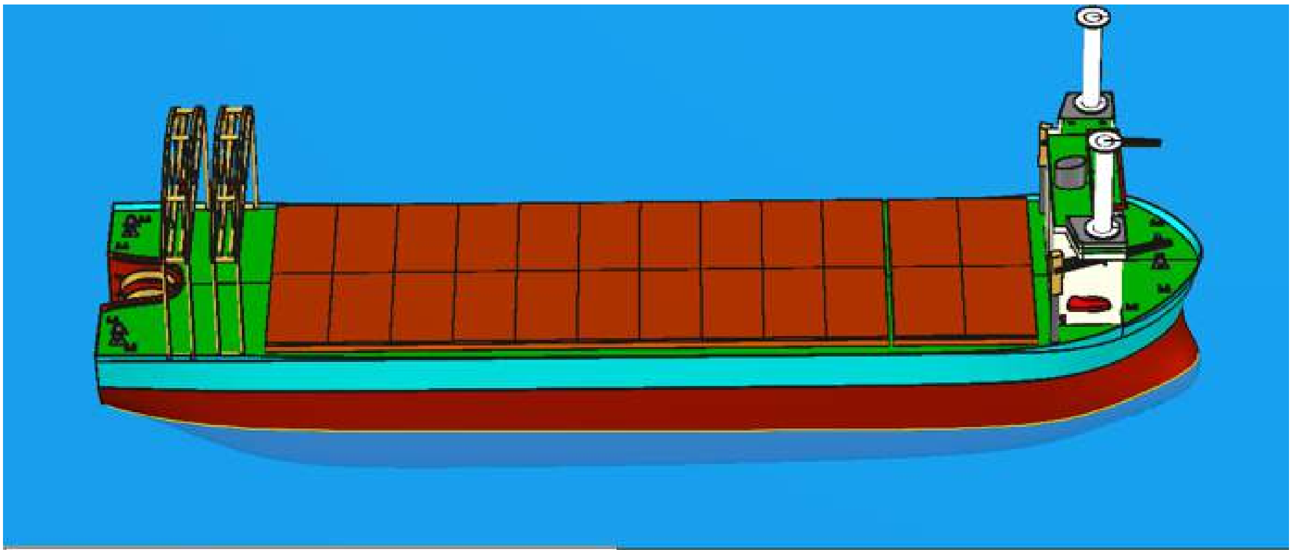


Figure 7-11 Decom Tools Vessel at Lightweight Equilibrium

7.10 Decom Tools Vessel Status at Full Ballast

In this section, all tanks onboard the designed vessel (ballast, fresh water, diesel, Lub oil and LNG tanks) are considered full, except heeling tanks are 50% full. Accordingly, the analysis shows that the vessel is floating on a fore draft of 9.3m and on an Aft draft of 11.5 m (Figure 7-12). The vessel has a liquid GM of 15.1 m. However, this GM is too high, which resulting in short roiling period and rapid rolling motion. Therefore, the rolling period will be assessed at the end of this chapter. Moreover, full stability assessment will be explained in the further section of this chapter.



FULLBALL - Intact

1	Draft Amidships m	10.401
2	Displacement t	76509
3	Heel deg	0.0
4	Draft at FP m	9.281
5	Draft at AP m	11.521
6	Draft at LCF m	10.483
7	Trim (+ve by stern) m	2.241
8	WL Length m	194.800
9	Beam max extents on WL m	47.931
10	Wetted Area m^2	10926.689
11	Waterpl. Area m^2	8301.077
12	Prismatic coeff. (Cp)	0.782
13	Block coeff. (Cb)	0.749
14	Max Sect. area coeff. (Cm)	0.958
15	Waterpl. area coeff. (Cwp)	0.889
16	LCB from zero pt. (+ve fwd) m	83.370
17	LCF from zero pt. (+ve fwd) m	81.994
18	KB m	5.726
19	KG fluid m	10.196
20	BMt m	19.570
21	BML m	291.326
22	GMt corrected m	15.100
23	GML m	286.856
24	KMt m	25.294
25	KML m	297.029
26	Immersion (TPc) tonne/cm	85.086
27	MTc tonne.m	1239.943
28	RM at 1deg = GMt.Disp.sin(1) tonne.m	20162.156
29	Max deck inclination deg	0.7253
30	Trim angle (+ve by stern) deg	0.7253

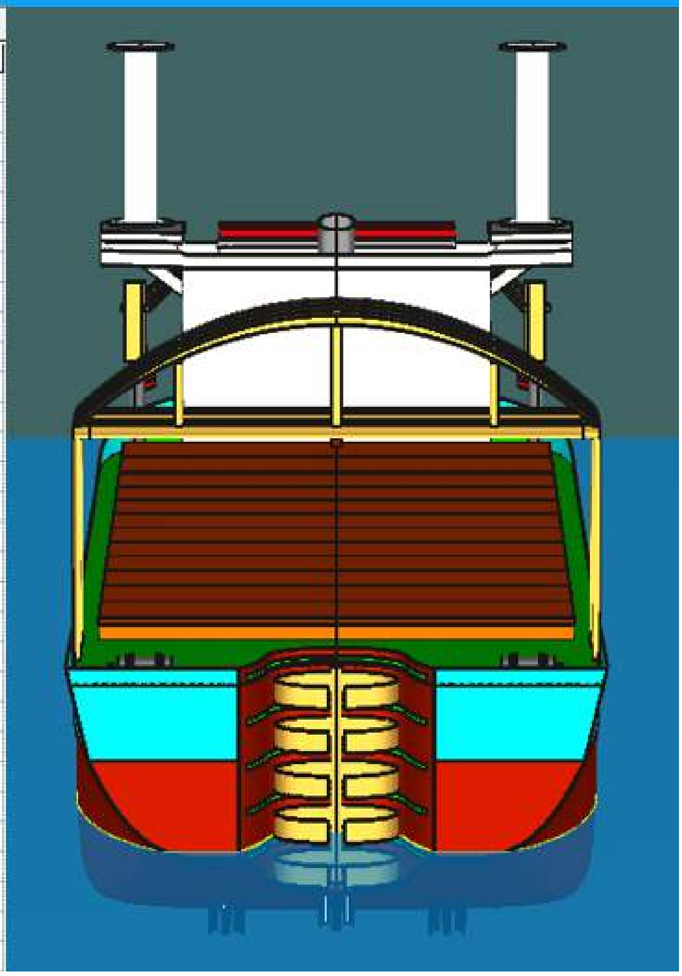


Figure 7-12 Decom Tools Vessel at full Ballast Equilibrium

7.11 Decom Tools Vessel Hydrostatic for Various Drafts

In order to calculate the stability of a ship, hydrostatic parameters of underwater hull shape at a range of drafts, at a zero or other fixed trim is required. Table 7-8 depicts the most important hydrostatic parameters for the designed vessel generated for a series of drafts in salt and steel water, where the water density is 1025 kg/m^3.

Table 7-8 Ship Hydrostatic Parameters for Various Drafts

Draft	Displacement	Displacement	Wetted Area	Waterpl. Area	Prismatic coeff. (Cp)	Block coeff. (Cb)	Max Sect. area coeff. (Cm)	LCB from zero pt. (+ve fwd)	LCF from zero pt. (+ve fwd)	KB	BMt	BML	KMt	KML	Immersion (TPc)	MTc
m	ton	m^3	m^2	m^2				m	m	m	m	m	m	m	tonne/cm	tonne.m
3	16878.0	16466.3	7263.6	6957.1	0.8	0.7	0.9	92.6	88.8	1.7	67.4	846.8	69.1	848.5	71.3	795.8
4	24193.0	23602.9	7810.2	7295.6	0.8	0.7	0.9	91.3	87.6	2.3	50.9	658.6	53.2	660.9	74.8	884.2
5	31817.0	31041.0	8332.8	7559.2	0.8	0.7	0.9	90.3	86.9	2.8	40.8	547.1	43.6	549.9	77.5	963.3
6	39668.0	38700.5	8812.8	7750.4	0.8	0.7	0.9	89.6	85.9	3.3	33.9	467.1	37.2	470.5	79.4	1023.0
7	47689.0	46525.9	9266.0	7890.8	0.8	0.8	0.9	88.9	85.2	3.9	29.0	406.5	32.9	410.4	80.9	1068.0
8	55839.0	54477.1	9717.8	8009.2	0.8	0.8	0.9	88.3	84.5	4.4	25.4	360.8	29.8	365.2	82.1	1108.0
9	64101.0	62537.6	10170.8	8111.3	0.8	0.8	0.9	87.8	83.8	4.9	22.6	325.0	27.5	330.0	83.1	1144.3
10	72464.0	70696.6	10632.9	8203.5	0.8	0.8	0.9	87.3	83.1	5.4	20.3	296.5	25.8	301.9	84.1	1178.7
11	80918.0	78944.4	11099.6	8290.4	0.8	0.8	1.0	86.8	82.3	6.0	18.5	273.4	24.5	279.4	85.0	1213.3
12	89439.0	87257.6	11562.4	8331.7	0.8	0.8	1.0	86.3	81.9	6.5	17.0	250.1	23.5	256.7	85.4	1226.1
13	97997.0	95606.8	12022.1	8364.6	0.8	0.8	1.0	85.9	81.7	7.0	15.7	230.2	22.7	237.3	85.7	1236.2
14	106584.0	103984.4	12484.7	8389.1	0.8	0.8	1.0	85.6	81.4	7.5	14.5	212.8	22.1	220.4	86.0	1242.8
15	115195.0	112385.4	12943.1	8414.0	0.8	0.8	1.0	85.3	81.3	8.1	13.6	198.1	21.6	206.2	86.2	1250.9
16	123831.0	120810.7	13402.5	8435.7	0.9	0.8	1.0	85.0	81.1	8.6	12.7	185.3	21.3	193.8	86.5	1258.2
17	132488.0	129256.6	13862.4	8455.2	0.9	0.8	1.0	84.7	81.0	9.1	12.0	173.9	21.1	183.0	86.7	1265.2
18	141164.0	137721.0	14321.1	8474.9	0.9	0.8	1.0	84.5	80.9	9.6	11.3	164.0	20.9	173.6	86.9	1273.2

A variety of calculation can be done by using the hydrostatic table, which includes calculation of transverse, and longitudinal stability. Figure 7-13 and Figure 7-14 depicts the identical information of the Table 7-8 but in a graphical layout, which makes hydrostatic data gathering for a given draft quick and easy.

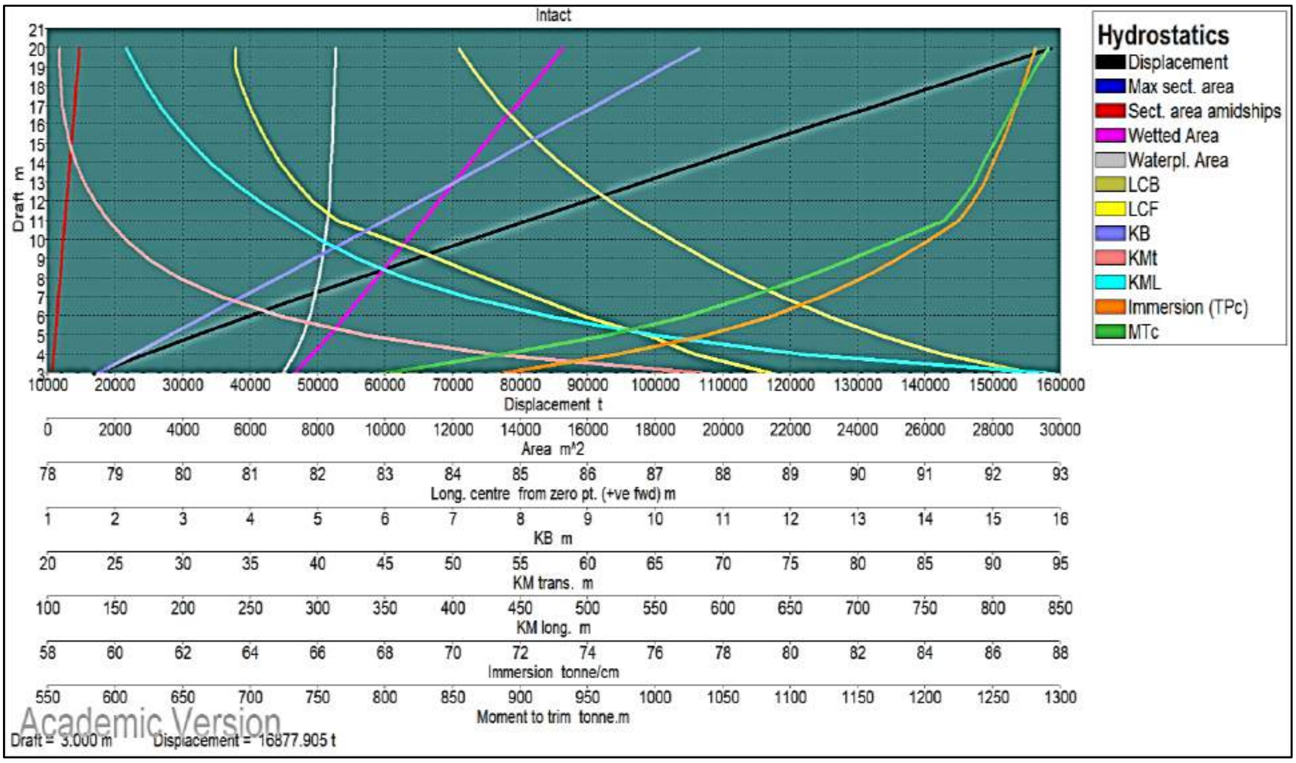


Figure 7-13 Hydrostatic Parameters of Decom Tools Vessel with respect to the draft

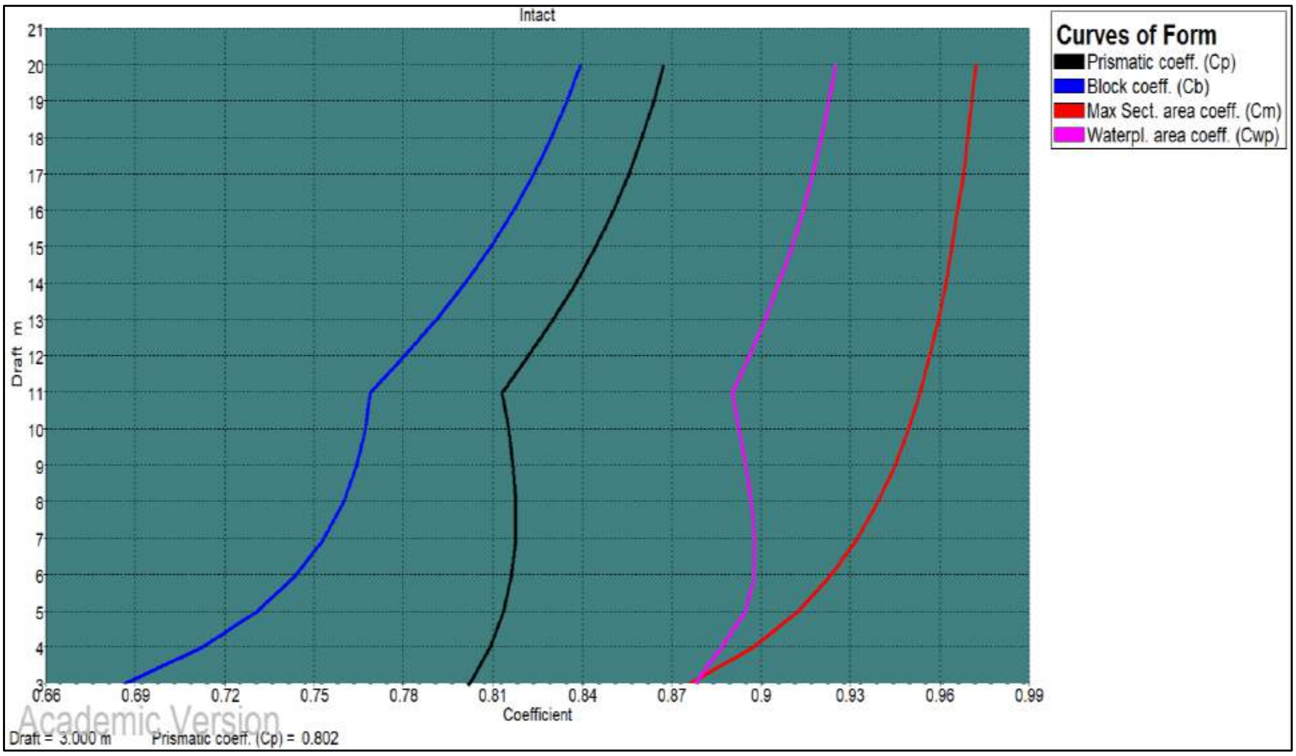


Figure 7-14 Curves of Form with Respect to Various Draft

7.12 Decom Tools Vessel KG Limit

Instead of a detailed assessment of the stability against the legal criteria a possibility to examine compliance with the code by means of a so-called limiting curve of the permissible KG_C or GM_C values could be a useful tool. In this case, all stability criteria are expressed by a single limiting value GM_C or KG_C.

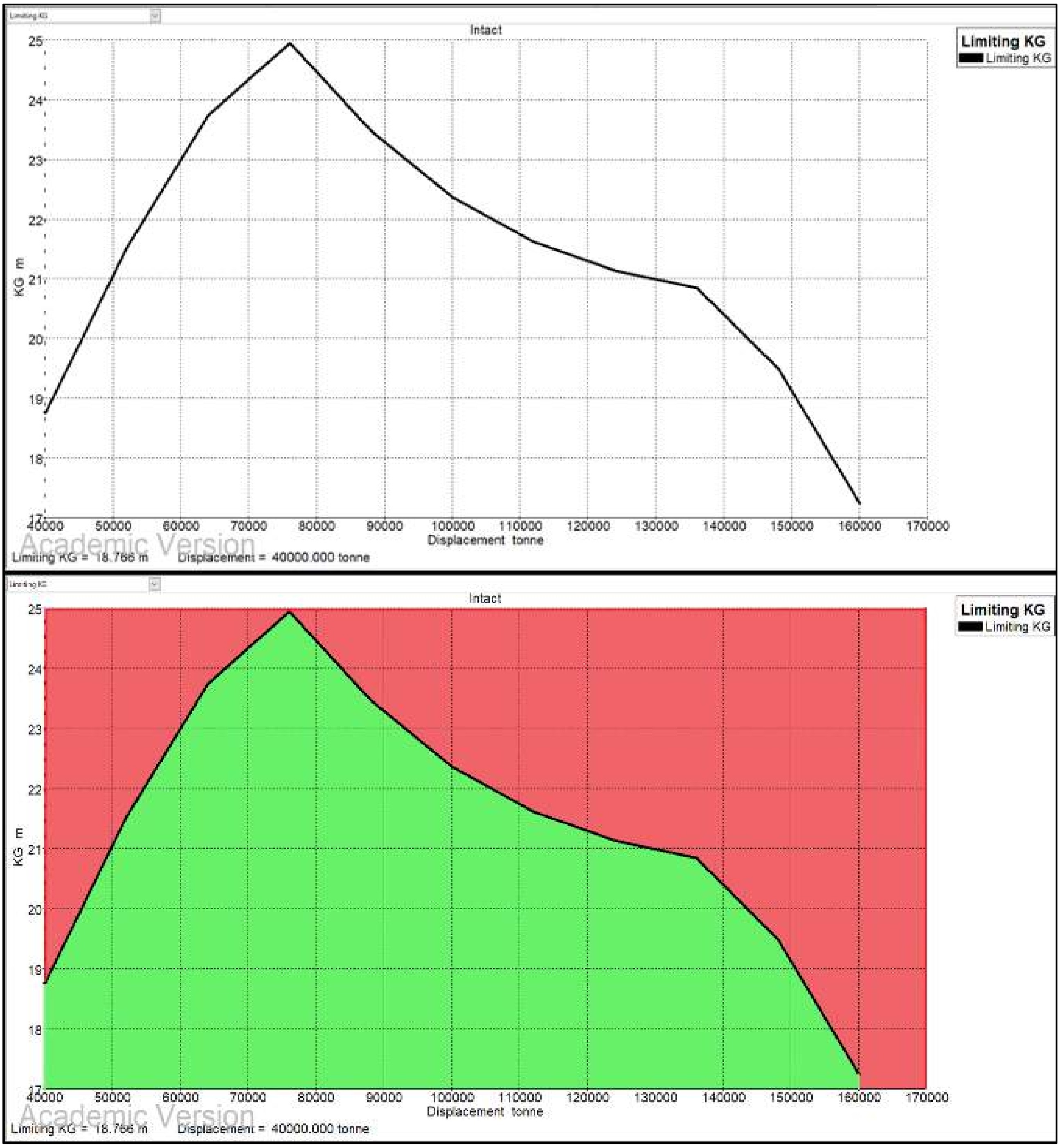


Figure 7-15 KG limit Based on IMO Intact Stability Criteria

Figure 7-15 represents the limiting KG curve at zero trim. The graph shows two different coloured areas, red and green. The red colour means that if the corrected KG is in this area the stability criteria will possibly not fully met, for instance it could affect the GZ curve and the dynamic stability as well, or even the GM will be not sufficient, so in this case loads arrangement on board have to be adjusted in order to fulfil the minimum required criteria. In contrast, any value for KG at any giving displacement in the green area will meet all the stability criteria and the vessel can procced with current arrangement or planned one.

Table 7-9 illustrates the result of limiting KG analysis for different displacement at different fixed trim.

Table 7-9 Decom Tools KG limit for Various Displacement

KG Limit For Different Displacements					
Displacement	**Trim -1**	**Trim 0**	**Trim +1**	**Trim +2**	**Trim +3**
40000	18.767	18.766	18.783	18.82	18.886
52000	21.491	21.536	21.598	21.682	21.785
64000	23.652	23.748	23.851	23.96	24.075
76000	24.872	24.961	25.044	25.121	25.192
88000	23.43	23.475	23.52	23.568	23.619
100000	22.344	22.372	22.405	22.442	22.484
112000	21.606	21.626	21.652	21.682	21.717
124000	21.128	21.143	21.163	21.189	21.219
136000	20.845	20.857	20.874	20.895	20.921
148000	19.594	19.499	19.4	19.301	19.208
160000	17.322	17.245	17.184	17.138	17.096

7.13 Decom Tools Vessel GZ & Cross Curve

The centre of buoyancy B is always the geometrical centre of the submerged hull volume. When an external force influences the ship the angle of heel changes, as the ship heel the centre of buoyancy B move from the ship's centreline. It is shifted in the direction of the heel and to the lower side of the underwater hull form in order to remain in the geometric centre of the submersed hull volume. The centre of buoyancy rotates about the metacentre M with changes the angle of heel. The Balanced forces weight and buoyancy move out of vertical alignment as the centre of buoyancy B shifts with change in the submersed hull volume. Furthermore, as an external force causes the ship to heel a righting moment occurs, which attempt to restore the vessel to state of stable equilibrium. As the ship heels, the centre of buoyancy will start shifting to the new geometric centre of the underwater hull volume underlines of action of two forces, gravity and buoyancy, this exerts a righting moment which attempt to return the ship to the upright position if the GM is positive. Figure 7-16 shows the heeled vessel and, the shifted centre of buoyancy from B to B_1, as well as GZ.

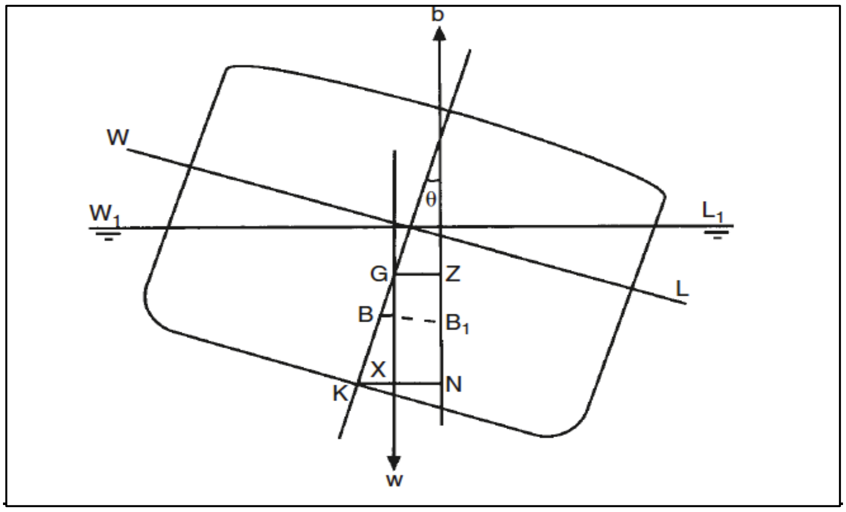


Figure 7-16 Heeled Vessel Due to External Loads (Barrass and Derrett 2006)

Upright vessel means that the vessel has no heel or list angle. In other words, the buoyancy B and the centre of gravity G align with ship's centreline. When the two equal and opposite forces weight and buoyancy are shifted out of their alignment, they are separated by distance called GZ. This distance is known as righting lever.

Righting moment (ton meters) = Displacement * GZ

The GZ curve is the stability curve for a ship and is obtained by plotting the righting lever (GZ) against varying heeling angles. In any stability analysis, the value of GZ is plotted over the entire range of heeling angles for which it is positive to form the GZ curve. GZ can be calculated by using the following formula

$$GZ = KN.KG \sin \emptyset$$

Where N is the point where the perpendicular from the keel point intersects with the vertical from M (the metacentre), See Figure 7-16. KN is a function of the underwater hull shape and can be found from KN curves of stability. Whereas GZ is the righting lever with respect to the Centre of Gravity, KN is the righting lever with respect to the Keel. Once the KN curve is derived for a particular displacement, GZ can be easily calculated for any loading condition.

Figure 7-17 shows the example of the Decom Tools vessel GZ curve. The left curve represents the vessel in the state of equilibrium upright status, while the right curve shows that the vessel in the state of equilibrium list (or heel, in case external forces, example wind).

Several information can be gathered from the curve, such as the range of stability, angle of vanishing stability, as well as the necessary information to calculate the dynamic stability

- Angle of vanishing stability: if the vessel heeled to this angle, that means, at this angle of heel the buoyancy B and centre Gravity G are in the same vertical line the GZ become zero and there is no righting moment exist. If the ship heeled bonyad this angle the centre of gravity G move out of the vertical alignment line with centre of buoyancy B to the wrong side, resulting in a moment which tends to capsize the ship because the righting arm is negative.

- Dynamic stability is measured with: GZ (righting lever) - the moment arm which the forces of gravity and buoyancy use when they try to return the ship to its original floating position.

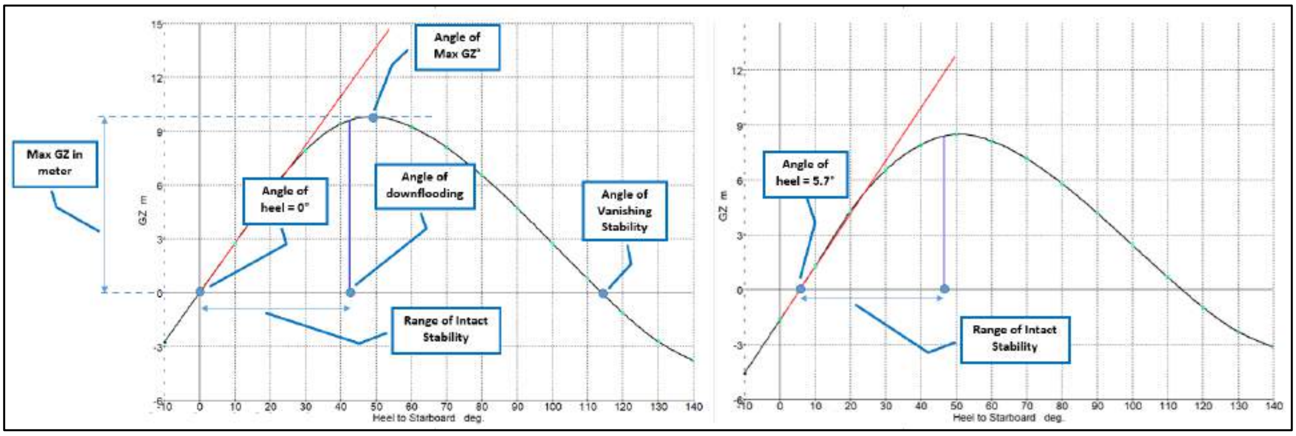


Figure 7-17 GZ Curve for Upright and Heeled Decom Tools Vessel

Therefore, in order to draw the GZ curve we need to know the KN value for each angle of heel. KN values for the Decom tools vessel are generated by using the MAXSURF stability software. KN values analysis for Decom Tools vessel has been set up to heel angle of 60 degrees, furthermore, the trim was considered zero. “Cross curves of stability is a set of curves from which the KN values for a set of constant heel-angle values at any particular displacement may be read”. (WÄRTSILÄ 2021). Figure 7-18 shows the Decom Tools KN curve.

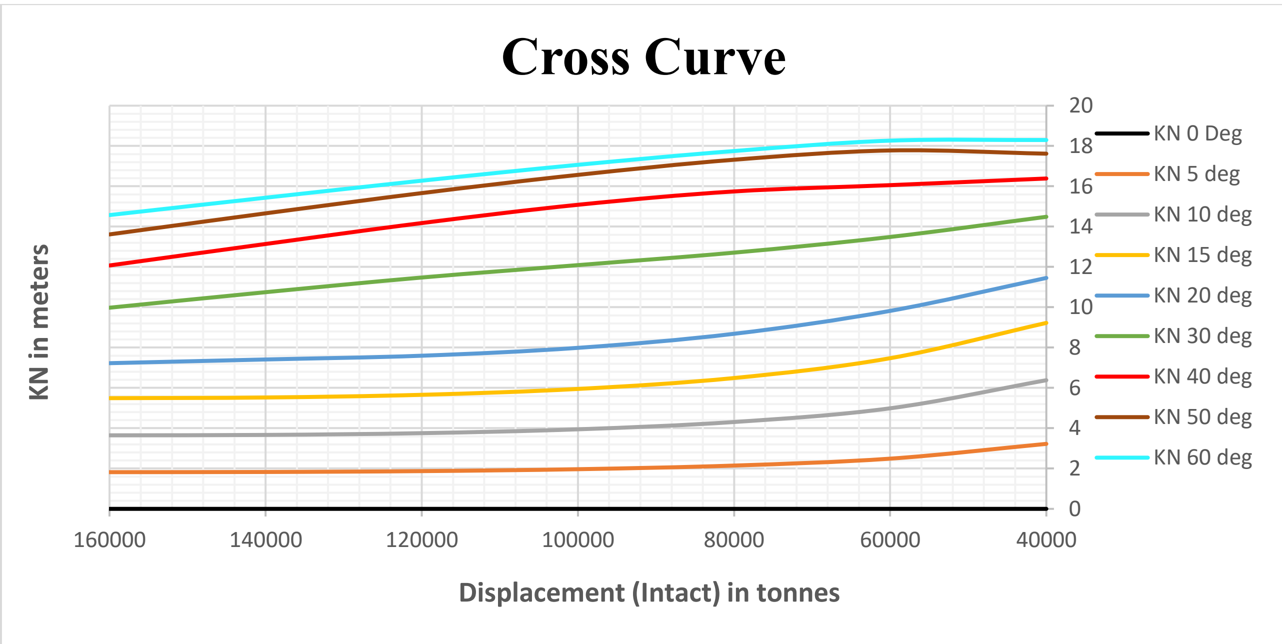


Figure 7-18 KN Curves of Decom Tools Vessel

7.14 Decom Tools Vessel Critical Openings

Critical openings are those that allow flooding water to enter into ship's hull. Relevant to intact calculations, critical openings are the unprotected openings in the hull, superstructures, or deckhouse, which cannot be closed watertight, allowing water at certain heel angle to have a progressive flooding from the sea. Progressive flooding is when flood water enters through unprotected and undamaged watertight intact compartments or damaged and intact compartments. The flooding water will affect the ship stability and the stability range is limited to an angle of heel at which these unprotected opening immerses.

The critical known opening on a ship could be either known or unknown openings. Progressive flooding through know opening occurs when flood water enters through doors, hatches, pipes, staircases, and so on, into an intact compartment. Progressive flooding also occurs through other openings. Flood water from damaged watertight compartments can enter intact ones, through non-watertight openings which are unknown. These could be cable penetrations through watertight bulkheads, leakage through doors (which should be watertight), or additional flooding through unknown penetrations at watertight bulkheads. Therefore, spaces adjacent to flooded compartments should be monitored for progressive flooding.

The designed ship does only have opening hatch covers in some stowage plans where hatch covers will be kept open during the transportation phase. For instance, hold no 1 will carry tower segments which are loaded on a vertical direction, each segment has height more than 60 meters. So, in order to calculate the dynamic stability, we should look always to the angle of down flooding at which angle will be occurred. The angle of heel at which these openings are immersed is called the angle of down flooding $\boldsymbol{\emptyset_f}$.

Accordingly, the coordinates of the opening points are illustrated in Table 7-10:

Table 7-10 Coordinate of Flooding Points

	Name	Long. Pos. m	Offset m	Height m	Type	Linked to	Flood from
1	DF1	150.000	21.500	28.000	Downflooding point	HOLD1ST	Sea
2	DF2	129.000	21.500	28.000	Downflooding point	HOLD1ST	Sea
3	DF3	125.000	21.500	28.000	Downflooding point	HOLD2PO	Sea
4	DF4	17.500	21.500	28.000	Downflooding point	HOLD2ST	Sea
5	DF1A	150.000	-21.500	28.000	Downflooding point	HOLD1PO	Sea
6	DF2A	129.000	-21.500	28.000	Downflooding point	HOLD1PO	Sea
7	DF3A	125.000	-21.500	28.000	Downflooding point	HOLD2PO	Sea
8	DF4A	17.500	-21.500	28.000	Downflooding point	HOLD2PO	Sea

These points are relevant only in case of both holds are kept open. Figure 7-19 shows the location of the opening points along the vessel, they are illustrated in blue line.

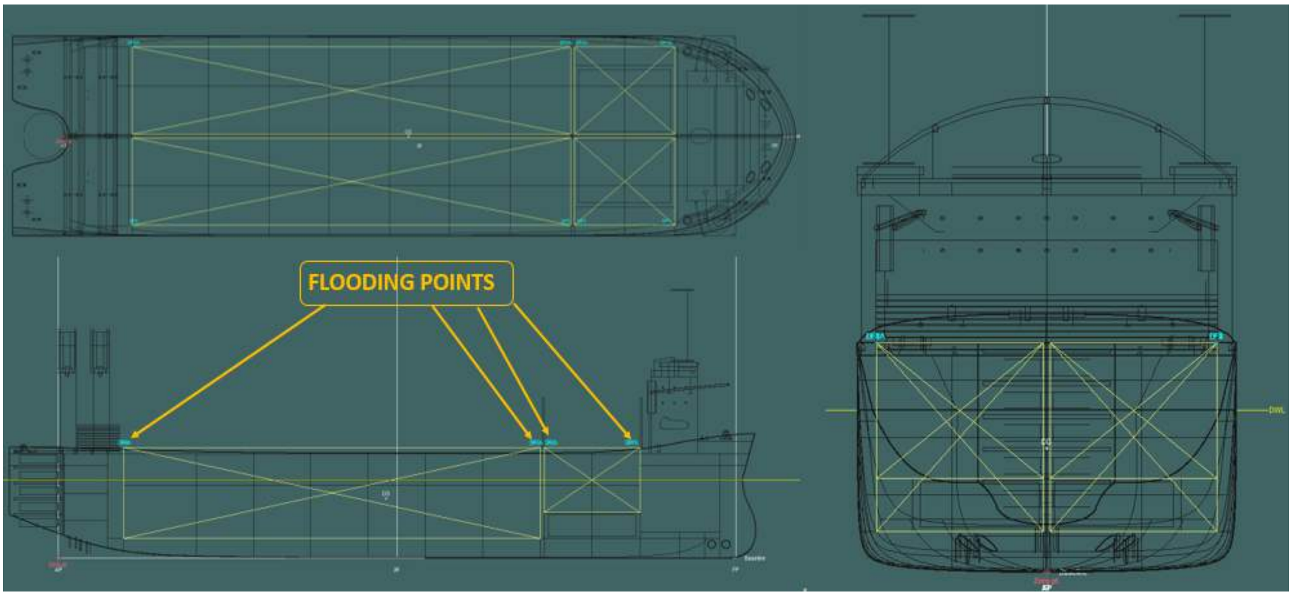


Figure 7-19 Flooding Point of the Decom Tools Vessel

For the upcoming analyses, only hold no 1 will be kept open and therefore the following points (DF1, DF2, DF1A, DF2A) will be included in the stability calculation.

7.15 Stability Assessment for 12 MW Wind Turbine

This section will analysis the intact stability of the designed ship during loading 8 complete sets of 12 MW which include 8 Nacelle, 24 blades, 8 towers (16 section). Table 7-11 describes the necessary dimension for the loaded components which will be used further on during the stowage and stability analysis.

Table 7-11 Weight and Dimension of 12 MW Wind Turbine

Weight and Dimension of 12 MW Wind Turbine	
Component Name	**Size**
Blade length (m)	107
Blade Diameter	5.5
Blade mass (t)	55
Max. chord (m)	6
Hub mass (t)	75
Nacelle mass (t)	600
Nacelle + Hub mass (t)	675
Nacelle dimensions (m) (L x W x H)	20.6 x 11 x 10.4
Nacelle with hub dimensions (m) (L x W x H)	29 x 11 x 10.5
Tower Mass (t)	880
Tower Height (m)	129
Tower top diameter (m)	5.5
Tower bottom diameter (m)	10

7.15.1 Overall COG and Weight of 8 Sets of 12 MW Wind Turbines

In order to find the overall centre of gravity for the loaded components firstly it is essential to estimate the COG for each single component, therefore, the following table (Table 7-12) will illustrate the methodology of calculating the Centre of Gravity for each turbine component.

Table 7-12 LCG, TCG & VCG Estimation

Components Description	Weight	Length	Width or Diameter	Height	LCG Blade is 33,3% & Nacelle is 50 %	TCG	VCG @ 60 % of Height (*)
Blade laid horizontally	55	107	5.5	5.5	35.6631	0	3.3
Hub	75	9	7	7	4.5	0	4.2
Nacelle	600	20.6	11	10.4	10.3	0	6.24
Nacelle + Hub	675	29.6	11	10.4	14.80	0	6.24
Tower Section 1 in hold No1	587		10	64.6	5	0	38.76
Tower Section 2 on top of Hatch cover 2	293		6.75	64.5	3.375	0	38.7

***Note:** In reality it could be less than 50% of the component's height, but due to lack of information and for increasing the safety we considered the VCG as 60% of the component height.

Figure 7-20 shows the centre of gravity for each part, only LCG and VCG. TCG is considered zero for all parts.

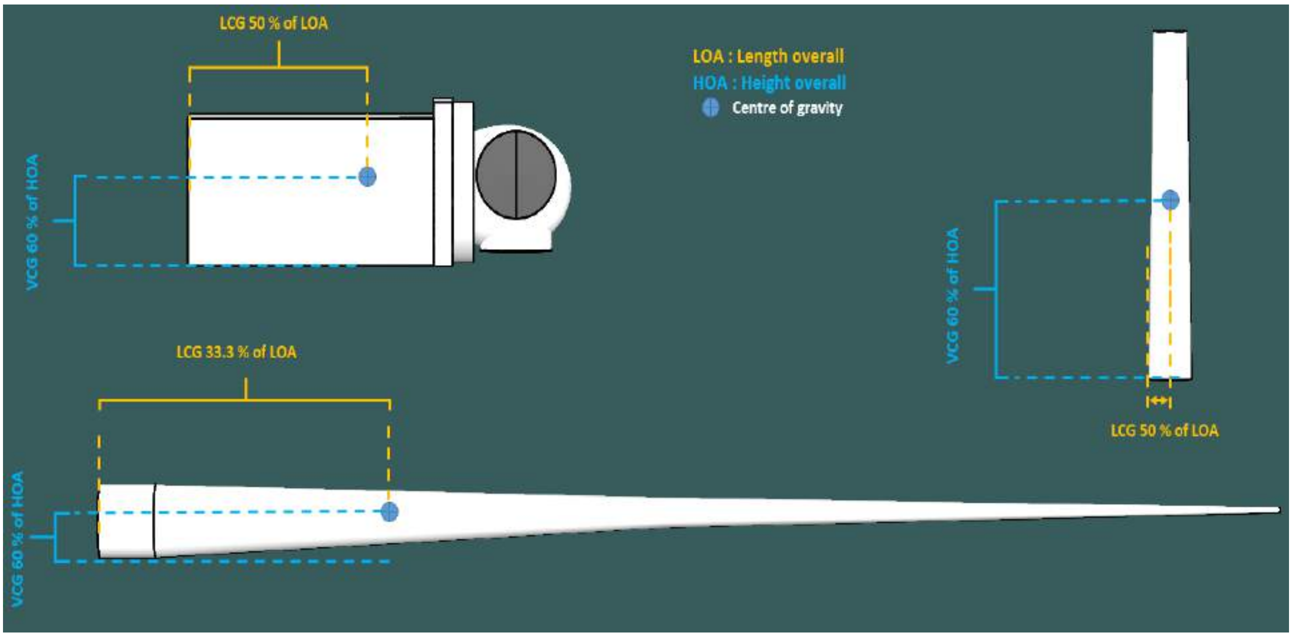


Figure 7-20 VCG, TCG & LCG of 12MW Wind Turbine

To calculate the overall centre of gravity for the proposed stowage plan, (Figure 7-21) determination of the COG for each component separately is a must. COG determination has to be in regard to the keel (VCG), Aft perpendicular (LCG), and centreline (TCG). Secondly, after gathering the exact location for the component's COG, adding all the information in the moment table can compute the final requested COG.

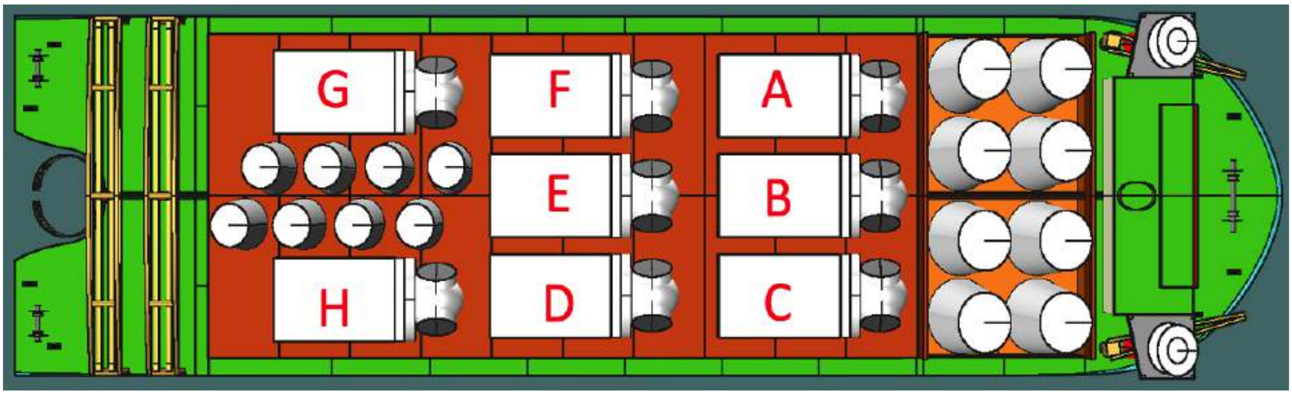


Figure 7-21 12 MW Wind Turbine Arrangement

VCG for Nacelle A is the vertical distance from keel to the centre of gravity of the Nacelle A, where the LCG of the Nacelle A is the positive longitudinal distance from the aft perpendicular to the COG of the Nacelle A, and finally, the TCG of Nacelle A is the negative transverse distance from the centre line to the COG of Nacelle. Below table shows the calculation of final VCG of the proposed stowage plan. The following formulas are in use for computing COG:

$$Final\ VCG = \frac{Vertical\ moment}{Final\ weight}$$

$$Final\ LCG = \frac{Longitudinal\ moment}{Final\ weight}$$

$$Final\ TCG = \frac{Transverse\ moment}{Final\ weight}$$

7.15.1.1 Departure Condition

During the analysis all tanks were full except Aft peck tanks were on 74% full, and heeling tanks were 50% full. Both Aft Peck Tanks as well as Heeling tanks generated free surface effect. The free surface correction is 0.081m, this correction has to be added to the KG solid, which give liquid KG of 15.302m. Following table shows the overall load arrangement for the proposed stowage plan. Loads arrangement contain all involved tanks during the stability calculation including their capacities, as well as the COG for each single tank, and the free surface moment for the slacked one. The overall weight of the turbine components is also part of this calculation.

Table 7-13 Calculation of Centre of Gravity for 12 MW Wind Turbine

Component Name	Qty	Weight For 1 Pcs.	Overall Weight	LCG	TCG	VCG	Long. Moment	Tran. Moment	Vertical moment
Unit		tonne	tonne	m	m	m	t.m	t.m	t.m
Blades end in direction to AFT	12	55	660	53.66	0	13.74	35417.6	0	9067.7
Blades end in direction to FWD	12	55	660	89.83	0	18.84	59292.3	0	12433.7
Nacelle + Hub (A)	1	675	675	110.1	-13.25	35.50	74320.8	-8943.7	23962.5
Nacelle + Hub (B)	1	675	675	110.1	0	35.50	74320.8	0	23962.5
Nacelle + Hub (C)	1	675	675	110.1 0	13.25	35.50	74320.8	8943.7	23962.5
Nacelle + Hub (D)	1	675	675	75.10	13.25	35.50	50695.8	8943.7	23962.5
Nacelle + Hub (E)	1	675	675	75.10	0	35.50	50695.8	0	23962.5
Nacelle + Hub (F)	1	675	675	75.10	-13.25	35.50	50695.8	-8943.7	23962.5
Nacelle + Hub (G)	1	675	675	42.10	-13.25	35.50	28420.8	-8943.7	23962.5
Nacelle + Hub (H)	1	675	675	42.10	13.25	35.50	28420.8	8943.7	23962.5
Towers in hold Numb 1	8	587	4696	139.5	0	50.26	655514.6	0	236020.9
Towers on top of Hatch cover 2 Aft	8	293	2344	38.36	0	67.30	89922.8	0	157751.2
Overall cargo			**13760**	**92.44**	**0**	**44.11**	**1272039.51**	**0**	**606973.6**

Table 7-14 Weights & COG of Loads (8 Set of 12 MW Wind Turbine)

Item Name	Quantity	Unit Mass	Total Mass	Unit Volume	Total Volume	Long. Arm	Trans. Arm	Vert. Arm
		tonne	tonne	m^3	m^3	m	m	m
Lightship	1	20744.7	20744.7			83.3	0.0	14.9
FPTS	100%	1197.5	1197.5	1168.3	1168.3	176.8	4.0	11.6
FPTP	100%	1196.7	1196.7	1167.5	1167.5	176.7	-4.0	11.6
DB1S	100%	351.2	351.2	342.7	342.7	165.5	6.2	2.9
DB1P	100%	351.2	351.2	342.7	342.7	165.5	-6.2	2.9
DB2S	100%	184.8	184.8	180.3	180.3	156.6	14.7	3.4
DB2P	100%	184.8	184.8	180.3	180.3	156.6	-14.7	3.4
DB2SC	100%	539.8	539.8	526.6	526.6	157.4	6.0	2.6
DB2PC	100%	539.8	539.8	526.6	526.6	157.4	-6.0	2.6

Item Name	Quantity	Unit Mass	Total Mass	Unit Volume	Total Volume	Long. Arm	Trans. Arm	Vert. Arm
		tonne	tonne	m^3	m^3	m	m	m
DB3S	100%	422.2	422.2	411.9	411.9	145.4	16.0	3.1
DB3P	100%	422.2	422.2	411.9	411.9	145.4	-16.0	3.1
DB3SC	100%	711.7	711.7	694.4	694.4	145.7	6.1	2.6
DB3PC	100%	711.7	711.7	694.4	694.4	145.7	-6.1	2.6
DB4S	100%	507.1	507.1	494.7	494.7	133.1	16.6	3.0
DB4P	100%	507.1	507.1	494.7	494.7	133.1	-16.6	3.0
DB4SC	100%	716.8	716.8	699.4	699.4	133.2	6.2	2.5
DB4PC	100%	716.8	716.8	699.4	699.4	133.2	-6.2	2.5
DB5S	100%	663.3	663.3	647.1	647.1	118.4	16.9	2.9
DB5P	100%	663.3	663.3	647.1	647.1	118.4	-16.9	2.9
DB5SC	100%	862.4	862.4	841.4	841.4	118.5	6.2	2.5
DB5PC	100%	862.4	862.4	841.4	841.4	118.5	-6.2	2.5
DB6S	100%	694.0	694.0	677.0	677.0	103.5	17.1	2.9
DB6P	100%	694.0	694.0	677.0	677.0	103.5	-17.1	2.9
DB6SC	100%	861.8	861.8	840.8	840.8	103.5	6.2	2.5
DB6PC	100%	861.8	861.8	840.8	840.8	103.5	-6.2	2.5
DB7S	100%	711.1	711.1	693.8	693.8	88.5	17.2	2.9
DB7P	100%	711.1	711.1	693.8	693.8	88.5	-17.2	2.9
DB7SC	100%	858.0	858.0	837.1	837.1	88.5	6.2	2.5
DB7PC	100%	858.0	858.0	837.1	837.1	88.5	-6.2	2.5
DB8S	100%	718.1	718.1	700.6	700.6	73.5	17.3	2.9
DB8P	100%	718.1	718.1	700.6	700.6	73.5	-17.3	2.9
DB8SC	100%	850.1	850.1	829.4	829.4	73.5	6.2	2.6
DB8PC	100%	850.1	850.1	829.4	829.4	73.5	-6.2	2.6
DB9S	100%	714.4	714.4	697.0	697.0	58.5	17.3	2.9
DB9P	100%	714.4	714.4	697.0	697.0	58.5	-17.3	2.9
DB9SC	100%	835.9	835.9	815.5	815.5	58.5	6.2	2.6
DB9PC	100%	835.9	835.9	815.5	815.5	58.5	-6.2	2.6
DB10S	100%	692.8	692.8	675.9	675.9	43.6	17.3	3.0
DB10P	100%	692.8	692.8	675.9	675.9	43.6	-17.3	3.0
DB10SC	100%	808.7	808.7	788.9	788.9	43.6	6.2	2.7
DB10PC	100%	808.7	808.7	788.9	788.9	43.6	-6.2	2.7
DB11S	100%	722.5	722.5	704.8	704.8	27.2	17.1	3.2
DB11P	100%	722.5	722.5	704.8	704.8	27.2	-17.1	3.2
DB11SC	100%	887.6	887.6	866.0	866.0	27.0	6.2	3.0
DB11PC	100%	887.6	887.6	866.0	866.0	27.0	-6.2	3.0
ST3S	100%	431.2	431.2	420.7	420.7	145.5	19.7	8.4
ST3P	100%	431.2	431.2	420.7	420.7	145.5	-19.7	8.4

Item Name	Quantity	Unit Mass	Total Mass	Unit Volume	Total Volume	Long. Arm	Trans. Arm	Vert. Arm
		tonne	tonne	m^3	m^3	m	m	m
LST3S	100%	134.1	134.1	130.8	130.8	145.0	22.3	15.2
LST3P	100%	134.1	134.1	130.8	130.8	145.0	-22.3	15.2
ST4S	100%	499.7	499.7	487.5	487.5	133.2	20.1	8.3
ST4P	100%	499.7	499.7	487.5	487.5	133.2	-20.1	8.3
LST4S	100%	185.5	185.5	181.0	181.0	133.1	22.6	15.1
LST4P	100%	185.5	185.5	181.0	181.0	133.1	-22.6	15.1
ST5S	100%	438.3	438.3	427.6	427.6	118.4	22.6	12.1
ST5P	100%	438.3	438.3	427.6	427.6	118.4	-22.6	12.1
ST6S	100%	464.4	464.4	453.1	453.1	103.5	22.6	12.0
ST6P	100%	464.4	464.4	453.1	453.1	103.5	-22.6	12.0
ST7S	100%	478.4	478.4	466.7	466.7	88.5	22.7	11.9
ST7P	100%	478.4	478.4	466.7	466.7	88.5	-22.7	11.9
ST8S	100%	486.4	486.4	474.5	474.5	73.5	22.7	11.9
ST8P	100%	486.4	486.4	474.5	474.5	73.5	-22.7	11.9
ST9S	100%	490.6	490.6	478.7	478.7	58.5	22.7	11.9
ST9P	100%	490.6	490.6	478.7	478.7	58.5	-22.7	11.9
ST10S	100%	490.1	490.1	478.2	478.2	43.5	22.7	11.9
ST10P	100%	490.1	490.1	478.2	478.2	43.5	-22.7	11.9
ST11S	100%	570.2	570.2	556.3	556.3	26.9	22.6	12.0
ST11P	100%	570.2	570.2	556.3	556.3	26.9	-22.6	12.0
TST3S	100%	210.6	210.6	205.4	205.4	145.5	22.6	22.7
TST3P	100%	210.6	210.6	205.4	205.4	145.5	-22.6	22.7
TST4S	100%	240.3	240.3	234.4	234.4	133.2	22.7	22.6
TST4P	100%	240.3	240.3	234.4	234.4	133.2	-22.7	22.6
TST5S	100%	297.6	297.6	290.4	290.4	118.5	22.7	22.5
TST5P	100%	297.6	297.6	290.4	290.4	118.5	-22.7	22.5
TST6S	100%	300.3	300.3	293.0	293.0	103.5	22.7	22.5
TST6P	100%	300.3	300.3	293.0	293.0	103.5	-22.7	22.5
TST7S	100%	301.1	301.1	293.7	293.7	88.5	22.7	22.5
TST7P	100%	301.1	301.1	293.7	293.7	88.5	-22.7	22.5
TST8S	100%	301.3	301.3	293.9	293.9	73.5	22.8	22.5
TST8P	100%	301.3	301.3	293.9	293.9	73.5	-22.8	22.5
TSTk9S	100%	301.3	301.3	294.0	294.0	58.5	22.8	22.5
TST9P	100%	301.3	301.3	294.0	294.0	58.5	-22.8	22.5
TST10S	100%	301.1	301.1	293.8	293.8	43.5	22.7	22.5
TST10P	100%	301.1	301.1	293.8	293.8	43.5	-22.7	22.5
TST11S	100%	374.9	374.9	365.7	365.7	26.6	22.7	22.5
TST11P	100%	374.9	374.9	365.7	365.7	26.6	-22.7	22.5

Item Name	Quantity	Unit Mass	Total Mass	Unit Volume	Total Volume	Long. Arm	Trans. Arm	Vert. Arm
		tonne	tonne	m^3	m^3	m	m	m
HTSTBD	50%	937.4	468.7	914.6	457.3	14.8	17.3	9.2
HTPORT	50%	937.4	468.7	914.6	457.3	14.8	-17.3	9.2
FWSTBD	100%	965.9	965.9	965.9	965.9	14.8	6.2	14.4
FWPORT	100%	965.9	965.9	965.9	965.9	14.8	-6.2	14.4
APTSTBD	74%	2406.9	1781.1	2348.2	1737.6	-4.9	15.1	14.9
APTPORT	74%	2406.9	1781.1	2348.2	1737.6	-4.9	-15.1	14.9
LNGSTBD	100%	874.0	874.0	1859.6	1859.6	139.5	8.5	8.3
LNGPORT	100%	874.0	874.0	1859.6	1859.6	139.5	-8.5	8.3
DO1STBD	100%	161.8	161.8	192.6	192.6	165.5	7.8	6.0
DO1PORT	100%	161.8	161.8	192.6	192.6	165.5	-7.8	6.0
LOSTBD	100%	126.6	126.6	137.6	137.6	157.0	15.7	6.0
LOPORT	100%	126.6	126.6	137.6	137.6	157.0	-15.7	6.0
DO2STBD	100%	187.5	187.5	223.3	223.3	157.4	6.2	6.0
DO2PORT	100%	187.5	187.5	223.3	223.3	157.4	-6.2	6.0
8 Sets - 12 MW WT		**13760.0**	**13760.0**			**92.4**	**0.0**	**44.1**
Total Load Case			**89253.6**	**57788.4**	**55652.8**	**86.3**	**0.0**	**15.2**
FS correction								**0.081**
VCG fluid								**15.302**

The abbreviations that are used in above table are stand for following terms:

- **FPTS:** Fore peak tanks STBD side
- **DB2PC:** Double bottom tanks number 2 port centre
- **ST3S:** Side tank number 3 STBD side
- **ST3P:** Side tank number 3 Port side
- **TST5S:** Top side tank number 5 STBD side
- **HTPORT**: Heeling tank Port side
- **FWSTBD**: Freshwater tank STBD side
- **APTPORT:** Aft peak tanks port side
- **LNGSTBD:** Liquefied naturel gas tank STBD side
- **DO1STBD:** diesel oil tank no 1 STBD side
- **LOPORT:** Lube oil tank port side

Figure 7-22 shows the result of the equilibrium analysis when the Decom Tools vessel was loaded with 8 set of 12 MW wind turbines at departure condition. The equilibrium analysis shows that the vessel under the proposed stowage plan is floating on an even keel draft of 11.979m, which resulted on 14.45 m freeboard. Furthermore, the corrected transvers metacentric height GM is 8.186 m which fulfils the IMO stability criteria.

12MW - Intact		
1	Draft Amidships m	11.979
2	Displacement t	89260
3	Heel deg	0.0
4	Draft at FP m	11.975
5	Draft at AP m	11.983
6	Draft at LCF m	11.979
7	Trim (+ve by stern) m	0.008
8	WL Length m	193.932
9	Beam max extents on WL m	47.963
10	Wetted Area m^2	11553.131
11	Waterpl. Area m^2	8331.007
12	Prismatic coeff. (Cp)	0.821
13	Block coeff. (Cb)	0.780
14	Max Sect. area coeff. (Cm)	0.957
15	Waterpl. area coeff. (Cwp)	0.896
16	LCB from zero pt. (+ve fwd) m	86.330
17	LCF from zero pt. (+ve fwd) m	81.920
18	KB m	6.490
19	KG fluid m	15.302
20	BMt m	16.998
21	BML m	250.607
22	GMt corrected m	8.186
23	GML m	241.795
24	KMt m	23.488
25	KML m	257.097
26	Immersion (TPc) tonne/cm	85.393
27	MTc tonne.m	1219.364
28	RM at 1deg = GMt.Disp.sin(1) tonne.m	12752.832
29	Max deck inclination deg	0.0025
30	Trim angle (+ve by stern) deg	0.0025

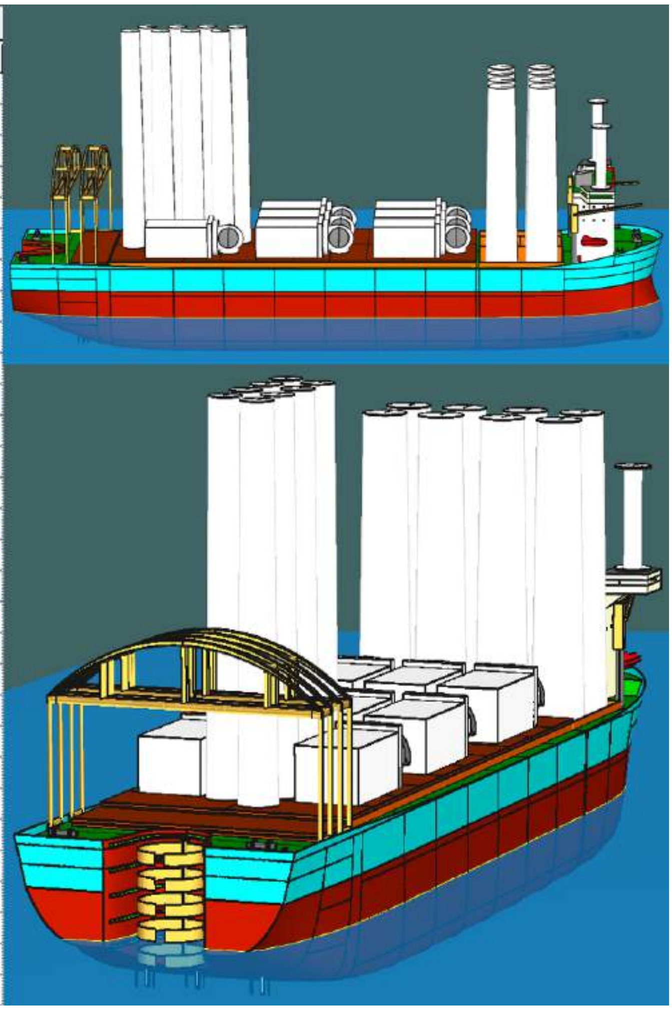


Figure 7-22 Equilibrium Status at Departure Condition While Loading 8x12MW WT

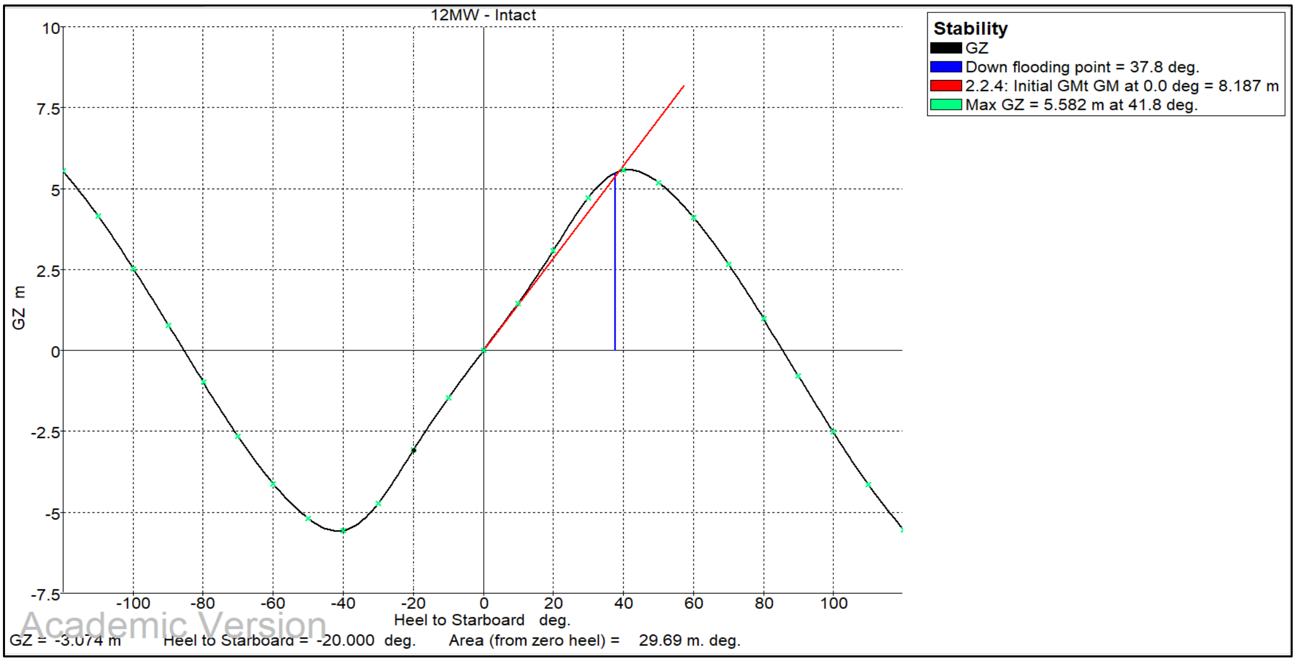


Figure 7-23 GZ Curve Departure Condition While Loading 8x12MW WT

Not only GM is important factor for testing and assessing the stability, but also does analysis of the GZ curve or (righting lever curve) is essential. GZ Curve can express more information about the stability condition for the vessel.

Figure 7-23 demonstrates the GZ curve for designed vessel for the proposed loading arrangement on departure condition. Heeling levers are plotted against heeling angles. The GZ curve has to fulfil several criteria, such as the area under curve (dynamic stability), maximum heeling lever, and angle of maximum GZ. The criteria for dynamic stability refer to the area under the GZ-curve up to the respective angle. Thus, A_{30} is the area under the curve between 0° and 30° and so on. The limit of 40° is valid when the angle of down flooding is greater than 40°. If it is less, the areas are to be calculated up to the angle of down flooding. The calculation of the areas under the GZ curve can be done by means of numerical integration. (IMO 2008). Calculating the dynamic stability in accordance with intact stability criteria can be done manually by using Simpson's Rules, See Table 7-15.

Table 7-15 Area under GZ calculation

ϕ	GZ(ϕ) [m]	Area up to 30°		Area up to 40°	
		Factor	Product	Factor	Product
10°		3		2	
20°		3	+	1	+
30°		1	+	2	+
40°				0,5	+
		Σ_1 =		Σ_2 =	
Areas [m·rad]		Factor 0,0654 $A_{30°}$ =		Factor 0,1164 $A_{40°}$ =	
				$-A_{30°}$ =	
				$A_{40°} - A_{30°}$ =	

The righting levers are inserted into the column "GZ" for the respective angle of heel. The factors for each area are derived from Simpson's Rules. As the GZ-curve is plotted in the unit degree, the sum of areas must be multiplied with a factor to get the result in the unit meter radian.

Table 7-16 shows the evaluation of intact stability criteria against the actual values. It is clearly visible that the vessel has sufficient transverse and dynamic stability. That means the proposed stowage plan is acceptable from the stability point of view, and the vessel could sail and transport the equipment and materials safely, if the materials are seafastened correctly.

The seafastening design for nacelle, tower, TP and MP is not in the scope of this research since there exist proof of concept methods.

Table 7-16 GZ Criteria According to Regulation VS Decom Tools GZ at Departure Condition

Code	Criteria	Value	Units	Actual	Status	Margin (%)
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 30	3.1513	m.deg	68.9385	Pass	+2087.62
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 40	5.1566	m.deg	109.0687	Pass	+2015.13
267(85) Ch2 - General Criteria	2.2.1: Area 30 to 40	1.7189	m.deg	40.1301	Pass	+2234.64
267(85) Ch2 - General Criteria	2.2.2: Max GZ at 30 or greater	0.200	m	5.582	Pass	+2691.00
267(85) Ch2 - General Criteria	2.2.3: Angle of maximum GZ	25.0	deg	41.8	Pass	+67.27
267(85) Ch2 - General Criteria	2.2.4: Initial GMt	0.150	m	8.187	Pass	+5358.00

7.15.1.2 Arrival Condition

However, another stability study has to be conducted for the arrival condition, where the vessel will consume fuel and fresh water which could result several slacked tanks, thus may cause free surface effect which will affect the centre of gravity which may result in trim and might also induce small angle of list. Free surface effect will also decrease the GM and will influence the GZ curve. This adverse effect on the stability is referred to as a "loss in GM" or as a "virtual rise in VCG" and is calculated as follows:

$$\text{Loss of GM} = \frac{\text{Free Surface Mmt} \quad \text{Tons.m}}{\text{Vessel Displacement} \quad \text{Tons}}$$

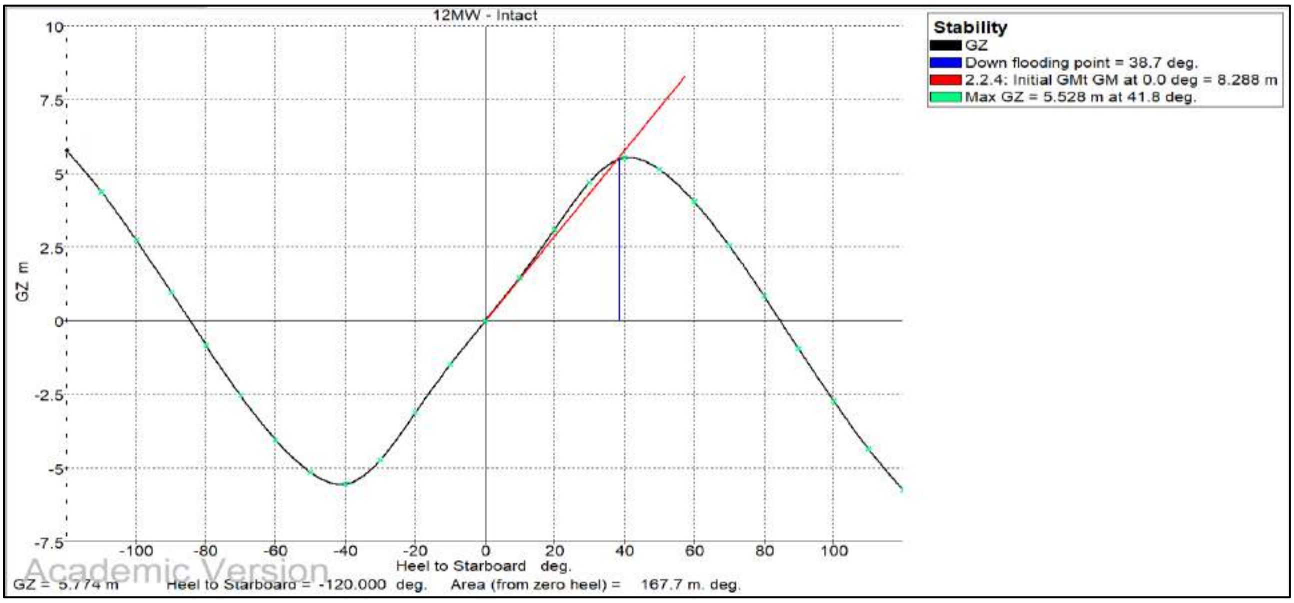


Figure 7-24 GZ Curve Arrival Condition While Loading 8x12MW WT

Figure 7-24 presents the GZ curve for the arrival condition. Arrival condition means arrive to the field or port. The aim for assessing the stability on arrival condition is to see if the vessel will comply with the intact stability criteria throughout the entire voyage. If not, weights have to be rearranged. Figure 7-24 shows that the vessel still has sufficing transverse and dynamic stability. Table 7-17 demonstrates the intact stability criteria for the arrival condition. It shows that the GM in this load configuration raised by 6mm even though the vessel has higher free surface effect. The reason for this increment is that the vessel draft has been changed thus causing the metacentre (M) also to move. In other words, due to the liquid consumption, the vessel draft decreased by few centimetres, consequently, the metacentre (M) has raised, and KM become longer than the departure scenario. Furthermore, due to the free surface effect the final VCG is increased as well, and as far as the GZ curve is dependent on KG value the heeling levers will be affected as well. Table 7-17 shows that the dynamic stability is slightly reduced comparing to the departure scenario. However, the vessel is having a good stability condition and fulfilling the intact stability criteria.

Table 7-17 GZ Criteria According to Regulation VS Decom Tools GZ at Arrival Condition

Code	Criteria	Value	Units	Actual	Status	Margin (%)
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 30	3.1513	m.deg	68.8145	Pass	+2083.68
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 40	5.1566	m.deg	113.2122	Pass	+2095.48
267(85) Ch2 - General Criteria	2.2.1: Area 30 to 40	1.7189	m.deg	44.3977	Pass	+2482.92
267(85) Ch2 - General Criteria	2.2.2: Max GZ at 30 or greater	0.200	m	5.518	Pass	+2659.00
267(85) Ch2 - General Criteria	2.2.3: Angle of maximum GZ	25.0	deg	40.9	Pass	+63.64
267(85) Ch2 - General Criteria	2.2.4: Initial GMt	0.150	m	8.193	Pass	+5362.00

7.16 Heeling Arm and Rolling at Sever Weather Condition

The purpose of the IMO weather criteria is to ensure the vessel is able to withstand the combined effects of beam wind and rolling. (IMO 2008)According to the IMO weather criteria, the vessel is subjected to steady wind based on windage area of the ship, and gust of wind which is relatively higher than steady wind pressure. Also, the ship is assumed to roll due to impact of wave. Initially the ship is subjected to a steady wind at a perpendicular to the ship centreline, which result in a steady wind moment lever.

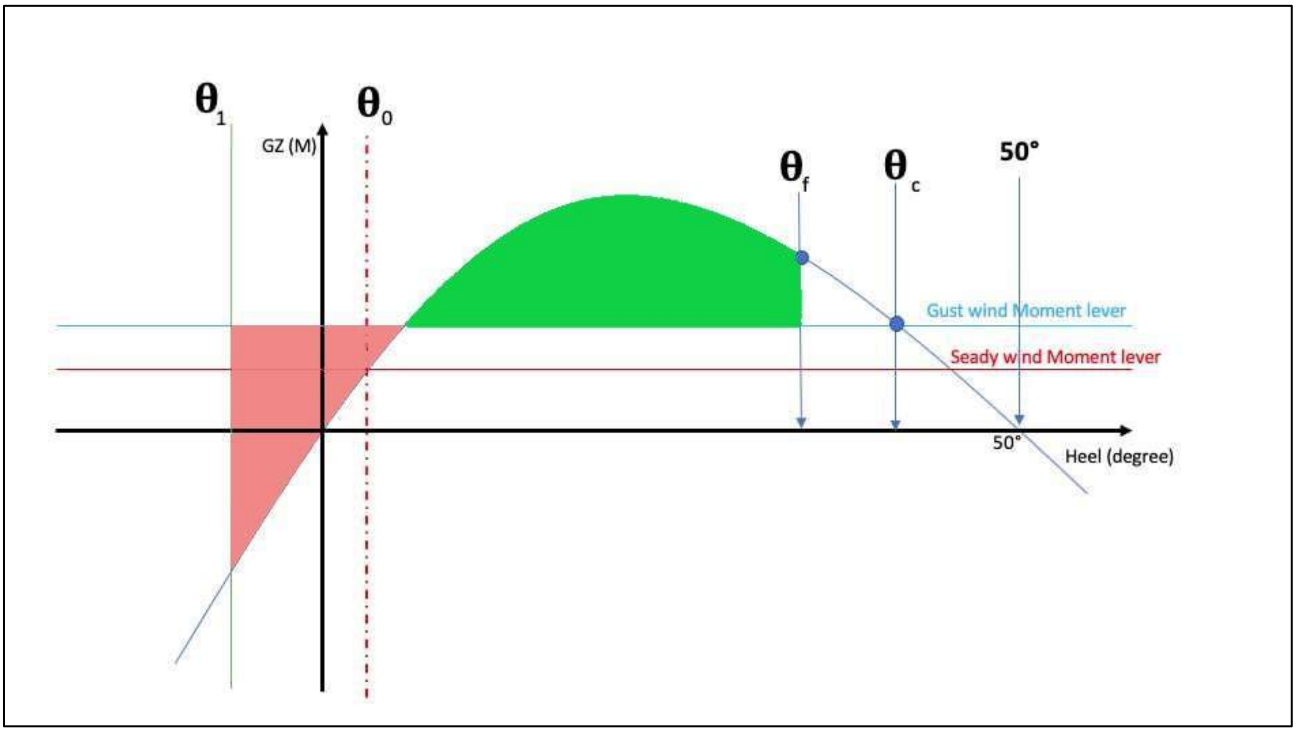


Figure 7-25 Sever Wind and Rolling GZ Curve

Referring to Figure 7-25 the point that GZ curve and wind lever cross represents the heel angle which is generated by impact of wind. The angle of heel θ_0 is representing angle of heel due to steady wind and shall not exceed 16° or 80% of deck edge emersion angle. The θ_1 is representing the roll angle to wind ward. Additionally, the ship is subjected to gust wind, which result in gust wind moment lever, this lever is assumed to be 50% higher than the steady wind lever. The static wind is assumed to have a 10-Beaufort wind force which is equals a pressure of 504 Pa.

The red area is the area above the GZ curve below the gust wind moment lever and between the roll angles. This area represents the total wave energy trying to capsize the ship. The angle θ1 is the assumed angle of roll. As it is assumed the vessel is rolling to the wind ward side, this is plotted to the left side. The angle of roll can be estimated by means of a procedure presented in the IS-Code. However Manual calculation will not be presented here, instead using a reliable software will give more accurate results. In contrast, it is important to calculate the area of the GZ curve which available to resist the capsizing energy.

Green area represents the remaining stability energy counteracting the leeward rolling motion. As long as green area is greater than red area the ship will survive the gust with higher chance. According to IMO weather criterium, to be able to have safe margin to maintain the stability under beam wind and rolling the green area must be equal or greater than the red area.

When plotting the green area, it must be remembered that the area is only considered up to an:

- angle of heel 50° = θ_2, or,
- $\theta_2 = \theta_f$ whichever is less. Where θ_f represents the angle of heel which the first unprotected opening immerses.
- or $\theta_2 = \theta_c$. the angle where the gust wind moment lever intercepts the GZ curve for the second time

Moreover, only the area above the gust wind moment lever is counted.

The steady wind heeling lever can be calculated by the following formula

$$\text{Steady wind heeling lever} = \frac{p.A.z}{1000.g.Displacment}$$

Where:

P= wind pressure (KN/m^2)

Z= vertical lever of forces (m)

A = lateral area (m^2)

Figure 7-26 shows the windage area as well as the underwater area at the even keel draft of 11.979 m for the Decom Tools vessel during loading the 8 sets of 12 MW wind turbine.

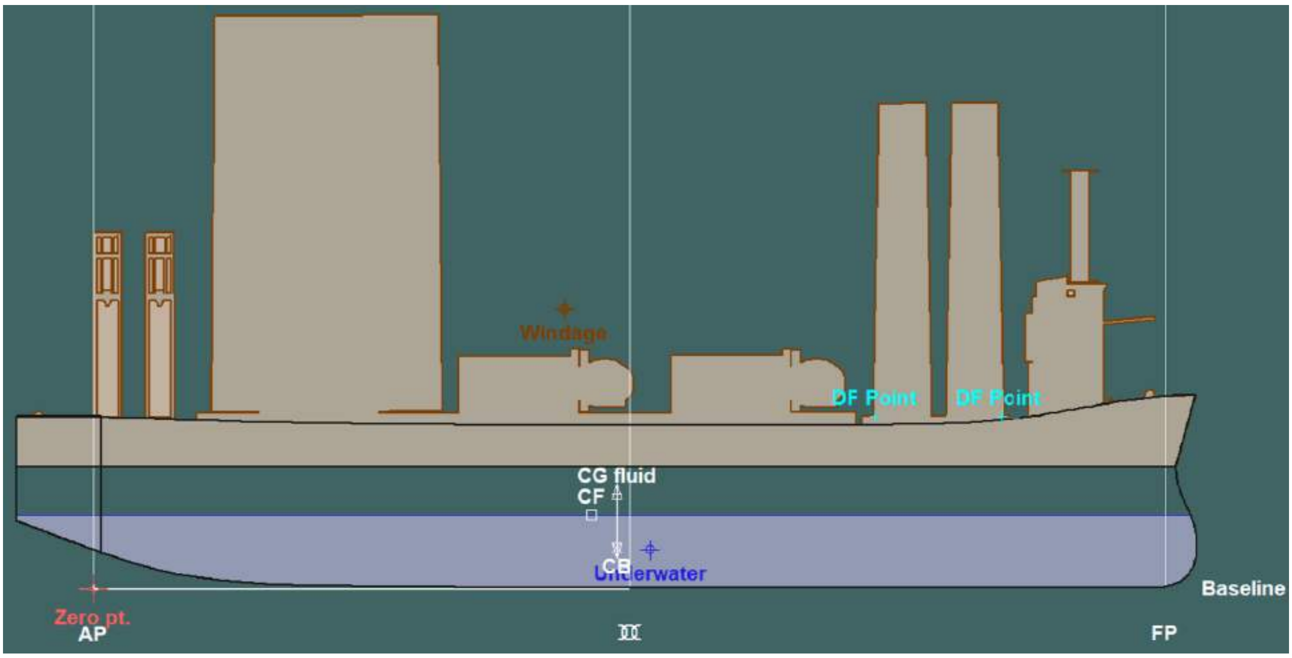


Figure 7-26 Decom Tools Vessel Windage Area After Loading 8 x 12MW WT

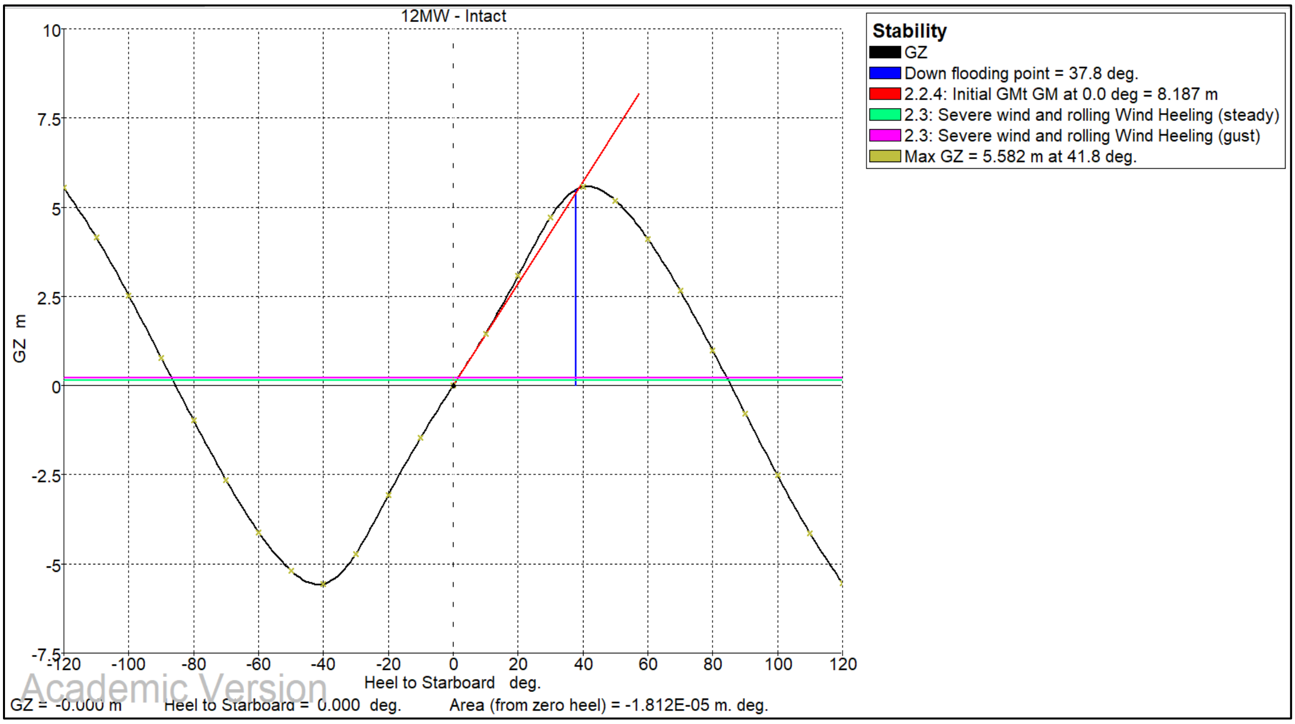


Figure 7-27 Decom Tools Vessel GZ Curve after Loading 8 x 12MW WT

Figure 7-27 shows the GZ curve as well as the steady wind lever and the gust lever. It is clearly shown that the capsizing area is so small, and even it is not visible, that conclude that the vessel has enough reserve stability, and she can easily resist the capsizing moment. Moreover, the vessel expected to have a steady heeling angle of 1.1 degree. Furthermore, Table 7-18 shows the actual value for the proposed stowage plan against the IMO weather criteria. All criteria have been passed and the vessel can sail safely.

Table 7-18 Assessing Decom Tools GZ Curve after Loading 8 x 12MW WT

Code	Criteria	Value	Units	Actual	Status	Margin (%)
267(85) Ch2 - General Criteria	2.3: Severe wind and rolling				Pass	
267(85) Ch2 - General Criteria	Angle of steady heel shall not be greater than (<=)	16.0	Deg.	1.1	Pass	+93.44
267(85) Ch2 - General Criteria	Angle of steady heel / Deck edge immersion angle shall not be greater than (<=)	80.00	%	3.31	Pass	+95.86
267(85) Ch2 - General Criteria	Area1 / Area2 shall not be less than (>=)	100.00	%	318.75	Pass	+218.75

7.17 Rolling Period

For this type of cargo and the proposed stowage plan, the extreme rolling must be kept to minimum, in order to eliminate any risk that could be induced by rolling motion. Therefore, to maintain the safety of the vessel and the onboard cargos, especially Seafastening of cargos**,** we have to assure that the vessel will not have either fast or too slow rolling motion. Accordingly, calculating the rolling period provides a better picture and understanding to see what the situation will be, and what could be the solution if the vessel has abnormal or unacceptable rolling period.

The natural rolling period T_{ϕ} is the overall seconds which the vessel takes to roll in still water, to complete one complete oscillation from any side to the opposite side back again to the first side. Furthermore, the produced angle due to roll defined as an amplitude and measured in degrees. (Georage 2005). To calculate the natural rolling period, the bellow equation is used (Barrass und Derrett 2006).

$$T_{\phi} = \frac{2K}{\sqrt{GM_T}}$$

Where the:

T_{ϕ} : roll period in seconds

K: roll radius of gyration $= 0.35 \cdot \mathrm{B}$ in general

B: moulded breadth in meters

$\sqrt{GM_T}$: the square root of the corrected fluid metacentric height in meter

During a routine voyage, a vessel will ordinarily subject to a mixture of external forces, or to an individual force, depending on the weather condition. The external forces are such as waves, winds and swells. Therefore, the developed rolling is called apparent rolling, which is entirely different to the natural rolling in the still water. However, the apparent rolling period can be measured only by observation, and the result will give an error compared with the calculated natural rolling period.

Vessel with short rolling period "stiff" has high transverse stability. As a consequence, the righting moment of the vessel is significant and causes the vessel to return quickly to the upright condition as soon as it inclined. The angular velocity of the roll will cause severe racking stresses and might initiate extreme acceleration strains on cargo lashings, which can lead to cargo shifting or cargo damage (Pursey und Wardle 2006).

Figure 7-28 shows the relationship between the metacentric height, and the rolling period for the various ship beams. Conversely, a "tender" vessel with high natural roll period has a small GM which means very high centre of gravity. Therefore, the righting levers are small and offer low resistance to being rolled, causing the vessel to roll to larger angles of heel. As far as the vessel starts to heel, will have an extreme roll for a relatively long time, and slowly return to the upright condition. This situation will generate higher stresses on cargo lashings, and in some cases, they develop the risk of cargo shifting.

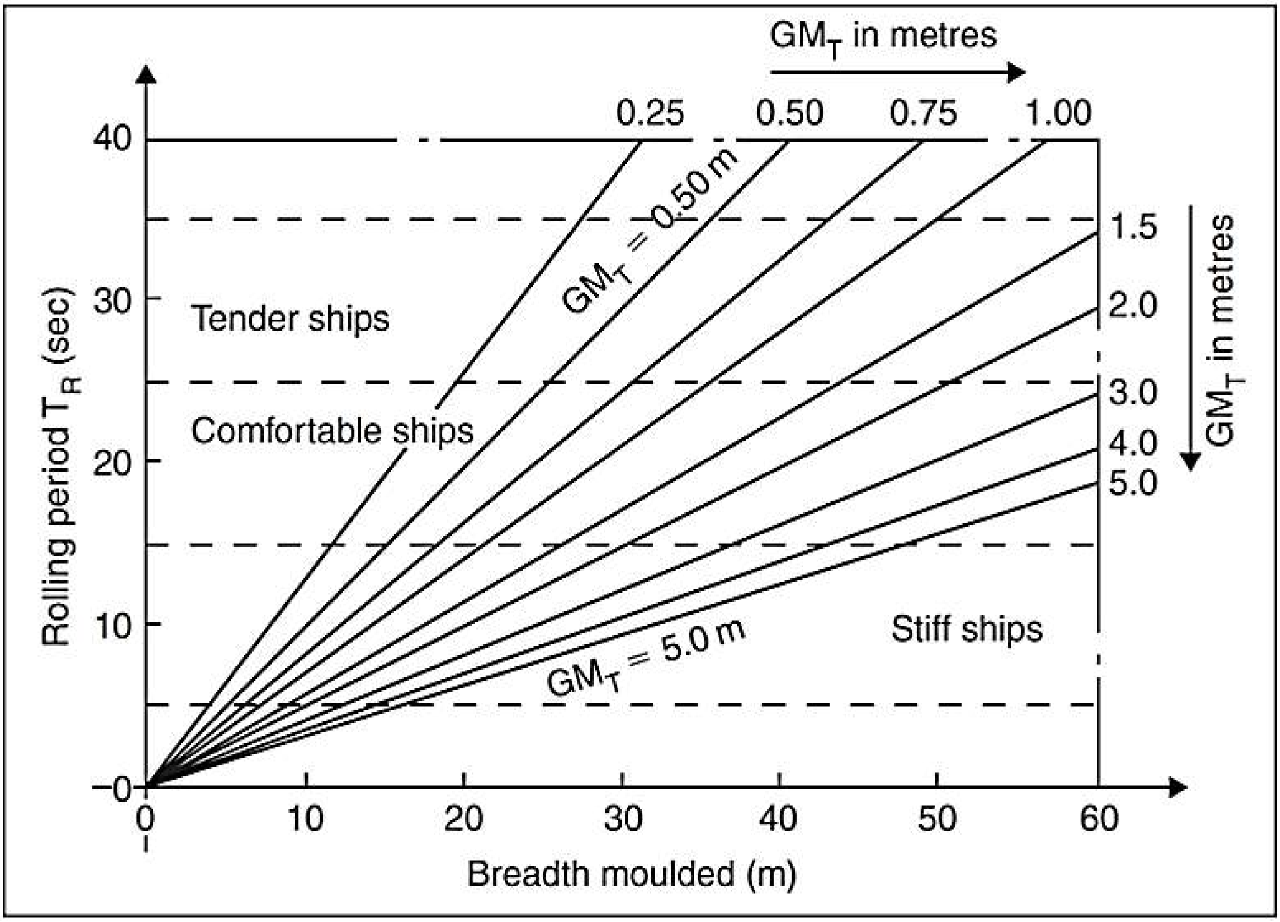


Figure 7-28 Relation Between Rolling Period and GM

By calculating the Natural rolling period for Decom Tools vessel during the load out arrangement of an 8-set of 12 MW wind turbine a closer overview can be obtained. Accordingly, the Decom tools vessel has:

$$T_{\phi} = \frac{2 * 0.35 * 48}{\sqrt{8.186}}$$

$$\boldsymbol{T_{\phi} = 11.74 \text{ seconds}}$$

The calculation shows that the Decom Tools vessel under this circumstance has about 12 seconds rolling period. Calling Figure 7-28, the vessel is under category of the stiff. That means that the initial stability is rather high, and the ship tends to severe rolling in a sea way.

Comfortable ship is a preferable condition for any loading condition, this means the rolling period have to be extended to the point where no excessive acceleration will occur. Therefore, to increase the rolling period we need to decrease the GM of the vessel. This situation could be achieved by changing ballast or by using anti rolling tanks, such as (passive anti rolling tanks: flume tank).

7.18 Impact of Heeling Tanks on Heeling Angles

Based on the designed heeling tanks, their location and capacity of them, heeling angle can compensate the heeling angle almost one degree during the full loading scenario (8 set of 12MW wind turbine). Table 7-19 shows the stability information after fully filling the STBD side heeling tank and fully deballasting the Port Side heeling tank. The resulted heeling angle at draft 11.98m is calculated as 1.3°. More heeling angles can be compensated by assigning more tanks to be heeling tanks.

Table 7-19 Impact of Heeling Tanks on Heeling Angles

12MW - Intact		
1	Draft Amidships m	11.978
2	Displacement t	89261
3	Heel deg	1.3
4	Draft at FP m	11.975
5	Draft at AP m	11.982
6	Draft at LCF m	11.979
7	Trim (+ve by stern) m	0.006
8	WL Length m	193.932
9	Beam max extents on WL m	47.974
10	Wetted Area m^2	11553.406
11	Waterpl. Area m^2	8332.491
12	Prismatic coeff. (Cp)	0.821
13	Block coeff. (Cb)	0.773
14	Max Sect. area coeff. (Cm)	0.946
15	Waterpl. area coeff. (Cwp)	0.896

12MW - Intact		
16	LCB from zero pt. (+ve fwd) m	86.330
17	LCF from zero pt. (+ve fwd) m	81.925
18	KB m	6.494
19	KG fluid m	15.352
20	BMt m	17.009
21	BML m	250.622
22	GMt corrected m	8.149
23	GML m	241.762
24	KMt m	23.499
25	KML m	257.051
26	Immersion (TPc) tonne/cm	85.408
27	MTc tonne.m	1219.198
28	RM at 1deg = GMt.Disp.sin(1) tonne.m	12694.841
29	Max deck inclination deg	1.3060
30	Trim angle (+ve by stern) deg	0.0021

7.19 Stability Analysis for 24 Numbers of 12 MW Tower (Segregate Load out Arrangement)

The Decom Tools vessel can carry out 24 numbers of tower of 12 MW wind turbine, see Figure 7-29. The tower has dimension and weight according to the Table 7-20. Therefore, in this section, stability analysis has been made for this scenario of cargo loading. It should be noted that it is considered that the towers are made of two sections, since they are so long.

Table 7-20 Specification of 12 MW WT Tower

Components Description	Dimension or Weight
Tower Mass (t)	880
Tower Height (m)	129
Tower top diameter (m)	5.5
Tower bottom diameter (m)	10

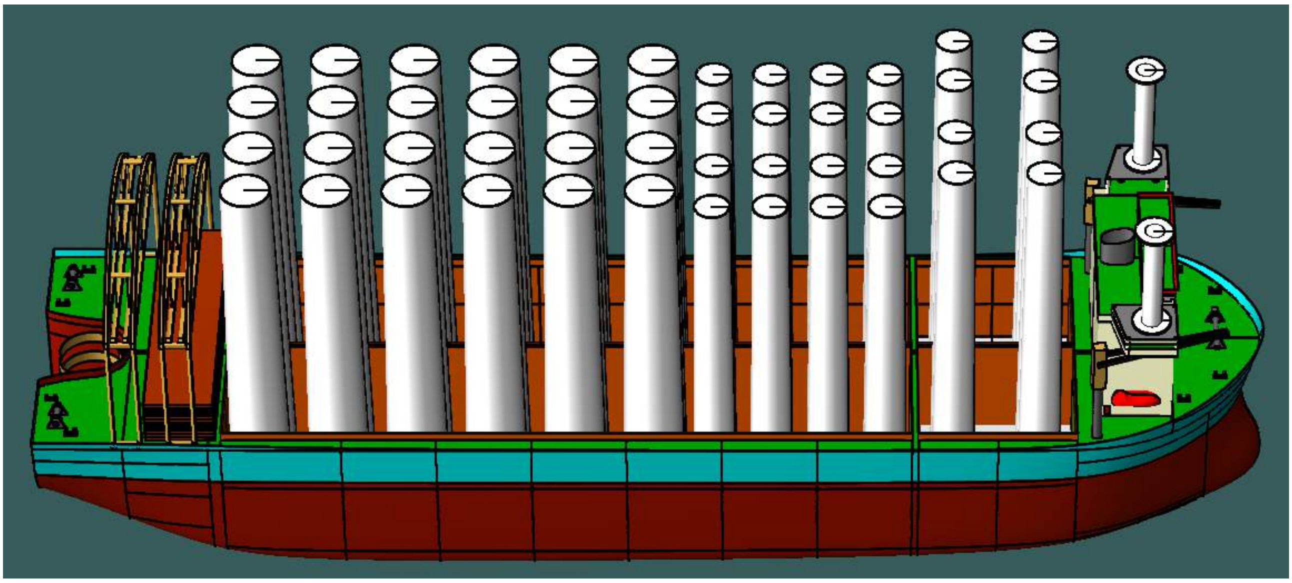


Figure 7-29 Load out of 24 Numbers of 12 MW WT Tower

Table 7-21 shows the calculation of final weight and COG for 24 towers of 12 MW.

Table 7-21 Stability Parameters after Loading 24 Sets of 12 MW Tower

Cargo Name	Qty	Weight Per Unit	Overall Weight	LCG	TCG	VCG	Long. moment	Tran. moment	Vert. moment
Towers in hold # 1	8	293.3	2346.6	139.3	0	46.10	326886.9	0	108180.1
Towers in hold # 2 FWD	16	293.3	4693.2	108.3	0	39.60	508282.2	0	185853.8
Towers in hold # 2 AFT	24	586.6	14080.0	53.9	0	40.10	758916.3	0	564611.2
Overall cargo			**21120**	**75.48**	**0**	**40.66**	**1594085.4**	**0**	**858645.2**

Table 7-22 displays the result of the equilibrium analysis for the Decom Tools vessel during loading 24 complete sets of 12 MW wind turbine towers. The result demonstrates that vessel has positive transvers stability (GM corrected 8.566m), and it is floating on the even keel draft of 9.97 m. In this analysis, ballast tanks are full and free surface effect kept to minimum.

Table 7-22 Results of Equilibrium Analysis After Loading 24 Sets of 12 MW Tower

Parameter's Name	Value	Parameter's Name	Value
Draft Amidships m	9.966	LCB from zero pt. (+ve fwd) m	87.264
Displacement t	72180	LCF from zero pt. (+ve fwd) m	83.091
Heel deg	0.0	KB m	5.431
Draft at FP m	9.963	KG fluid m	17.257
Draft at AP m	9.969	BMt m	20.392
Draft at LCF m	9.966	BML m	297.322
Trim (+ve by stern) m	0.006	GMt corrected m	8.566
WL Length m	191.862	GML m	285.496
Beam max extents on WL m	47.896	KMt m	25.823
Wetted Area m^2	10616.918	KML m	302.753
Waterpl. Area m^2	8200.436	Immersion (TPc) tonne/cm	84.054
Prismatic coeff. (Cp)	0.815	MTc tonne.m	1164.251
Block coeff. (Cb)	0.767	RM at 1deg = GMt.Disp.sin(1) tonne.m	10791.083
Max Sect. area coeff. (Cm)	0.949	Max deck inclination deg	0.0019
Waterpl. area coeff. (Cwp)	0.892	Trim angle (+ve by stern) deg	0.0019

Figure 7-30 shows the GZ curve for the Decom Tools vessel while carrying 24 numbers of tower of 12 MW wind turbine.

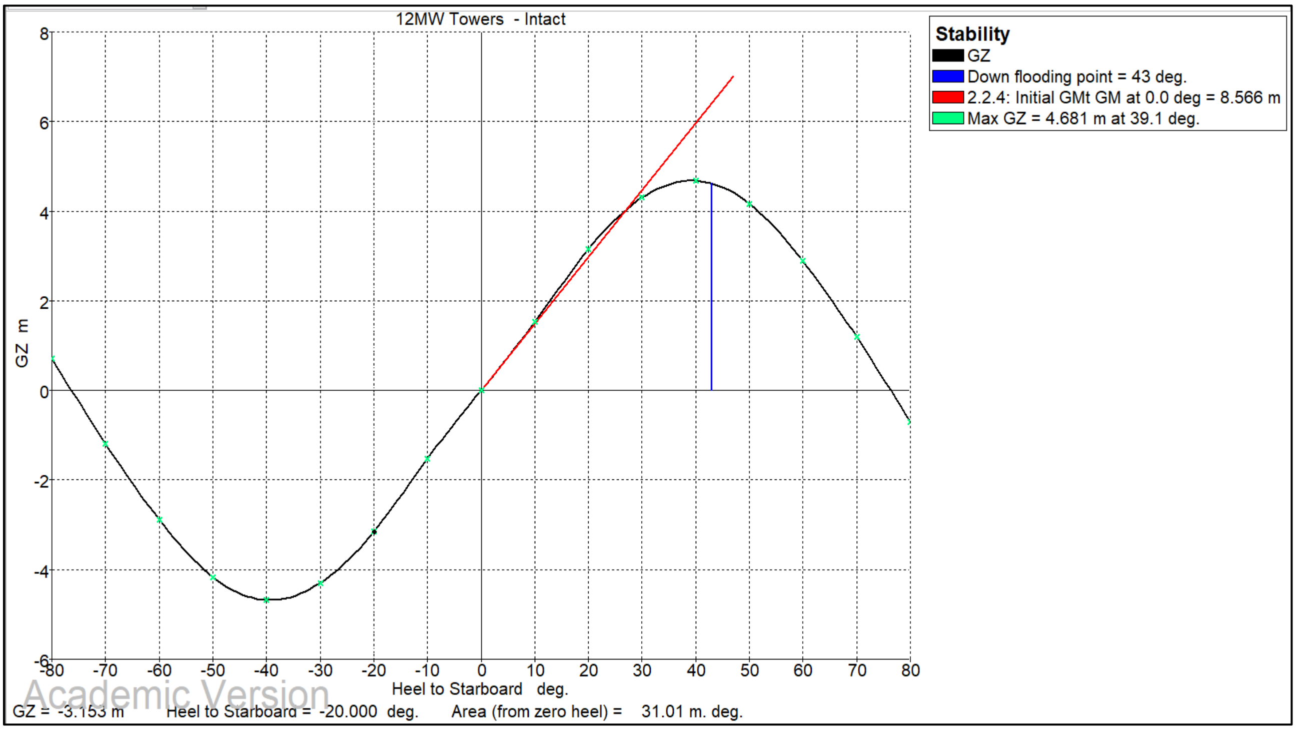


Figure 7-30 GZ Curve after Loading 24 Sets of 12MW Tower

Table 7-23 shows that the static and dynamic stability for the Decom Tools vessel during loading 24 numbers of 12 MW wind turbine towers is satisfying all the required intact stability criteria. So, this load out arrangement is safe subject to the appropriate seafastening of the cargos.

Table 7-23 GZ Curve after Loading 24 Set of 12 MW Towers VS Regulation

Code	Criteria	Value	Units	Actual	Status	Margin (%)
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 30	3.15	m.deg	68.84	Pass	+2084.6
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 40	5.15	m.deg	114.44	Pass	+2119.3
267(85) Ch2 - General Criteria	2.2.1: Area 30 to 40	1.71	m.deg	45.59	Pass	+2552.8
267(85) Ch2 - General Criteria	2.2.2: Max GZ at 30 or greater	0.2	m	4.68	Pass	+2240.5
267(85) Ch2 - General Criteria	2.2.3: Angle of maximum GZ	25.0	Deg.	39.1	Pass	+56.3
267(85) Ch2 - General Criteria	2.2.4: Initial GMt	0.15	m	8.56	Pass	+5610.6

7.20 Stability Analysis for 26 Numbers of 12 MW Nacelle (Segregate Load out Arrangement)

This section will evaluate the stability status of Decom Tools vessel while 26 sets of 12MW GE X-Heliade nacelle are loaded. Table 7-24 shows the Nacelle dimension, while Figure 7-31 shows the purposed stowage plan.

Table 7-24 Dimension and Weight of 12 MW Nacelle and Hub

Components Description	Dimension or Weight
Nacelle mass (t)	600
Nacelle + Hub mass (t)	675
Nacelle dimensions (m) (L x W x H)	20.6 x 11 x 10.4
Nacelle with hub dimensions (m) (L x W x H)	29 x 11 x 10.5

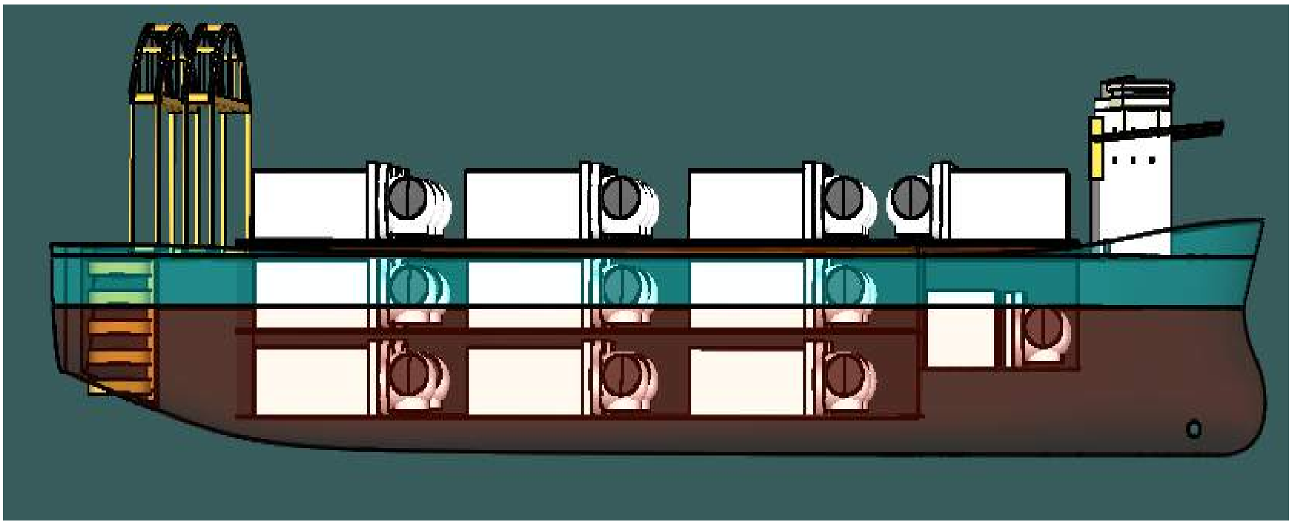


Figure 7-31 Lod out of 26 Number of 12 MW Nacelle

Table 7-25 calculates the final COG as well as the final weight for the proposed stowage plan. This information will be used in the MAXSURF stability software, in order to calculate the transvers, longitudinal stability.

Table 7-25 Stability Parameters after Loading 26 Numbers of 12 MW Nacelle + Hub

Cargo Name	Qty	Weight Per Unit	Overall Weight	LCG	TCG	VCG	Long. moment	Tran. moment	Vert. moment
	Unit	t	t	m	m	m	t.m	t.m	t.m
Nacelle on top of hold # 1	3	675	2025	133.6	0	33.90	270540	0	68647.5
Nacelle in hold # 1	2	675	1350	138.6	0	16.50	187110	0	22275
Nacelle on top of hold # 2	9	675	6075	70.95	0	33.90	431021.25	0	205942.5
Nacelle on top of tween deck hold # 2	6	675	4050	70.95	0	22.00	287347.5	0	89100
Nacelle in hold No 2	6	675	4050	70.95	0	10.30	287347.5	0	41715
Overall cargo			**17550**	**83.38**	**0**	**24.37**	**1463366.2**	**0**	**427680**

Table 7-26 shows the result of the equilibrium analysis for the Decom Tools vessel when 26 numbers of 12 MW nacelle are loaded on board. The result speculates that the vessel has positive transverse stability, and it has a draft of 12.325 m and having trim by 40 cm to stern.

Table 7-26 Results of Equilibrium Analysis After Loading 26 Numbers of 12MW Nacelle

Parameter's Name	Value	Parameter's Name	Value
Draft Amidships m	12.325	LCB from zero pt. (+ve fwd) m	85.532
Displacement t	92370	LCF from zero pt. (+ve fwd) m	81.765
Heel deg	0.0	KB m	6.682
Draft at FP m	12.085	KG fluid m	12.704
Draft at AP m	12.564	BMt m	16.511
Draft at LCF m	12.343	BML m	243.524
Trim (+ve by stern) m	0.479	GMt corrected m	10.488
WL Length m	193.888	GML m	237.502
Beam max extents on WL m	47.974	KMt m	23.192
Wetted Area m^2	11733.585	KML m	250.205
Waterpl. Area m^2	8349.411	Immersion (TPc) tonne/cm	85.581
Prismatic coeff. (Cp)	0.822	MTc tonne.m	1239.432
Block coeff. (Cb)	0.787	RM at 1deg = GMt.Disp.sin(1) tonne.m	16908.056
Max Sect. area coeff. (Cm)	0.960	Max deck inclination deg	0.1551
Waterpl. area coeff. (Cwp)	0.898	Trim angle (+ve by stern) deg	0.1551

Figure 7-32 depicts the GZ curve of the Decom Tools vessel after the above-mentioned load out arrangement. The angle of down flooding has not been considered in this calculation, because the hatch covers for both holds were close during the sailing mode. Therefore, calculating the dynamic stability will not consider the down flooding angle, instead angle 40°.

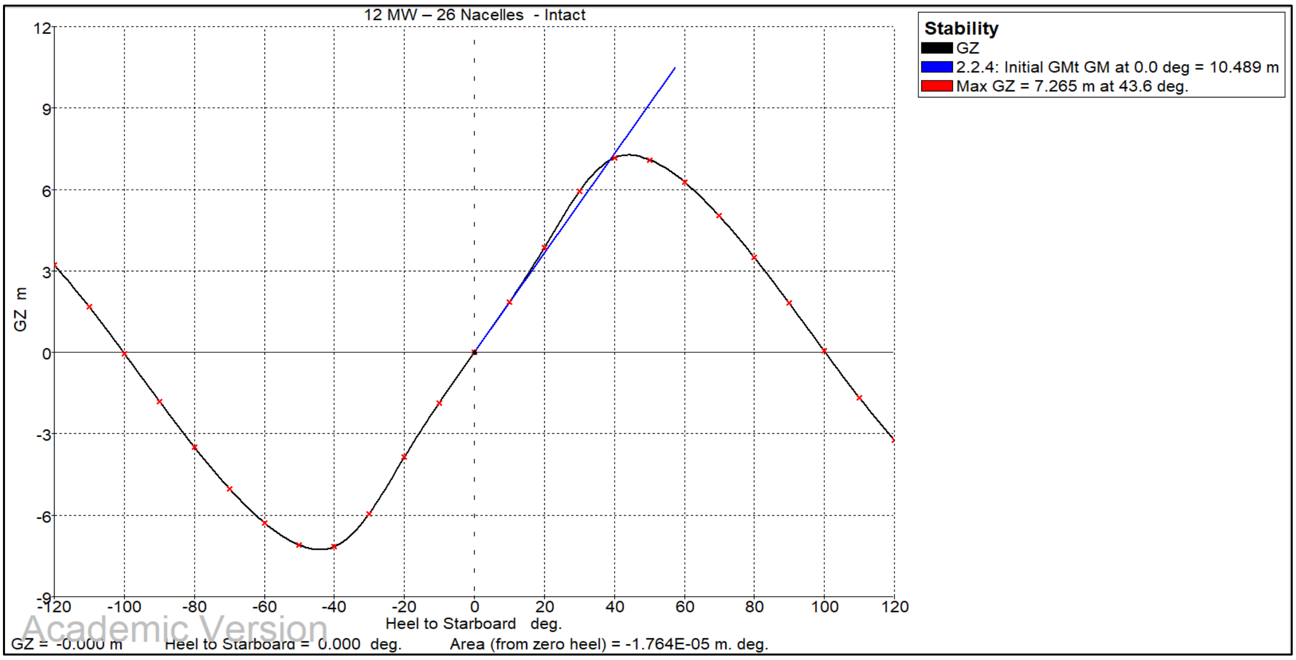


Figure 7-32 GZ Curve after Loading 26 numbers of 12MW Nacelle

Table 7-27 presents that the static and dynamic stability for the Decom Tools vessel during loading of 26 Nacelles of 12 MW wind turbine is fulfilling all the required intact stability criteria, where all the actual values are higher than the intact minimum criteria.

Table 7-27 Criteria Check after Loading 26 Number of 12 MW Nacelle

Code	Criteria	Value	Units	Actual	Status	Margin (%)
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 30	3.1513	m.deg	86.9806	Pass	+2660.15
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 40	5.1566	m.deg	153.5609	Pass	+2877.95
267(85) Ch2 - General Criteria	2.2.1: Area 30 to 40	1.7189	m.deg	66.5804	Pass	+3773.43
267(85) Ch2 - General Criteria	2.2.2: Max GZ at 30 or greater	0.200	m	7.265	Pass	+3532.50
267(85) Ch2 - General Criteria	2.2.3: Angle of maximum GZ	25.0	Deg.	43.6	Pass	+74.54
267(85) Ch2 - General Criteria	2.2.4: Initial GMt	0.150	m	10.489	Pass	+6892.67

The above stability analysis shows that the vessel fulfils the required criteria which are set by the IMO regulators, namely the International Code on Intact Stability. Thus, the vessel can load 26 numbers of nacelle with mentioned arrangement and can transport safely.

7.21 Stability Analysis for 48 Numbers of 12 MW Blades (Segregate Load Out)

In this loadout arrangement, 48 numbers of 12 MW blades of turbine model GE X-Heliad can be loaded onboard the Decom Tools vessel. Under this section stability of the vessel will be evaluated when these cargos are onboard the vessel. Prior to showing the stability of the vessel, the size and weight of the mentioned blades are listed in the following table (Table 7-28).

Table 7-28 Weight and Dimension of 12 MW Blades

Weight and Dimension of 12 MW Wind Turbine	
Component Name	**Size / Weight**
Blade length (m)	107
Blade Diameter	5.5
Blade mass (t)	55
Max. chord (m)	6

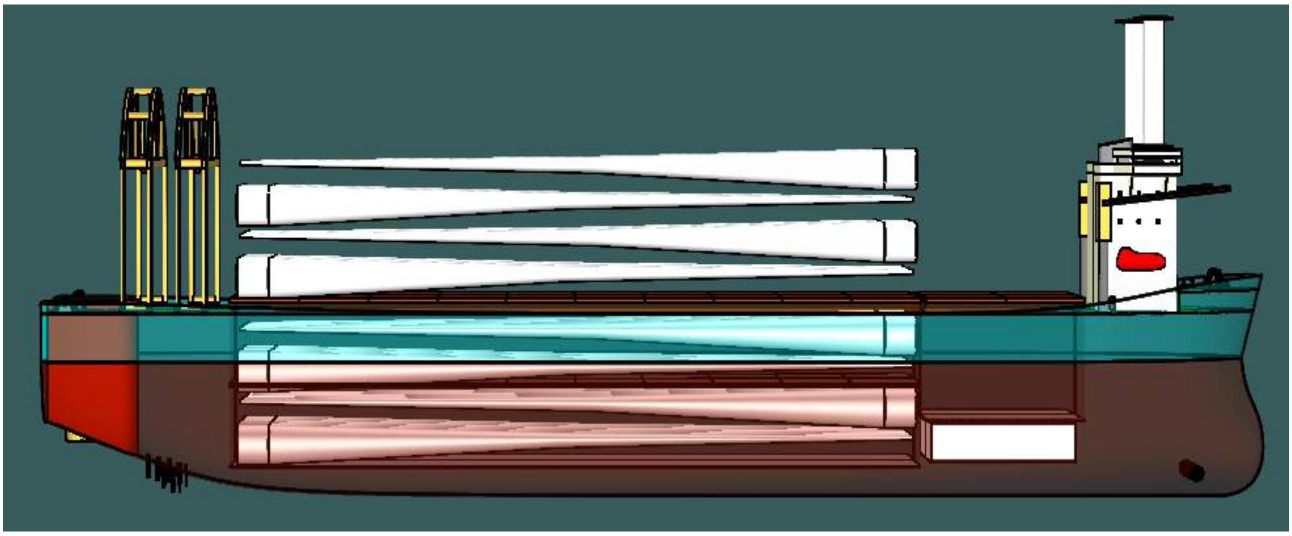


Figure 7-33 Decom Tools Vessel is Loaded with 48 Numbers of Blades

Figure 7-33 shows how 48 numbers of blades are loaded onboard the Decom Tools vessel. 24 Blades loaded on top of the hatch cover No 2 and 24 blades in hold No 2. Table 7-29 calculates the final COG as well as the final weight for the proposed stowage plan. The resulted information will be used in the MAXSURF stability software, to calculate the transvers and longitudinal stability.

Table 7-29 Stability Parameters after Loading 48 Numbers of 12 MW Blades

Cargo Name	Qty	Weight Per Unit	Overall Weight	LCG	TCG	VCG	Long. moment	Tran. moment	Vert. moment
	Unit	t	t	m	m	m	t.m	t.m	t.m
Blades on the Weather Deck	24	55	1320	71.75	0	39.50	94710	0	52140
Blades In Hold	24	55	1320	71.75	0	16.20	94710	0	21384
Overall Cargo			**2640**	**71.75**	**0**	**27.85**	**189420.00**	**0**	**73524**

Table 7-30 demonstrates stability information for the Decom Tools vessel during loading the 48 sets of 12 MW wind turbine blades, in the equilibrium status. The result shows that vessel has positive transvers stability, and she is on draft of 10.516 m, and having trim by 56 cm to stern.

Table 7-30 Results of Equilibrium Analysis After Loading 48 Numbers of 12MW Blades

Parameter's Name	Value	Parameter's Name	Value
Draft Amidships m	10.516	LCB from zero pt. (+ve fwd) m	86.098
Displacement t	76978	LCF from zero pt. (+ve fwd) m	82.400
Heel deg	0.0	KB m	5.733
Draft at FP m	10.236	KG fluid m	10.532
Draft at AP m	10.796	BMt m	19.365
Draft at LCF m	10.536	BML m	286.044
Trim (+ve by stern) m	0.560	GMt corrected m	14.565
WL Length m	194.177	GML m	281.244
Beam max extents on WL m	47.922	KMt m	25.097
Wetted Area m^2	10901.746	KML m	291.775
Waterpl. Area m^2	8272.006	Immersion (TPc) tonne/cm	84.788
Prismatic coeff. (Cp)	0.807	MTc tonne.m	1223.148
Block coeff. (Cb)	0.768	RM at 1deg = GMt.Disp.sin(1) tonne.m	19567.619
Max Sect. area coeff. (Cm)	0.954	Max deck inclination deg	0.1812
Waterpl. area coeff. (Cwp)	0.889	Trim angle (+ve by stern) deg	0.1812

Figure 7-34 presents the GZ curve of the vessel while loading of 48 blades of 12 MW wind turbine. Hence the angle of down flooding has not been considered in this calculation, because the hatch covers for all holds were close during the sailing mode, therefore, calculating the dynamic stability will not consider the down flooding angle.

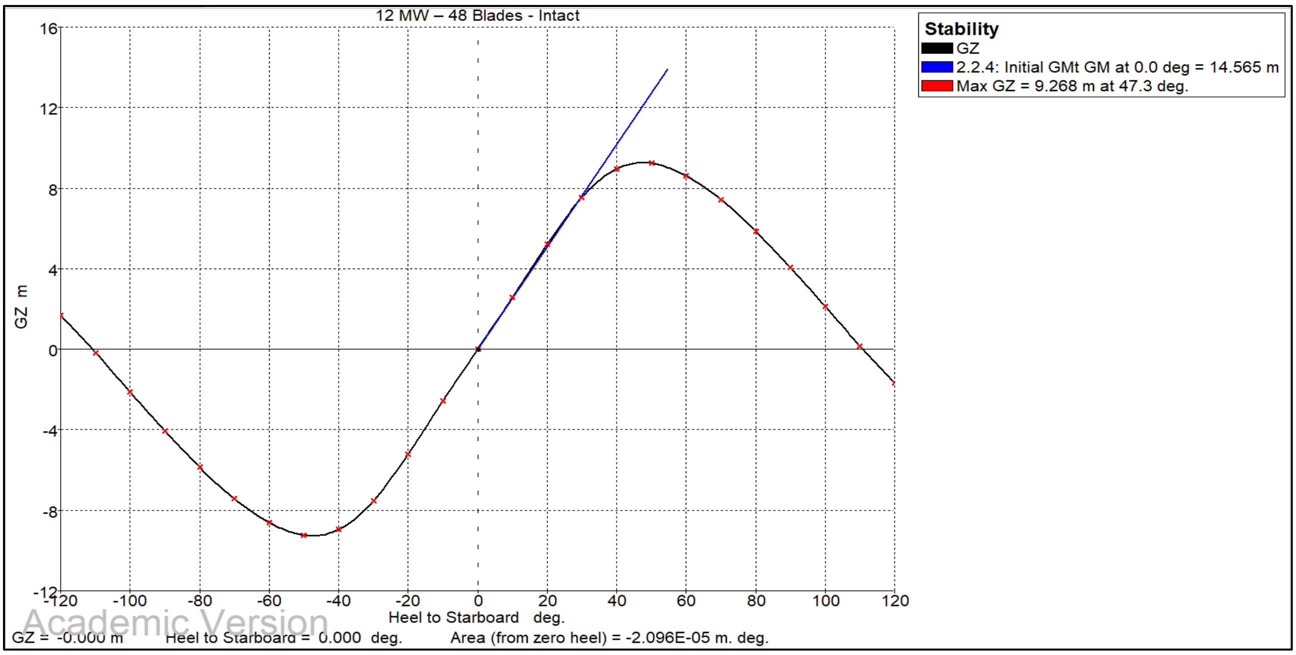


Figure 7-34 GZ Curve after Loading 48 numbers of 12MW Blades

Table 7-31 illustrate that the static and dynamic stability for the Decom Tools vessel during the loading of 48 blades of 12 MW wind turbine is fulfilling all the required intact stability criteria since all the actual values are higher than the intact stability criteria which are set by regulators.

Table 7-31 Criteria Check after Loading 48 Number of 12 MW Blades

Code	Criteria	Value	Units	Actual	Status	Margin (%)
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 30	3.151	m.deg	115.95	Pass	+3579.75
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 40	5.156	m.deg	199.25	Pass	+3764.14
267(85) Ch2 - General Criteria	2.2.1: Area 30 to 40	1.718	m.deg	83.29	Pass	+4746.01
267(85) Ch2 - General Criteria	2.2.2: Max GZ at 30 or greater	0.200	m	9.26	Pass	+4534.00
267(85) Ch2 - General Criteria	2.2.3: Angle of maximum GZ	25.0	Deg.	47.3	Pass	+89.09
267(85) Ch2 - General Criteria	2.2.4: Initial GMt	0.15	m	14.56	Pass	+9610.00

The above stability analysis shows that the vessel fulfils the required criteria which are set by the regulators. Thus, the vessel can load 48 numbers of blades with mentioned arrangement and can transport safely.

7.22 Stability Analysis for 5MW Wind Turbine

Under section 6.11.2 it is shown that 24 full set of 5 MW wind turbine can be loaded onboard the Decom Tools vessel. In the section stability analysis will be conducted for this loadout arrangement, see Figure 7-35.

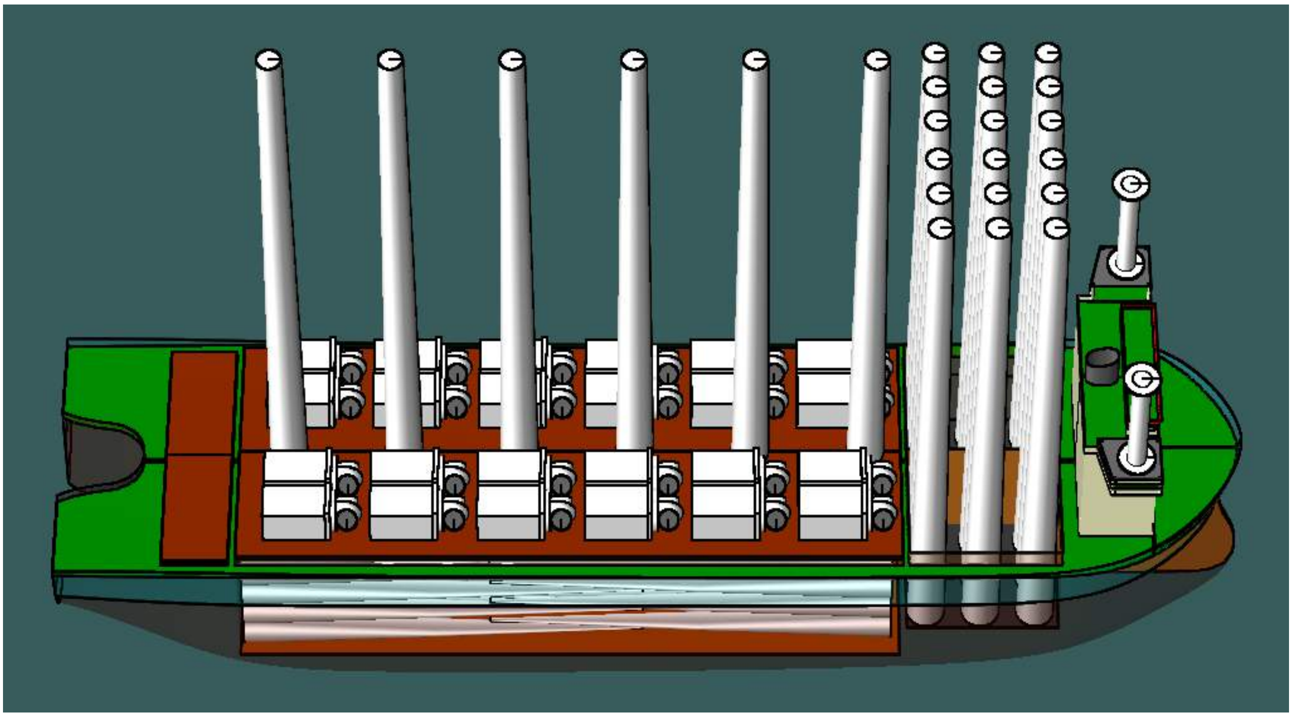


Figure 7-35 24 Sets of 5MW Wind Turbine are Loaded Out

Table 7-32 shows the weight and dimensions of various components of this wind turbine. The values of the mentioned table are used to calculate the stability parameters of the vessel.

Table 7-32 Weight and Dimension of 5MW Wind Turbine

Weight and Dimension of 5MW Wind Turbine	
Component Name	**Size/ Weight**
Blade length (m)	66
Blade Diameter	4
Blade mass (t)	23.33
Max. chord (m)	5.0
Hub mass (t)	67.78
Nacelle mass (t)	240
Nacelle + Hub mass (t)	307.78
Nacelle dimensions (m) (L x W x H)	16 x 6.3 x 6.3
Nacelle with hub dimensions (m) (L x W x H)	21 x 6.3 x 6.3
Tower Mass (t)	347.46
Tower Height (m)	87.6
Tower top diameter (m)	3.87
Tower bottom diameter (m)	6

Table 7-33 shows the calculation of the final COG as well as the final weight for loading 24 complete sets of 5 MW. The resulted information will be used further on in the MAXSURF stability software, in order to calculate the transvers and longitudinal stability.

Table 7-33 Stability Parameters after Loading 24 Sets of 5 MW WT

Cargo Name	Qty	Weight Per Unit	Overall Weight	LCG	TCG	VCG	Long. moment	Tran. moment	Vert. moment
		t	t	m	m	m	t.m	t.m	t.m
Blades	72	17.74	1277.28	67.73	0	16.68	86515.28	0	21305.03
Towers	24	347.46	8339.04	122.48	0	56.66	1021440.67	0	472481.66
Nacelles	24	307.78	7386.72	74.16	0	31.93	547865.63	0	235850.58
Overall cargo			**17003.04**	**97.38**	**0**	**42.91**	**1655821.59**	**0**	**729637.28**

Table 7-34 displays the result of the equilibrium analysis for the Decom Tools vessel when the vessel is loaded with 24 complete sets of 5 MW wind turbine. The result shows that vessel has positive transvers stability GM 6.95 m, and she is on even keel draft of 12.49 m.

Table 7-34 Results of Equilibrium Analysis After Loading 24 sets of 5MW Turbine

Parameter's Name	Value	Parameter's Name	Value
Draft Amidships m	12.493	LCB from zero pt. (+ve fwd) m	86.120
Displacement t	93657	LCF from zero pt. (+ve fwd) m	81.789
Heel deg	0.0	KB m	6.759
Draft at FP m	12.490	KG fluid m	16.107
Draft at AP m	12.497	BMt m	16.293
Draft at LCF m	12.493	BML m	239.981
Trim (+ve by stern) m	0.007	GMt corrected m	6.946
WL Length m	193.693	GML m	230.633
Beam max extents on WL m	47.975	KMt m	23.053
Wetted Area m^2	11789.078	KML m	246.740
Waterpl. Area m^2	8349.118	Immersion (TPc) tonne/cm	85.578
Prismatic coeff. (Cp)	0.826	MTc tonne.m	1220.367
Block coeff. (Cb)	0.785	RM at 1deg = GMt.Disp.sin(1) tonne.m	11353.394
Max Sect. area coeff. (Cm)	0.958	Max deck inclination deg	0.0023
Waterpl. area coeff. (Cwp)	0.898	Trim angle (+ve by stern) deg	0.0023

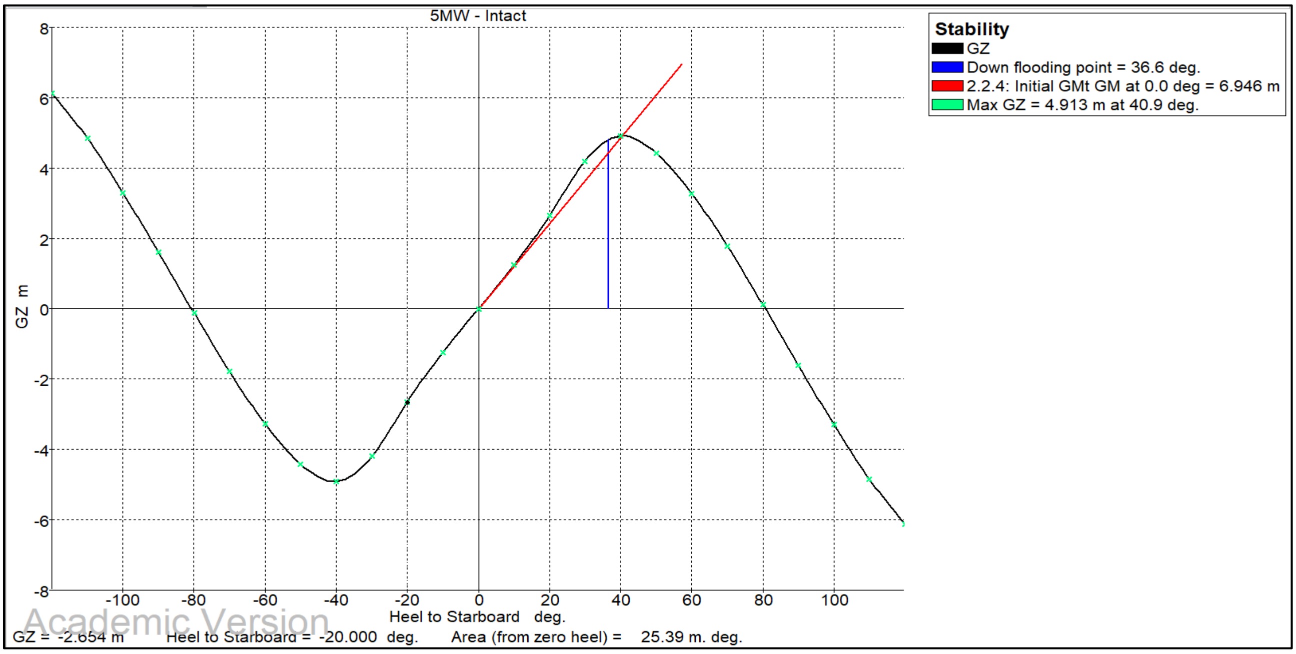


Figure 7-36 GZ Curve after Loading 24 sets of 5 MW Wind Turbine

Figure 7-36 presents the GZ curve of the vessel while loading 24 complete sets of 5 MW wind turbine. Having considered that the angle of down flooding here is less than 40°, so the dynamic analysis should be conducted to the angle of down flooding (36.6 degree).

Table 7-35 Criteria Check after Loading 24 Sets of 5 MW

Code	Criteria	Value	Units	Actual	Status	Margin (%)
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 30	3.151	m.deg	59.85	Pass	+1799.28
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 40	5.156	m.deg	89.65	Pass	+1638.59
267(85) Ch2 - General Criteria	2.2.1: Area 30 to 40	1.718	m.deg	29.80	Pass	+1633.69
267(85) Ch2 - General Criteria	2.2.2: Max GZ at 30 or greater	0.20	m	4.91	Pass	+2356.50
267(85) Ch2 - General Criteria	2.2.3: Angle of maximum GZ	25.0	Deg.	40.9	Pass	+63.64
267(85) Ch2 - General Criteria	2.2.4: Initial GMt	0.150	m	6.94	Pass	+4530.67

Table 7-35 displays that the static and dynamic stability for the Decom Tools vessel during loading 24 complete sets of 5 MW wind turbine is fulfilling the required intact stability criteria. Thus, the Decom Tools Vessel can transport 24 set of 5 MW wind turbine safely.

7.23 Stability Analysis for 3.6 MW Wind Turbine

Under section 6.11.3 it is shown that 33 full set of 3.6 MW wind turbine can be loaded onboard the Decom Tools vessel. In the section stability analysis will be conducted for the load out arrangement, see Figure 7-37. The dimension and weight of 3.6 MW wind turbine are listed in the Table 7-36.

Table 7-36 Weight and Dimension of 3.6 MW wind Turbine

Weight and Dimension of 3.6 MW Wind Turbine	
Component Name	**Size/ Weight**
Blade length (m)	58.5
Blade Diameter	3.5
Blade mass (t)	17.74
Max. chord (m)	4
Hub mass (t)	25
Nacelle mass (t)	125
Nacelle + Hub mass (t)	150
Nacelle dimensions (m) (L x W x H)	12.5 x 5 x 5.5
Nacelle with hub dimensions (m) (L x W x H)	17 x 5 x 5.5
Tower Mass (t)	210
Tower Height (m)	90
Tower top diameter (m)	3.2
Tower bottom diameter (m)	5

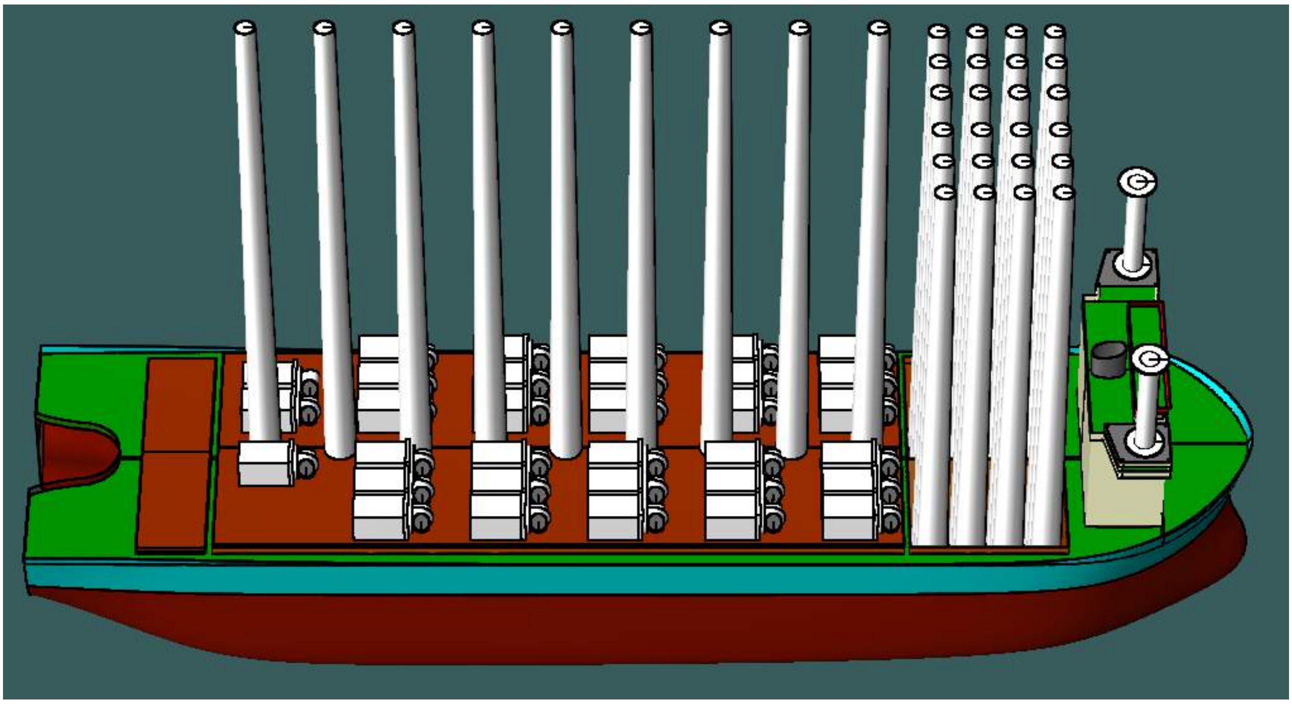


Figure 7-37 33 Sets of 3.6 MW WT Loaded on the Decom Tools Vessel

Table 7-37 represents 3.6 MW components COG calculation and the overall weight which will be used in the stability calculation.

Table 7-37 Stability Parameters after Loading 33 Sets of 3.6 MW WT

Cargo Name	Qty	Weight Per Unit	Overall Weight	LCG	TCG	VCG	Long. moment	Tran. moment	Vert. moment
		t	t	m	m	m	t.m	t.m	t.m
Blades	99	23	2277	72.30	0	16.8	164631.65	0	38383.38
Towers	33	210	6930	121.25	0	57.5	840304.08	0	399091.7
Nacelles	33	150	4950	78.43	0	31.4	388268.1	0	155845.8
Overall Cargo			**14157**	**98.41**	**0**	**41.91**	**1393203.83**	**0**	**593320.95**

Table 7-38 shows the result of the equilibrium analysis for the Decom Tools vessel during loading the 33 sets of 3.6 MW wind turbine. The result shows that vessel has positive transvers stability, and she is on draft of 12.13 m even keel.

Table 7-38 Results of Equilibrium Analysis After Loading 33 Sets of 3.6 MW Blades

Parameter's Name	Value	Parameter's Name	Value
Draft Amidships m	12.128	LCB from zero pt. (+ve fwd) m	86.268
Displacement t	90534	LCF from zero pt. (+ve fwd) m	81.881
Heel deg	0.0	KB m	6.568
Draft at FP m	12.124	KG fluid m	15.069
Draft at AP m	12.131	BMt m	16.788
Draft at LCF m	12.128	BML m	247.443
Trim (+ve by stern) m	0.007	GMt corrected m	8.287
WL Length m	193.865	GML m	238.942
Beam max extents on WL m	47.967	KMt m	23.356
Wetted Area m^2	11621.119	KML m	254.011
Waterpl. Area m^2	8336.462	Immersion (TPc) tonne/cm	85.449
Prismatic coeff. (Cp)	0.823	MTc tonne.m	1222.161
Block coeff. (Cb)	0.781	RM at 1deg = GMt.Disp.sin(1) tonne.m	13093.340
Max Sect. area coeff. (Cm)	0.957	Max deck inclination deg	0.0023
Waterpl. area coeff. (Cwp)	0.896	Trim angle (+ve by stern) deg	0.0023

Figure 7-38 shows how the GZ curve of the Decom Tools vessel will be after loading 33 sets of 3.6 MW Wind Turbine.

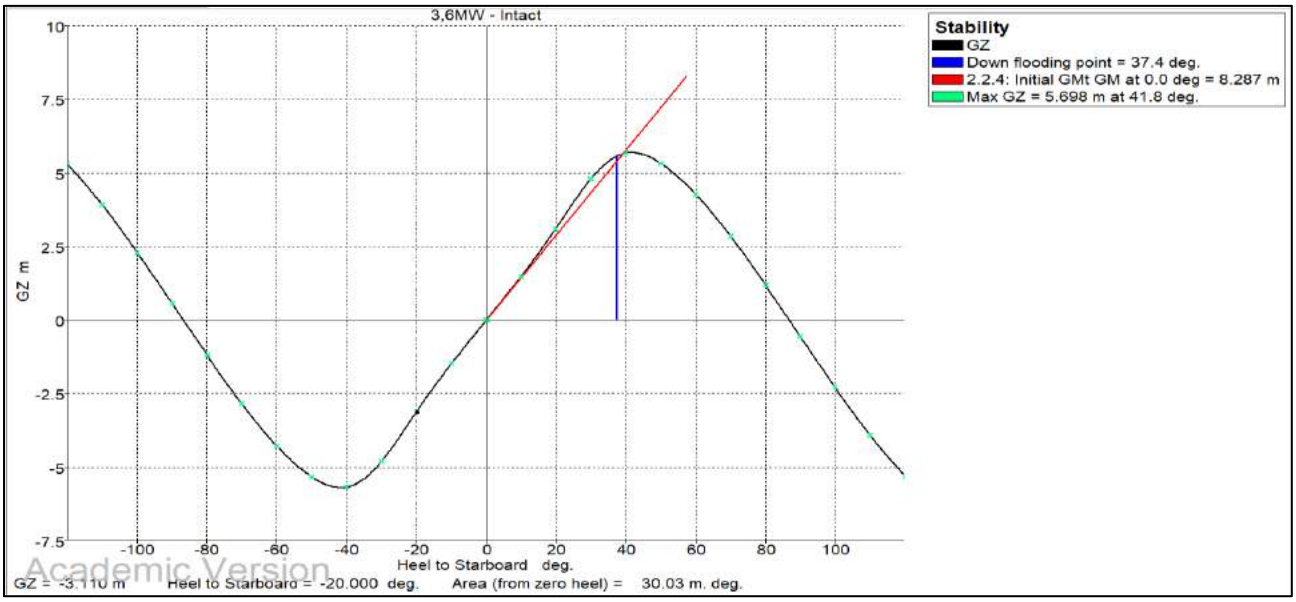


Figure 7-38 GZ Curve after Loading 33 sets of 3.6MW Wind Turbine

Table 7-39 shows that the static and dynamic stability of the vessel for loading 33 complete set of 3.6 MW wind turbine satisfying all the required intact stability criteria which are set by the international regulators.

Table 7-39 Criteria Check after Loading 33 Sets of 3.6 MW Blades

Code	Criteria	Value	Units	Actual	Status	Margin (%)
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 30	3.1513	m.deg	69.8500	Pass	+2116.54
267(85) Ch2 - General Criteria	2.2.1: Area 0 to 40	5.1566	m.deg	108.7346	Pass	+2008.65
267(85) Ch2 - General Criteria	2.2.1: Area 30 to 40	1.7189	m.deg	38.8846	Pass	+2162.18
267(85) Ch2 - General Criteria	2.2.2: Max GZ at 30 or greater	0.200	m	5.698	Pass	+2749.00
267(85) Ch2 - General Criteria	2.2.3: Angle of maximum GZ	25.0	Deg.	41.8	Pass	+67.27
267(85) Ch2 - General Criteria	2.2.4: Initial GMt	0.150	m	8.287	Pass	+5424.67

Having considered above results, the Decom Tools vessel can transport 33 full sets of 3.6 MW wind turbine safely without stability problems.

8 Ship Motion Analysis

8.1 Disclaimer

Unless expressly mentioned otherwise, all the tables and figures in this section are self-made based on information received from the motion's result of the Decom Tools vessel. Furthermore, unless expressly mentioned otherwise, this motion analysis is based on information obtained from the MAXSURF Motion manual.

In this paper, motion theories that the software use will not be explained, but rather only the motions results are described. Accordingly, all the software's equations to calculate the motion are not part of this paper. Motion theories and their equations are explained in detail in the MAXSURF motion manual. The motion manual is attached to the CD.

8.2 Introduction To Motion Analysis

In this section, the results of the conducted motions study for the Decom Tools are explained. The main objective is to predict the motion and response of the vessel in different sea states in order to find out an operational limit for two specific types of marine operations, which might the vessel involve in. These limitations are to ensure that the vessel can accomplish the assigned mission in a safe manner, for the ship itself, crew, and the offshore assets.

This chapter will centralize two main ideas: firstly, introducing the basic information about the ship motion and the possibilities to counter these motions. Secondly, tuning the analysis by setting up the correct parameters and running the analysis.

8.3 Ship Motions – Degrees of Freedom

Floating ships at sea are experiencing six degrees freedom and motions namely surge, sway and heave which are translation motions. While the roll, pitch, and yaw are rotational motions. All motions are measured relatively to the vessel itself. Figure *8-1* shows all these six motions which are acting through three axes X, Y, Z. The centre of these axes represents the ship's centre of gravity. (Lehmann and Bernhardt 2009, 878) The ship motions of heave, pitch and roll are oscillatory in nature, this is due to the restoring force created by changes in buoyancy involved in these motions (Bentley Group 2021). Roll, heave and pitch are a dynamic and restorative motions which can lead to excessive rolls when a ship encounters wave periods close to its natural roll period. (Clark 2008, 190)

The roll motion is one of the most important factors to obtain the ship's seaworthiness. Many factors are influencing due to large roll amplitudes. It is narrowing the capability of the vessel to carry out the task. Furthermore, it affects the general performance of a vessel, by obstructing the work routine, and possible cause of cargo damage due to excessive roll accelerations. In other words, large rolling causes the vessel to go to stand-by mode which decrease the productivity of the vessel and the operation.

Pitch motion is a rotational motion about the transvers Y-axis where the bow is going upward and stern going downward, and vice-versa.

While heave motion is a linear vertical upward and downward motion along the vertical axis (Z). Heave motion happens when waves hit a vessel, and it results alteration in buoyancy and weight forces. This tends to lift the vessel up at a certain section (Menon 2021).

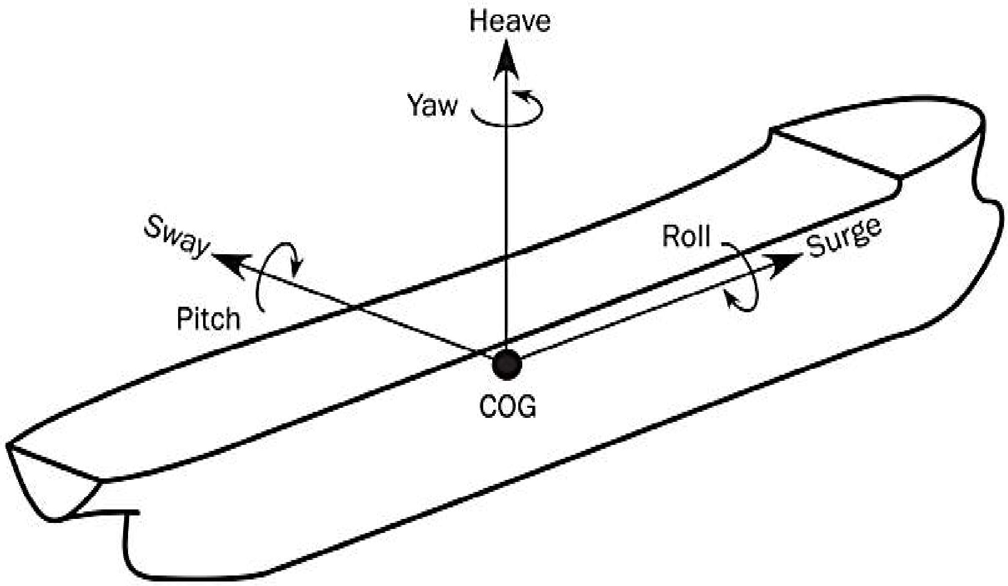


Figure 8-1 Motions of a Floating Vessel

The surge and sway motions are translational motions. Surging motions occurs when wave action produce action that accelerates and deaccelerates the vessel forward and backwards along the longitudinal axis. At the same time, swaying is the lateral movement due to force being resulted from wave action along the transverse axis.

Also, yawing is when wave action rotates the ship around its vertical axis (Z-axis). In other words, the vessel will continually swing back and forth from its desired course.

In general, either DP system or position anchor winches (PAW) can control three motions namely surge, yaw and sway. Controlling the other three motions cannot be attained by either DP or PAW and heavily depends on the specification of the vessel, the sea state and so on.

The importance of each motion in marine operation depends on the type of operation. In this document, roll, heave, and pitch are the most critical factors that could affect the vessel stability and safety of crew during sensitive maritime operations.

8.4 Motion Compensation Systems

Motion compensation (damping) systems are those systems that can initiate forces against the original motions forces which are due to environmental forces such as waves, currents, and wind.

Motion compensation systems are used to increase the operational window, enlarge the scope of operations, and improve the safety level for the vessel itself, crew, and the involved asset.

For each degree of freedom, there is a solution for damping; for instance, rolling motion of the vessel can be damped (reduce the roll, not meant to achieve the zero-roll degrees) by the bilge keel and by other active or passive anti-rolling tanks, flume tank as well as by fins stabilizer. In addition, the Voith Schneider propulsion system can reduce the roll too.

Pitch motion can also be decreased by using an active fins stabilizer. However, the heave motion for the entire vessel itself cannot be damped. Nevertheless, the heave can be reduced for a specific equipment such as gangway and crane. Gangway which is equipped with heave compensation system makes the transfer of crew from vessel to the platform easier and safer. It prevents the clash of gangway with platform.

Additionally, given that the Decom Tools vessel is equipped with the DP system and VSP, thus, the surge, sway, and yaw motion can be counteracted by the DP system to maintain the desired position and the heading, also the rolling can be compensated by VSP as well as anti-rolling tank etc.

Thus, three motions which can be adjusted and responded by DP namely surge, sway, and yaw are excluded from the motion assessment.

8.5 Motion Analysis Assessment

As it stated before, the Decom Tools vessel is a multi-function and multi-purpose green vessel. The motion analysis has been conducted for three modes of operation including, the stationary mode, the pile extraction mode, and the cable recovery operations.

8.5.1 Monopile Extraction

Finding the ship motion in irregular seas for the monopile extraction operation is essential. Thus, the motion analysis should be carried out to identify under which circumstance and sea state the vessel can perform this operation safely. However, this kind of recommendations are provided by the ship designers to the ship management companies/owner. The responsible crew onboard the vessel such as construction superintendent and vessel master can override the recommendations. In this analysis, a comprehensive study has been done regarding motions such as roll, heave, and pitch to ascertain that the vessel can serve this function.

8.5.2 Subsea Cable Extraction and Removal

Like the pile extraction, predicting ship motion for the cable removal is significantly important, since excessive motion could affect the tension that are applied to the cable. Any severe motion could break the cable. Throughout this assessment the vessel speed is considered 1 knot.

8.6 Vessel Stability Information During the Analysis

Table 8-1 shows the vessel information which will be used during the analysis. Throughout the analysis, the vessel is on an even keel draft of 10.11 m and on an upright condition.

The COG is (87.217m, 0m, 9.892m). The vessel's GM is relatively high which will induce a short rolling period and excessive lateral acceleration.

Therefore, the result of rolling motion analysis could be a relatively high.

Table 8-1 Vessel Stability Parameters During Motion Analysis

Description	Value	Description	Value
Draft Amidships m	10.108	LCB from zero pt. (+ve fwd) m	87.363
Displacement t	72640	LCF from zero pt. (+ve fwd) m	83.419
Heel deg	0	KB m	5.538
Draft at FP m	10.108	KG fluid m	9.892
Draft at AP m	10.108	LCG m	87.217
Draft at LCF m	10.108	BMt m	20.144
Trim (+ve by stern) m	0	BML m	294.448
WL Length m	192.137	GMt corrected m	15.790
Beam max extents on WL m	47.831	GML m	290.094
Wetted Area m^2	10535.097	KMt m	25.682
Waterpl. Area m^2	8185.383	KML m	299.986
Prismatic coeff. (Cp)	0.814	Immersion (TPc) tonne/cm	83.910
Block coeff. (Cb)	0.763	MTc tonne.m	1190.535
Max Sect. area coeff. (Cm)	0.947	RM at 1deg = GMt.Disp.sin(1) tonne.m	20017.488
Waterpl. area coeff. (Cwp)	0.891	Trim angle (+ve by stern) deg	0

8.7 Sea State Code

For analysing the vessel motions, it is essential to have a view on the sea state code, in order to choose the correct wave height. Table 8-2 shows the world meteorological organization sea state code, which describing the range and mean of the significant wave height for each sea state code.

Table 8-2 World Meteorological Organization Sea state code

Sea State Code	Significant Wave Height Range [m]	Significant Wave Height Mean [m]	Description
	Range	Mean	
0	0	0	Calm (glassy)
1	0.0 - 0.1	0.05	Calm (rippled)
2	0.1 - 0.5	0.3	Smooth (wavelets)
3	0.5 - 1.25	0.875	Slight
4	1.25 - 2.5	1.875	Moderate
5	2.5 - 4.0	3.25	Rough
6	4.0 - 6.0	5.0	Very rough
7	6.0 - 9.0	7.5	High
8	9.0 - 14.0	11.5	Very high
9	over 14.0	over 14.0	Phenomenal

8.8 Ship's Speed During the Motion Analysis

Since the motion analysis carried out for two modes of operations, two different speeds are tunned during the upcoming analysis.

The first mode is the zero-knot speed. In this mode the Decom Tools Vessel is supposed to be involved in the pile extraction operation (gripping the monopile). Therefore, the motion analysis is conducted to evaluate the motion of the vessel at gripper location with the given assumption. Since the monopile can induce forces to the gripper which will impact the natural response of the vessel, analysis of the pile extraction and impact of the extraction on the vessel motion is not studies here. This study needs to be conducted case by case which depends on the soil condition, length of the pile, length of penetration into the seabed, pile diameter and so forth. Thus, the intention is to study the vessel motion is to predict the motion on the gripper, such as vertical motion, velocity, and acceleration. This study can be done for vertical, longitudinal, and lateral motion on a specific point too.

Table 8-3 Chosen vessel Speed

Sr.	Name	Speed (kn)
1	Gripping Speed	0
2	Cable Removal Speed	1

The second mode is when the vessel is involved in cable recovery operation with speed of 1 knot (in the calculation it is supposed that the speed of cable recovery for export cable is 2km/day which means the vessel speed is about 0.04 knots. The motions of the vessel at 1 knot is much more than 0.04 knots). Similar to the above-mentioned information, the motion will be studied in the 3D dimension as well. Table 8-3 show the speed of the vessel which are used for motion assessment during different operations. In the table, gripping means when the vessel holds the monopile firmly which in this case, the vessel has stationary position. Gripping speed also can be considered for other operation, for instance, heavy lift operation (loading the dismantled turbine components into the Decom Tools Vessel). This means the result can be transferred to other tasks as well.

8.9 Wave Direction

During the upcoming analysis, motion in seven relative wave directions to the ship's bow will be assessed. Table 8-4 represents the chosen wave direction that will be studied to predict the motion. Headings are chosen from 0° to 180°. Since the hull of the vessel is designed symmetric from both sides, STBD and PS, the wave headings from 180° to 360° will give the identical result of what has been previously chosen, therefore heading from 180° to 360° will be ignored.

Table 8-4 Wave Direction

Name	Wave Heading (deg)
Head Seas	180°
Bow Seas	150°
Between Beam and Bow Seas	120°
Beam Seas	090°
Between Beam and Quartering Seas	060°
Quartering seas	030°
Following Seas	000°

8.10 Motion Analysis of Desired Locations

The desired operations for motion analysis are cable recovery and pile extraction. Therefore, the effective point of vessel which are involved in these operations need to be identified for further study. The effective points which are listed in the Table 8-5 shows the points in which the motion will be evaluated. These points are measured in meters from the reference point. Figure 8-2 shows the reference point which is coordinated in (0,0,0).

Table 8-5 Remote Locations

Remote Location name	Long. Pos. (m)	Offset (m)	Height. (m)
Cable Removal Point	-12.7	23.5	26.8
Gripping Point	-5	0	18

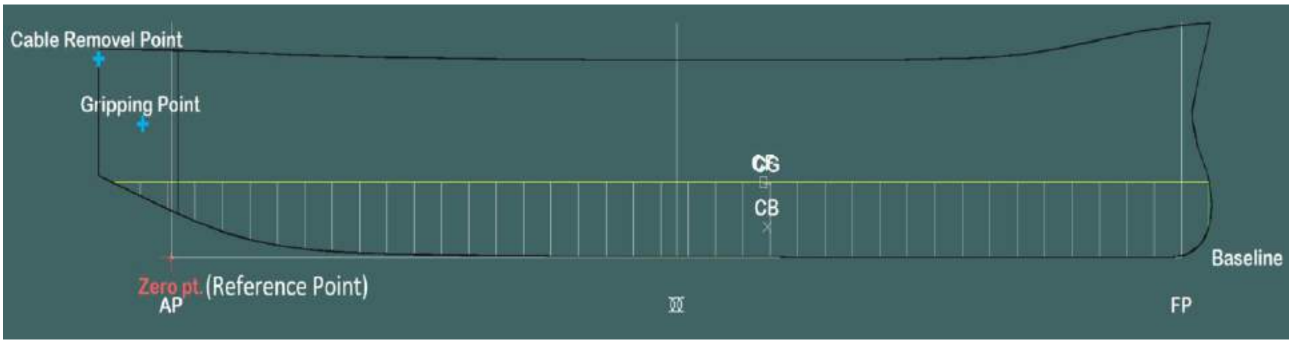


Figure 8-2 Reference Points

8.11 Tuning The Analysis Settings

For the motion analysis, the software by the name of the MAXSURF motion is used. For conducting the motion analysis, the geometry of the Decom Tools vessel need be imported into the MAXSURF Motion software. Furthermore, the software works based on some theories. In order to have reliable results at the end, the appropriate setting should be done, and right theory should be selected. The following section explain the selected theories.

8.11.1 Motion Theories

MAXSURF motion software is able to use one of two methods to calculate the vessel response either a linear strip theory method or the panel methods.

The six degrees of freedom can be generated by using the panel method. However, this method is only limited to zero speed. While the linear strip theory which is a frequency-domain method is able to calculate the motion with different speeds. In addition, it is used to compute heave and pitch response of the vessel. Furthermore, the roll response is computed using linear roll damping theory.

Accordingly, for above mentioned operations, both theories for analysing the motion need to be used. The panel methods will be chosen for analysing the vessel’s motion during the gripping operation. While the strip theory will be used for analysing the vessel during the cable removal operation.

8.11.2 Wave Spectrum

Wave spectrum is the collective set of waves under consideration consisting of random superimposed waves of various wavelengths, amplitude and periods. All of these parameters are equally important. These give the complete real-time data of the ocean condition in theoretical terms.

According to Table 8-6 five different waves spectra are studied for the analysis. The JONSWAP (Joint North Sea Wave Project) spectrum represent the real characteristics of real wave energy spectra in North Sea region. Each significant wave height has different wave period, periods are measured in seconds (s).

Note: The JONSWAP wave spectrum is used throughout the entire analysis.

Table 8-6 Wave Spectrum

Name	Type	Char. Height (m)	Model Period (s)	Average Period (s)	Zero Crossing Period (s)
Smooth	JONSWAP	0.3	9.967 s	8.346 s	7.854 s
Slight	JONSWAP	0.875	9.967 s	8.346 s	7.854 s
Moderate	JONSWAP	1.875	9.972 s	8.350 s	7.858 s
Rough	JONSWAP	3.25	9.972 s	8.350 s	7.858 s
Very rough	JONSWAP	5	9.984 s	8.360 s	7.868 s

8.11.3 Damping Factors

In the motion study, one can evaluate the impact of damping system of the vessels. Vessels are usually equipped with one or more anti-rolling devices, for instance bilge Keel, stabilizing fin, anti-rolling tanks, etc. Bilge keel is the most usable device that can be seen almost in every commercial vessel. They are "fixed longitudinal plates fitted at the turn of the bilge so that their drag dampens roll amplitudes" (WÄRTSILÄ n.d.). The bilge keel is not designed for the Decom Tools vessel yet. Therefore, the effect of bilge keel is not studied in the upcoming analysis too Therefore, the damping factor for roll motion will be considered as zero.

Figure 8-3 Bilge Keel

In addition, we did not consider any damping technology for heave and pitch motion. Therefore, the damping factor for heave and pitch will also kept as zero.

8.12 Motion Assessment

The analysis concentrates on roll, heave, and pitch motion in order to examine under which circumstances the Decom Tools vessel could operate safely. Motion assessment will be conducted at the vessel's centre of gravity and at the two predefined locations namely the gripper point, and cable removal point.

8.12.1 Motion at the Centre of Gravity

Assessment of vessel's motion before any offshore operation is crucial since it could save the resources and reduce risks. Therefore, in order to define operational limits, we will examine how the vessel could behave in different wave spectrum as well as in various headings and speeds.
The purpose of studying the vessel motion at its centre of gravity is to have an overall view of the motion's magnitude on each wave spectrum. Five wind spectrums namely smooth, slight, moderate, rough and very rough sea state which are explained in the Table 8-2 and Table 8-6 are selected for the all motion analysis.

8.12.2 Heave

In this motion, the vessel will be subjected to two phases, the heave up and heave down phases. In the first phase, due to the action of a moving wave the vessel will be situated on top of the wave crest, and by the time running, the vessel will be situated later in a position in the wave through, which is reflecting the second phase. In other words, with the passage of the time, the vessel buoyancy moves between wave crests and troughs. If the wave troughs predominant, buoyancy falls and the ship sinks, while if the wave crests predominant, the ship rises. The overall height between the two phases is the heave motion in meters. Figure 8-4 describe the terms that define a wave.

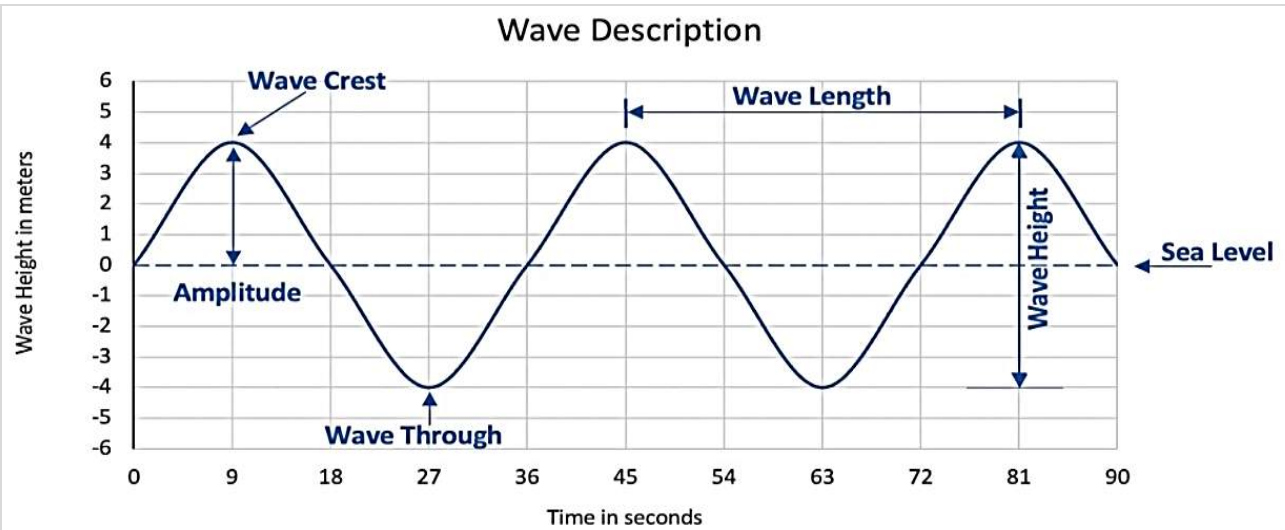


Figure 8-4 Wave Description

Figure 8-5 represents the magnitude of heave motion of the Decom Tools vessel at the centre of gravity on the slight sea state (for the period and wave height of the slight sea state please refer to the Table 8-6 and Table 8-2). Figure 8-5 illustrates that the minimum heave motion is about 3 cm when the wave hit the stern of the vessel, whereas it is recorded to be about 4 cm when the wave hit the vessel from the bow. However, by changing the heading, heave motion is increasing rapidly, where the maximum heave motion occur on beam seas.

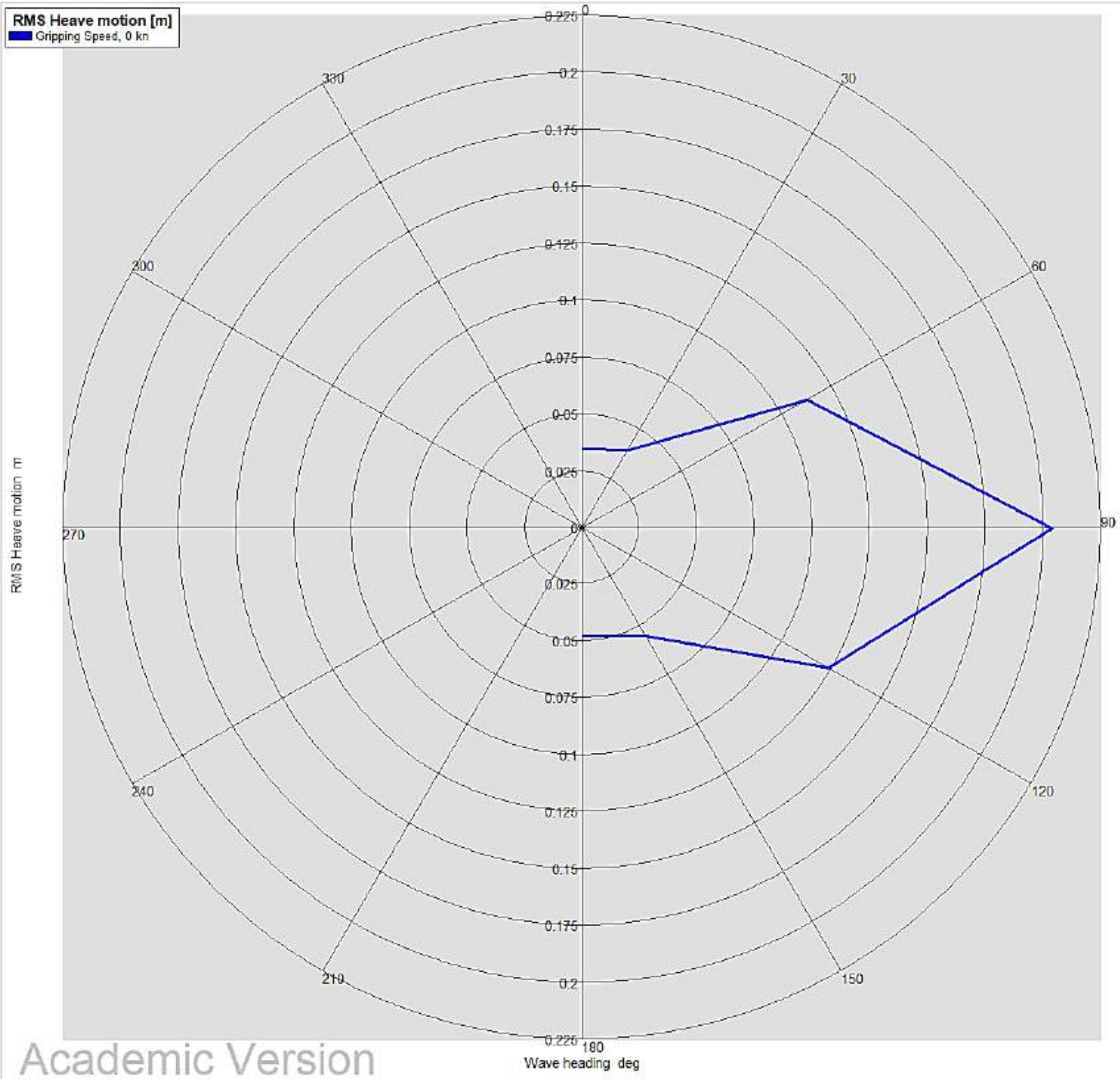


Figure 8-5 Heave Motion at COG – Slight Sea state

Source: MAXSURF Motion

To have more overview about the impact of different sea states on heave motion, heave motion of the vessel for the different sea states as well as various ship headings analysis which are shown in Figure 8-6.

According to Figure 8-6 , the heave motion is escalating with the severity of the sea state. In addition, wave heading and vessel speed play significant role in the heave height, where the highest heave motion for the Decom Tools vessel can be expected in beam seas.

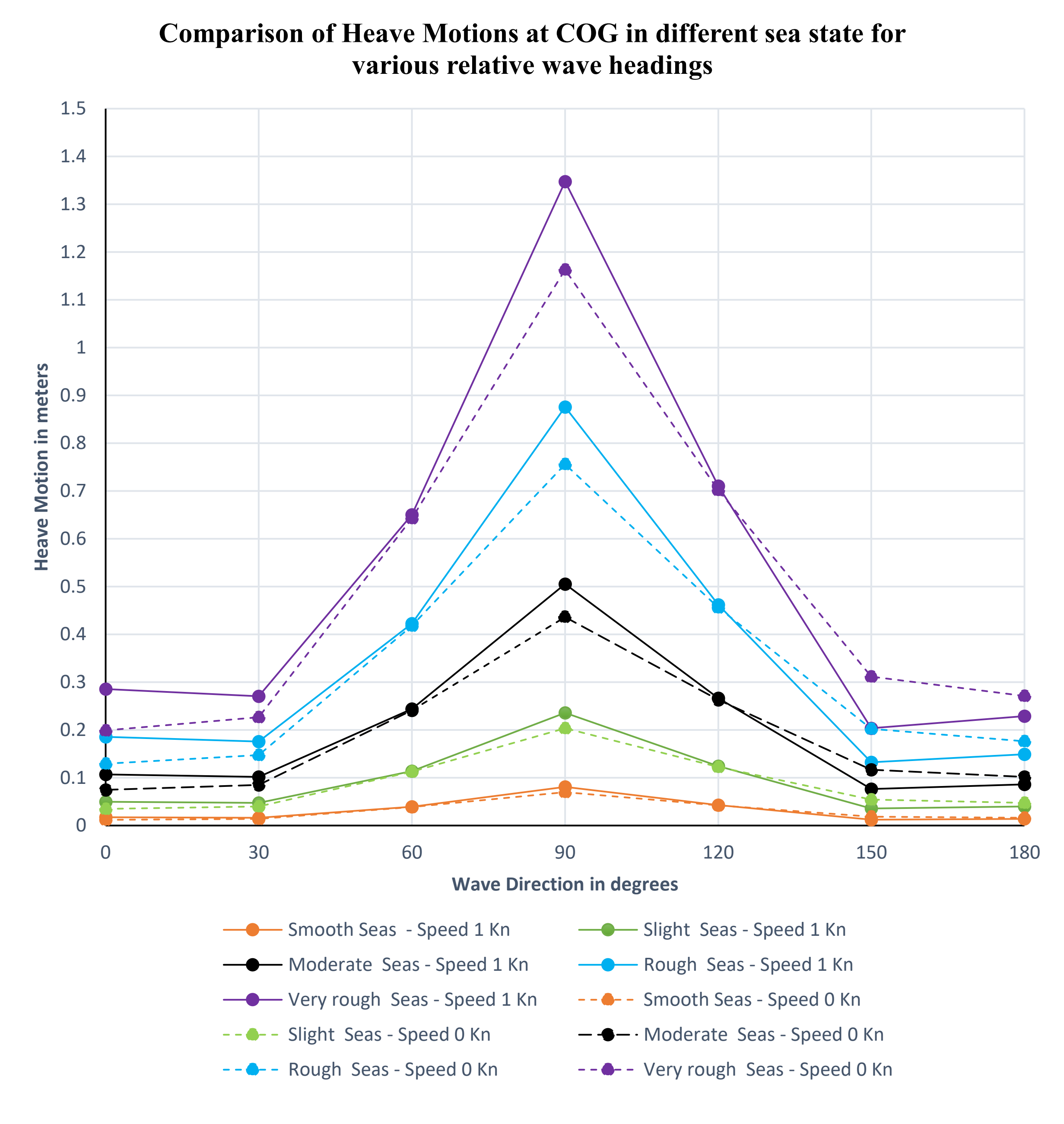


Figure 8-6 Comparison of Heave Motions at COG in different sea states

During the forward speed of one knot, the lowest heave motion can be expected in head seas. In other hand, when the vessel has zero speed the lowest heave motion can be expected in following seas. For instance, in very rough sea state, the Decom Tools vessel have 1.35 m heave on beam seas at one knot speed, and 1.16 at zero knot.

Furthermore, in following seas, in forward speed the heave was predicted as 0.3 m, while in stationary mode was predicted as 0.2m. Besides, the heave motion is predicted in head sea to be 0.23 m for forward speed and 0.28 m for stationary mode.

8.12.3 Pitch

There is direct relation between the length of vessel and the pitch angle. Shorter vessel has a larger pitching angle than a vessel with a greater length in the same environmental condition. However, the pitch angle depends on the wave period and wave direction too.

Figure 8-7 depicts the pitch motion at the vessel's COG on slight sea stats. The largest pitch angles in stationary mode (zero speed) occur on relative heading of 60°and 120°, while the minimum pitch angle can be expected in beam seas (90°). The impact of head and following seas are almost the same on pitching angle. For instance, the pitch angle due to wave action in slight sea at zero speed on following seas is 0.105°, while the pitch angle in head seas is 0.1°.

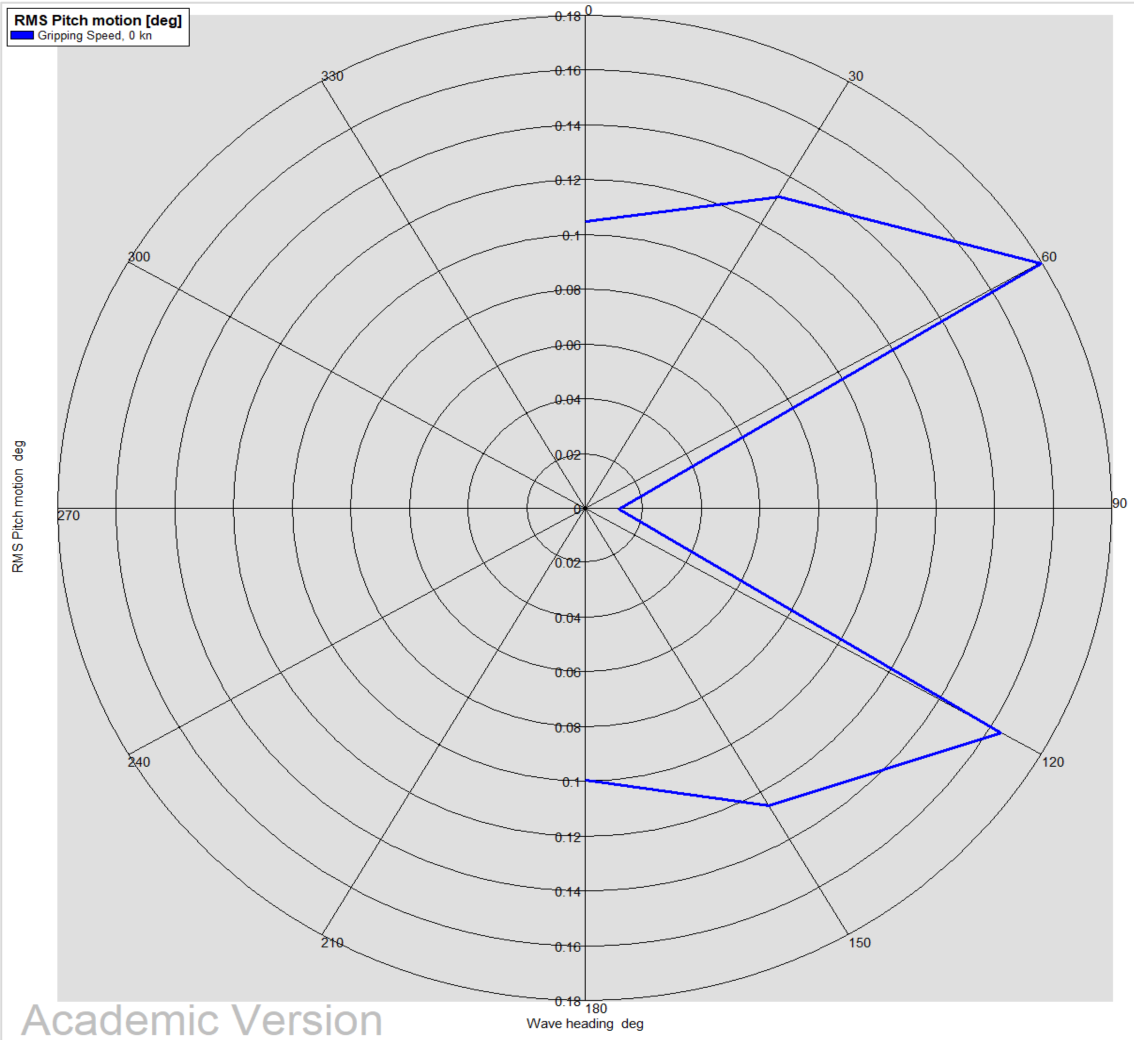


Figure 8-7 Pitch Motion at COG – Slight Sea state

Source: MAXSURF Motion

Furthermore, by increasing the ship's speed to one knot the pitch angle will be slightly increased. The analysis revealed that in the very rough sea state, by increasing the vessel speed from zero speed to 1 knot, the pitch angle increased half degree. However, if the vessel speed reach 1 Kn, the utmost pitch angle observed on 060° (quarter-beam sea) relative wave heading, see Figure 8-8.

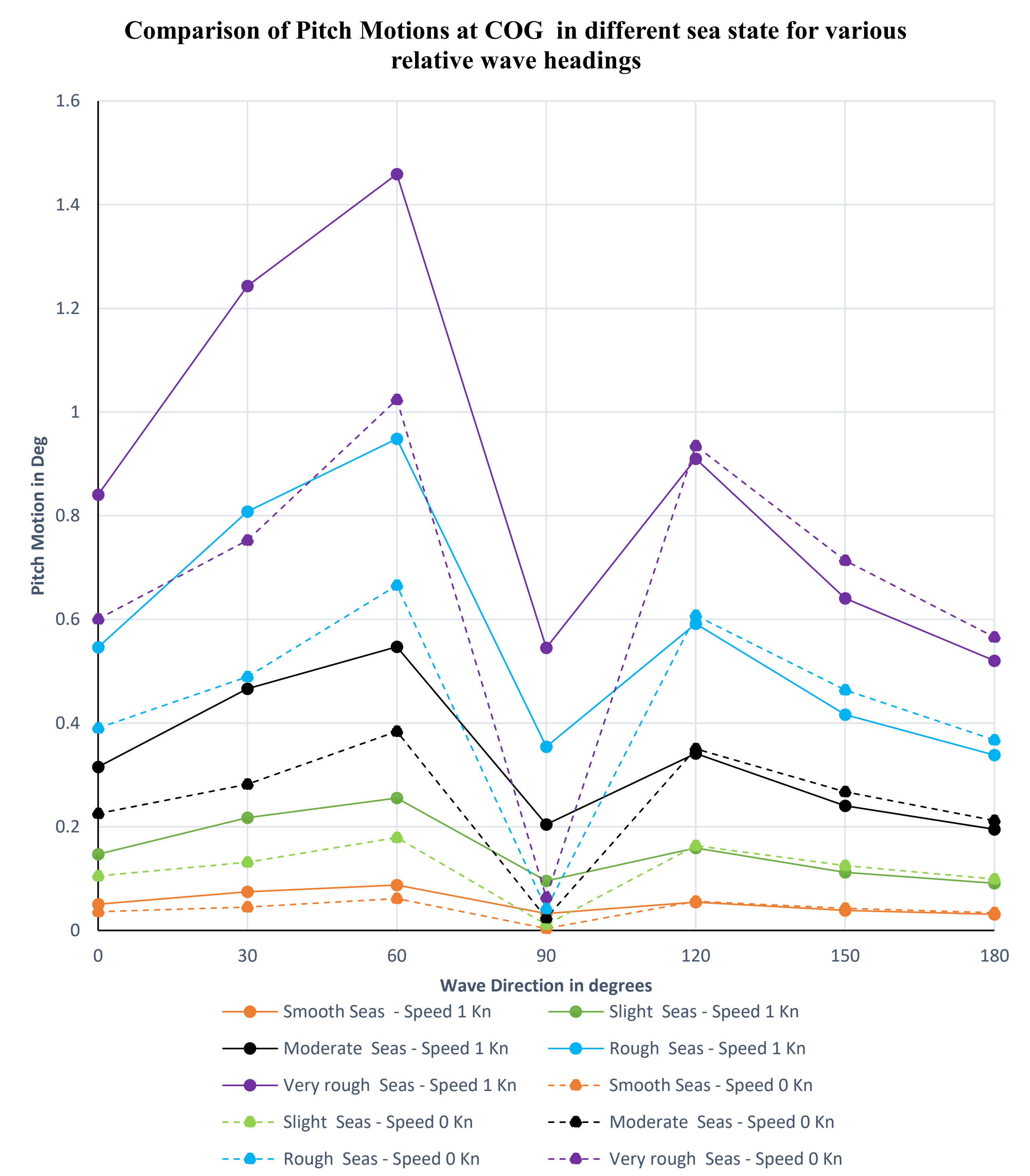


Figure 8-8 Comparison of Pitch Motions at COG in different sea state

8.12.4 Roll

Roll is the oscillatory motion of the vessel athwartships about the longitudinal axis (fore to aft) of the vessel. When the starboard side is down and the port side is up, i.e., the vessel is turning in a clockwise sense when viewed from in a longitudinal direction looking forward towards the bow from aft (+X direction), the roll angle is said to be positive (Ghosh 2021).

The roll angle happens due to wave action that strikes the vessel from the side. The most significant wave angle can be expected when the wave hits the vessel's hull perpendicular to the vessel ship's centreline (the x-axis). Figure 8-9 shows that the largest angle of roll was predicted on beam seas with 1.1°, however, the lowest rolling angle is in head seas and following seas.

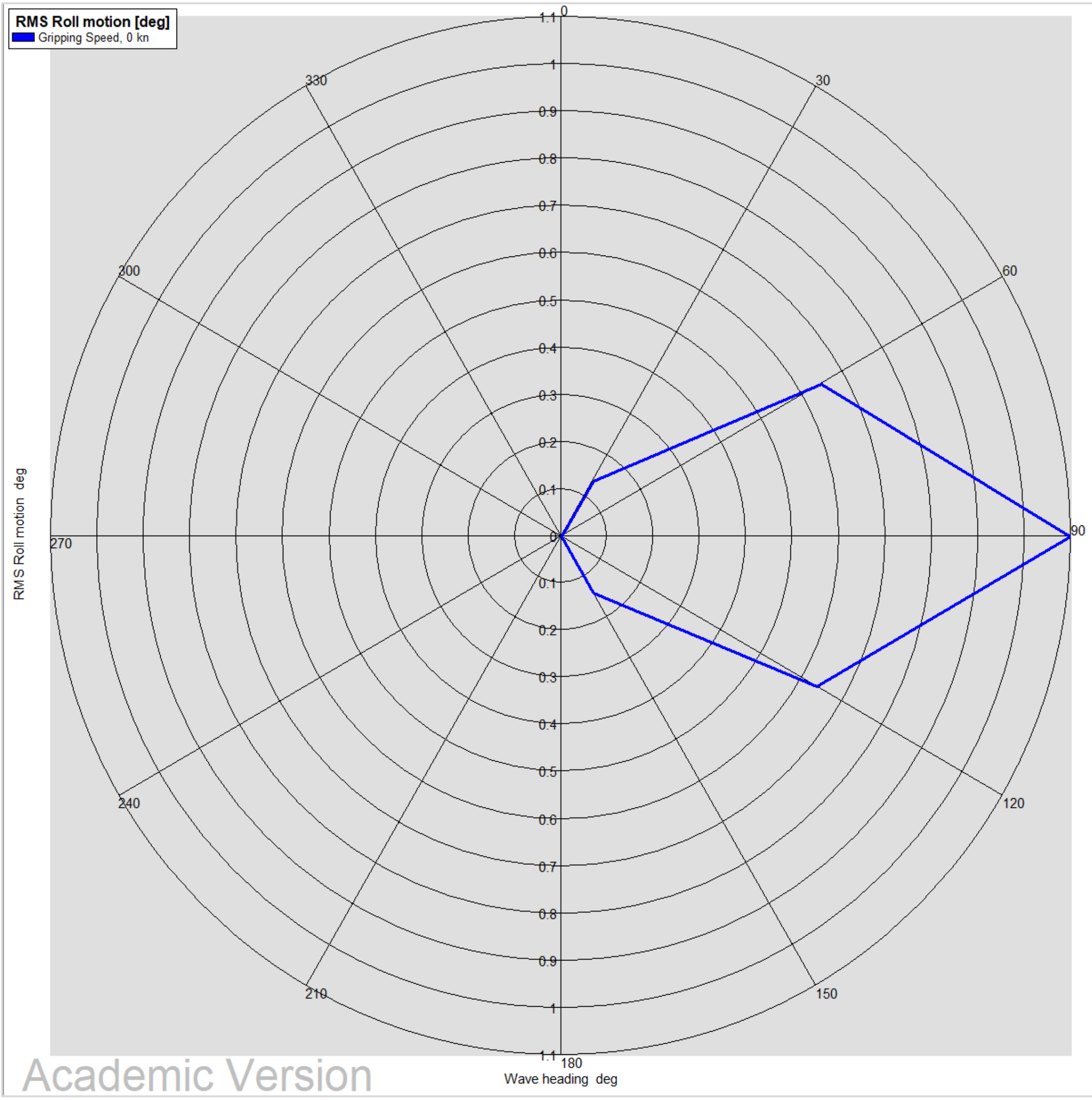


Figure 8-9 Roll Motion at COG – Slight Sea state

Source: MAXSURF Motion

Figure 8-10 shows the roll motion for the Decom Tools vessel in different sea states and different wave headings. Obviously, the vessel will have the highest impact due to wave action from the beam side. However, with increasing the vessel speed, the second-largest roll angle can be expected at a heading of 120 and 060 (Beam-head seas). At the same time, the lowest roll motion can be expected on the head and following seas which equal to zero. Furthermore, by increasing the speed, the roll angle will be increased on the bow seas and decreased in the quarter seas. For instance, the bow seas and quarter seas during the stationary mode were almost the same value.

However, increasing the speed makes the roll angle larger at bow seas and less significant at quarter seas.

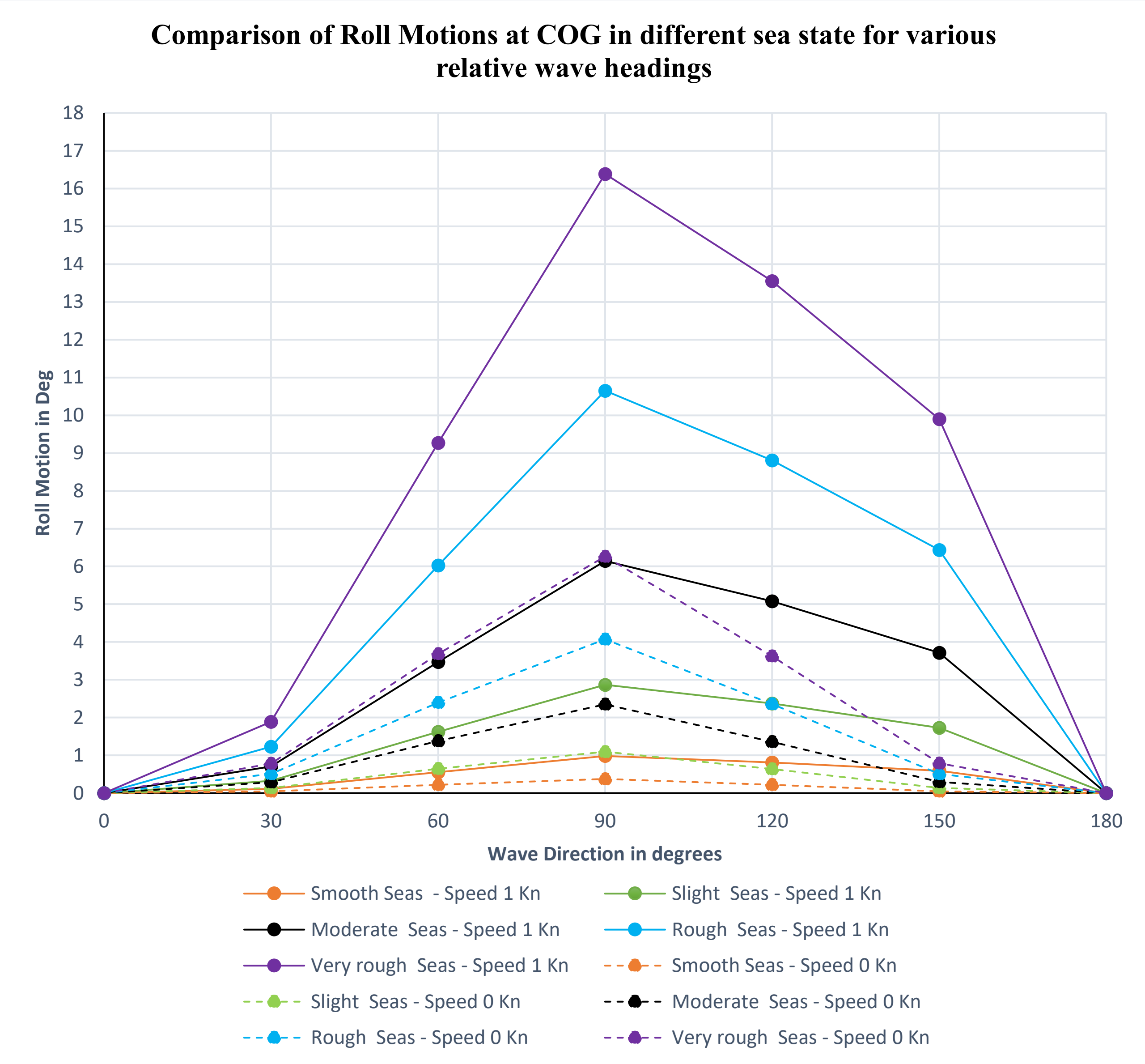


Figure 8-10 Comparison of Roll Motions at COG in different sea state

8.13 Motions at the Desired Locations

All vessels are always subject to the external forces such as wind and waves, current etc., causing several motions during its service time. These motions could affect the smoothness of any operation, for instance, pile extraction and cable removal operation.

Motion analysis has been conducted for the defined location which in this section the results will be shown. The results indicate how the selected points (gripper and cable removal points) behave in different sea states. The result will be illustrated in three-dimensional space. Firstly, the vertical motion along the Z-axis, which is due to the heave motion. Secondly, the longitudinal motion along the X-axis, which is due to the vessel pitch motion. Finally, the lateral motion along the Y-axis, which is due to the vessel roll motion.

8.13.1 Motions at Gripper Point

Finding how many centimetres the gripper moves in three-dimensional spaces due to the effect of vessel motion is an essential step. The benefit behind predicting the motion at a specific point is to outline the required characteristics and specification of the motion compensation systems for the gripper to safely accomplish the extraction operation without occurrent of accident to the gripper, vessel, and asset. Moreover, in the operation manual of the vessel, the weather criteria for safe pile extraction operation should be recommended by vessel manufacturer which is result of motion analysis.

The pile extraction is a sensitive operation which an oversight, an omission or a mistake can endanger the safety of the personnel and assets. Therefore, the vessel motion must be as minimum as possible to avoid the action of violent waves that could cause damage. Referring to the Figure 8-6, Figure 8-8 and Figure 8-10 the minimum motion can be expected for the sea with a mean significant wave height not more than 0.875 m. Accordingly, further analysis will concentrate on a comparison among three different sea states, smooth, slight, and moderate sea states. It should be noted that pile extraction can be conducted when the vessel has stationary position, so, the speed is considered zero (0) in the motion analysis.

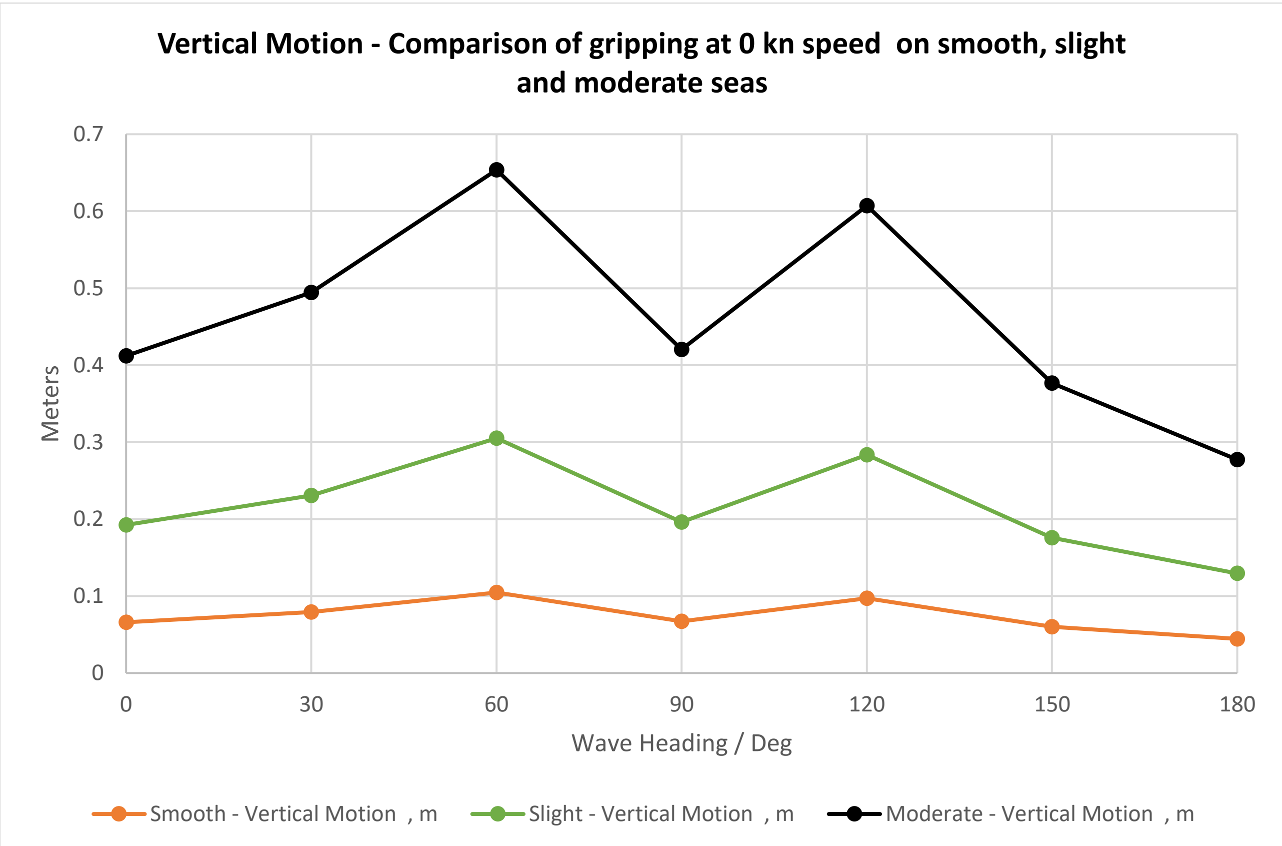


Figure 8-11 Absolute Vertical Motion at Gripper point on three different Sea States

Figure 8-11, Figure 8-12, and Figure 8-13 show the effect of heave motion on the selected point (the gripper point). Figure 8-11 illustrates the vertical motion in meters that the gripper point is subjected to under the effect of different sea states. While Figure 8-12 shows the longitudinal motion, and Figure 8-13 shows the lateral movement.

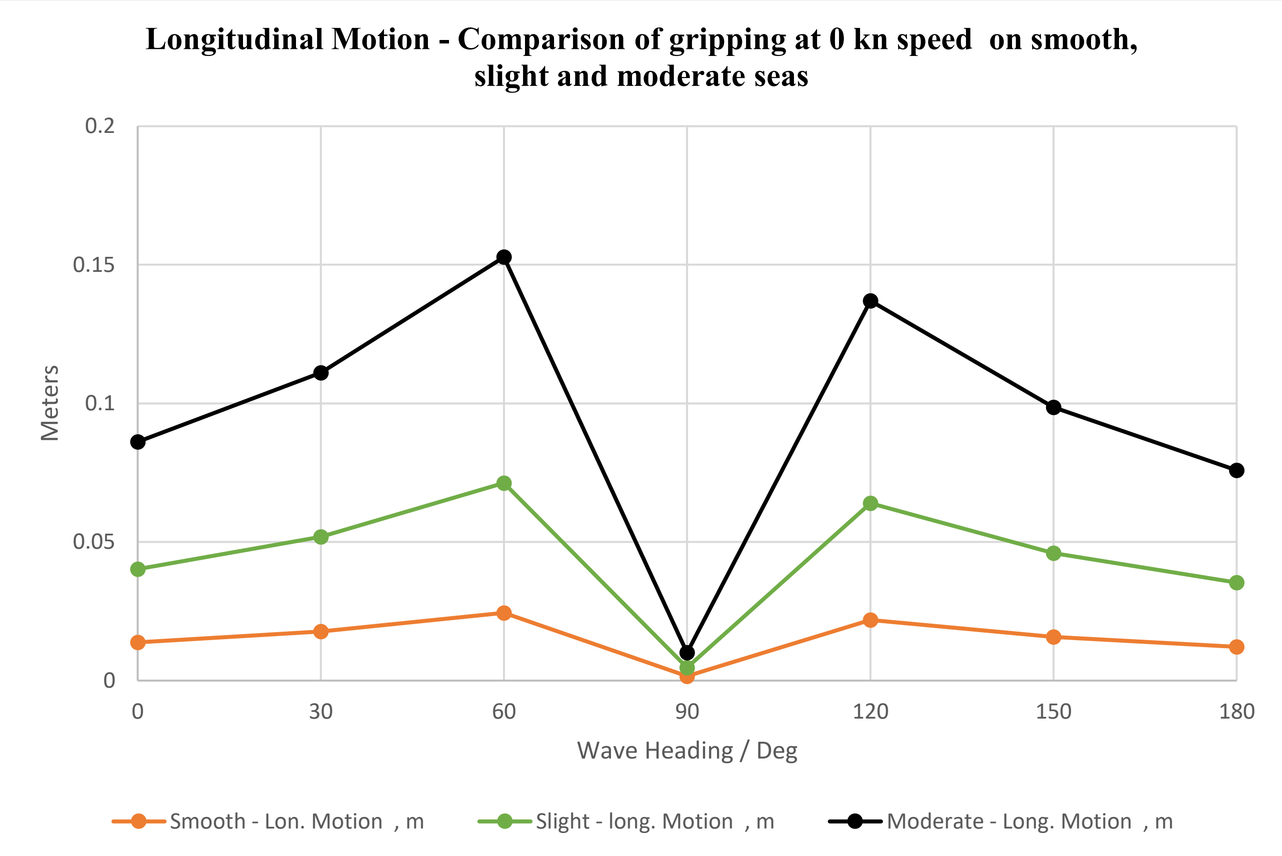


Figure 8-12 Longitudinal Motion at Gripper point on three different Sea States

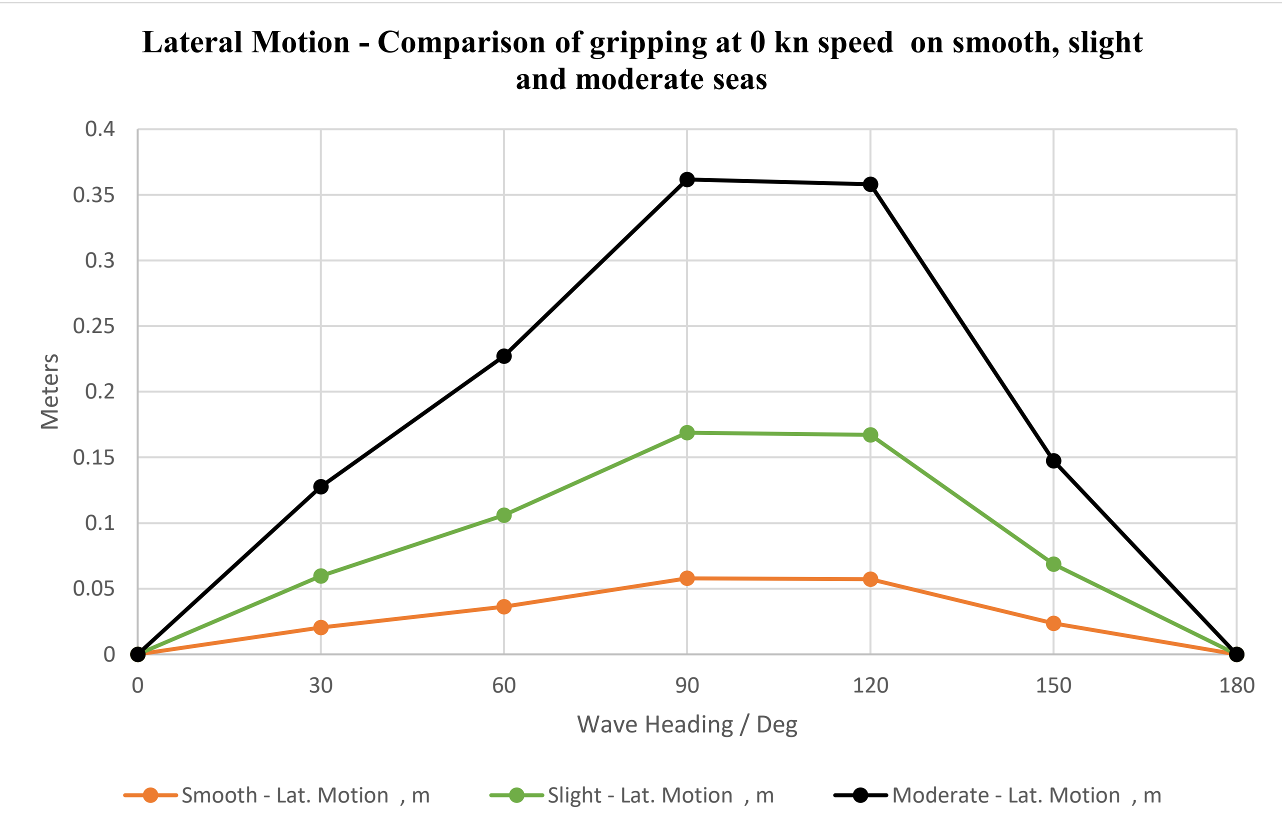


Figure 8-13 Lateral Motion at Gripper point on three different Sea States

The lowest vertical motion can be expected on head seas (180°), where in slight sea the maximum absolute vertical motion is 13 cm, while in moderate sea is 28 cm. Furthermore, the longitudinal motion at slight sea on head seas predicted 3 cm, where the lateral motion on same sea state predicted zero. The zero lateral motion because the roll motion almost zero in head seas.

8.13.1.1 Ship Motions in Irregular Seas During Gripping Operation

Irregular ocean waves are often characterized by a "wave spectrum", this describes the distribution of wave energy (height) with frequency.[78] It should be noted that naturally in the sea, the waves are irregular.

One of the characteristics of the irregular waves which distinguish them from regular waves is the non-recurrence of their form in time. Figure 8-14 and Figure 8-15 shows the result of 35 seconds of vessel motion animation in irregular slight seas at the vessel centre of gravity, in head and following seas. These figures show the difference in wave amplitude as well as the waveform.

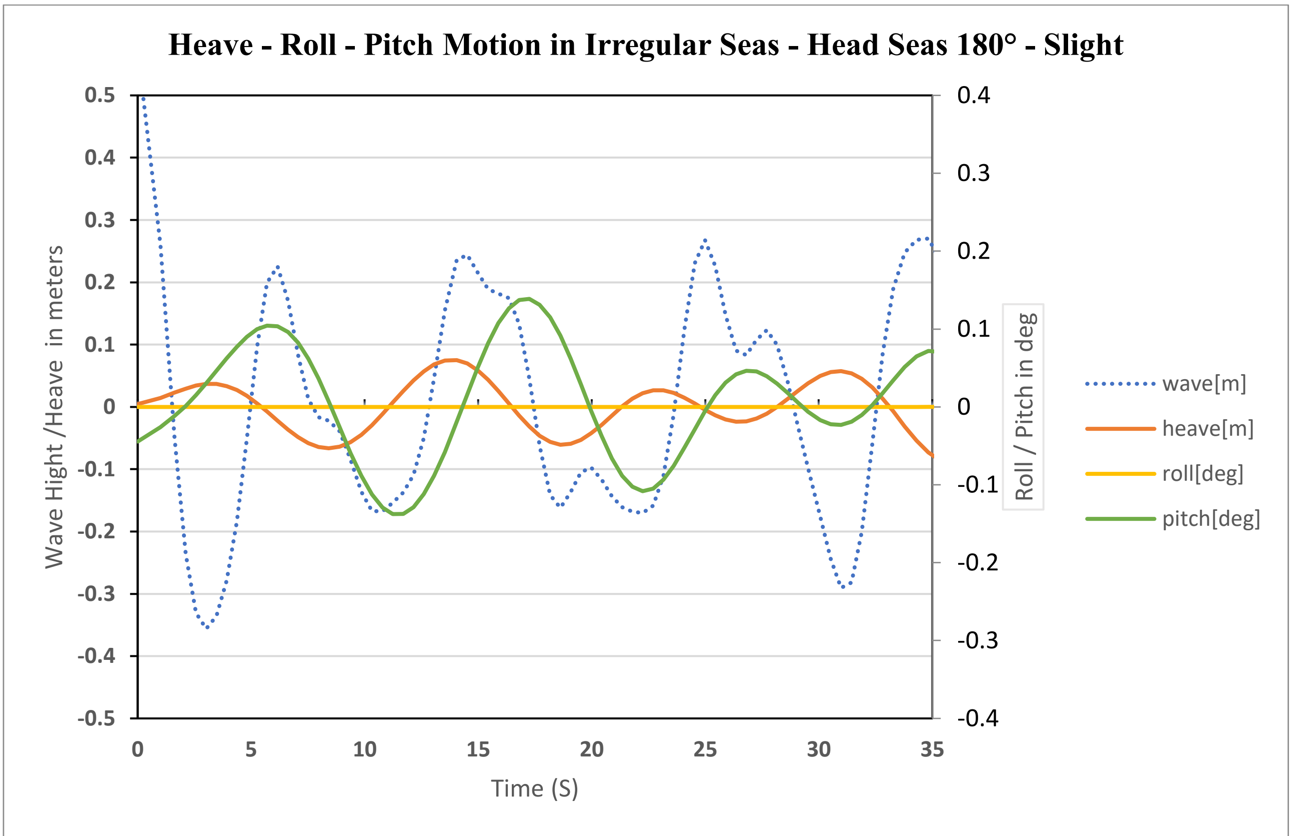


Figure 8-14 Motion in irregular head seas – Slight Seas

According to Figure 8-14 during the head seas at zero speed, the vessel is subjected to have a minimum roll, which is almost zero. While the pitch and heave motions vary. The significant heave

[78] MAXSURF motion manual, page 8

motion is approximately 15 cm, and the lowest is about 5 cm. Besides, the largest pitch angle predicted to be about 0.13°and the smallest angle is about 0.03°.

Similar in following seas (Figure 8-15), roll angle is zero, while the largest pitch angle is about 0.1°. Furthermore, the max heave motion is predicted to be 10 cm, while the lowest heave motion is 5 cm.

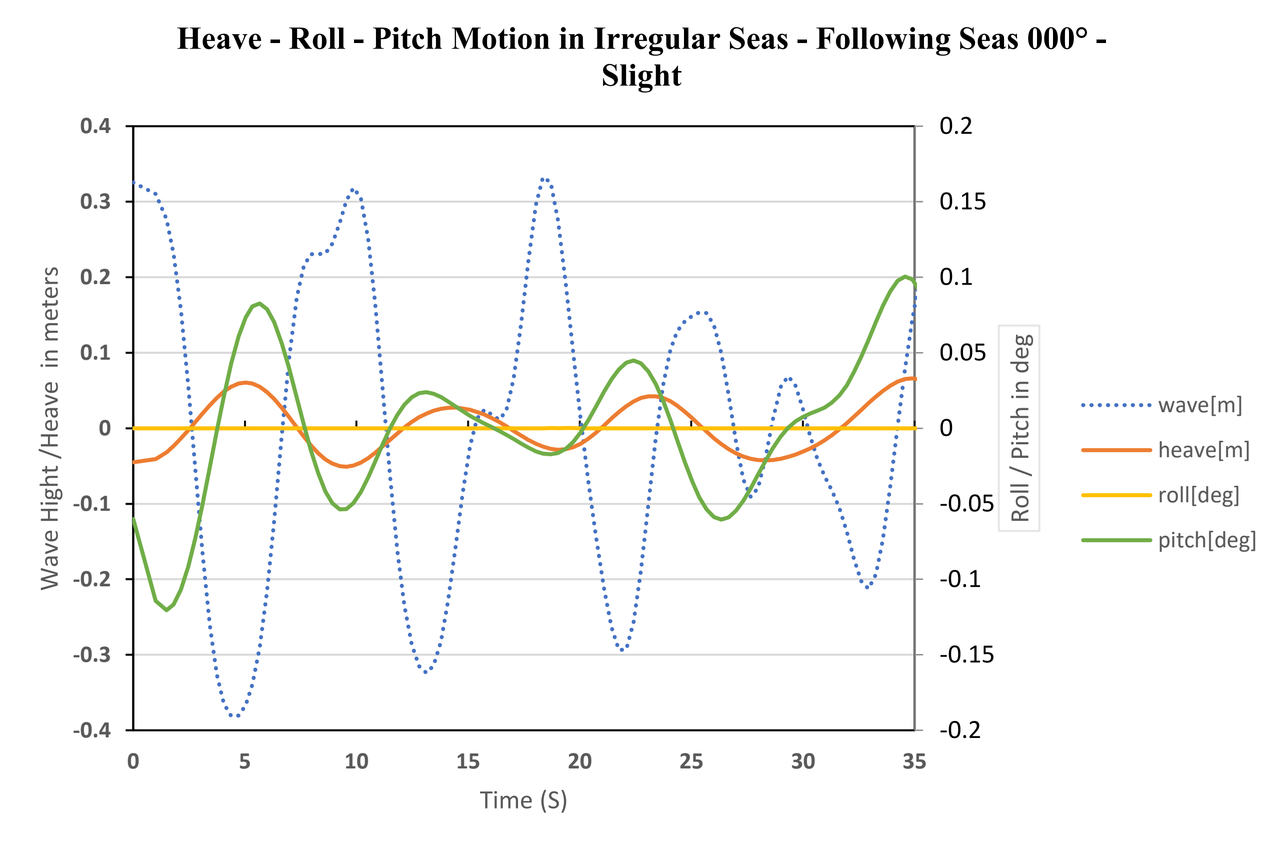


Figure 8-15 Motion in irregular following seas – Slight

8.13.2 Motions at Cable Removal Point

Vessel motions can exert extra tension to the cable which may break the cable during recovery operation. Therefore, a motion study at a specified point (cable removal point) can provide an overview regarding the reaction of the vessel in the different sea state and finally to identify under which weather criteria the vessel can perform the task safely.

Unlike the pile extraction operation, choosing the favourite wave headings for recovery of the cable is not possible. In other words, the cable route identifies the heading of the vessel. Therefore, inevitably, the vessel face with a number of headings. Accordingly, during the operation of cable retrieval, the motion of the vessel cannot be minimized by manoeuvring the vessel and changing the heading, however, the only option is to reduce the speed of recovery.

Figure 8-16, Figure 8-17 and Figure 8-18 show the effect of the vessel heave, pitch and roll on the cable retrieval point.

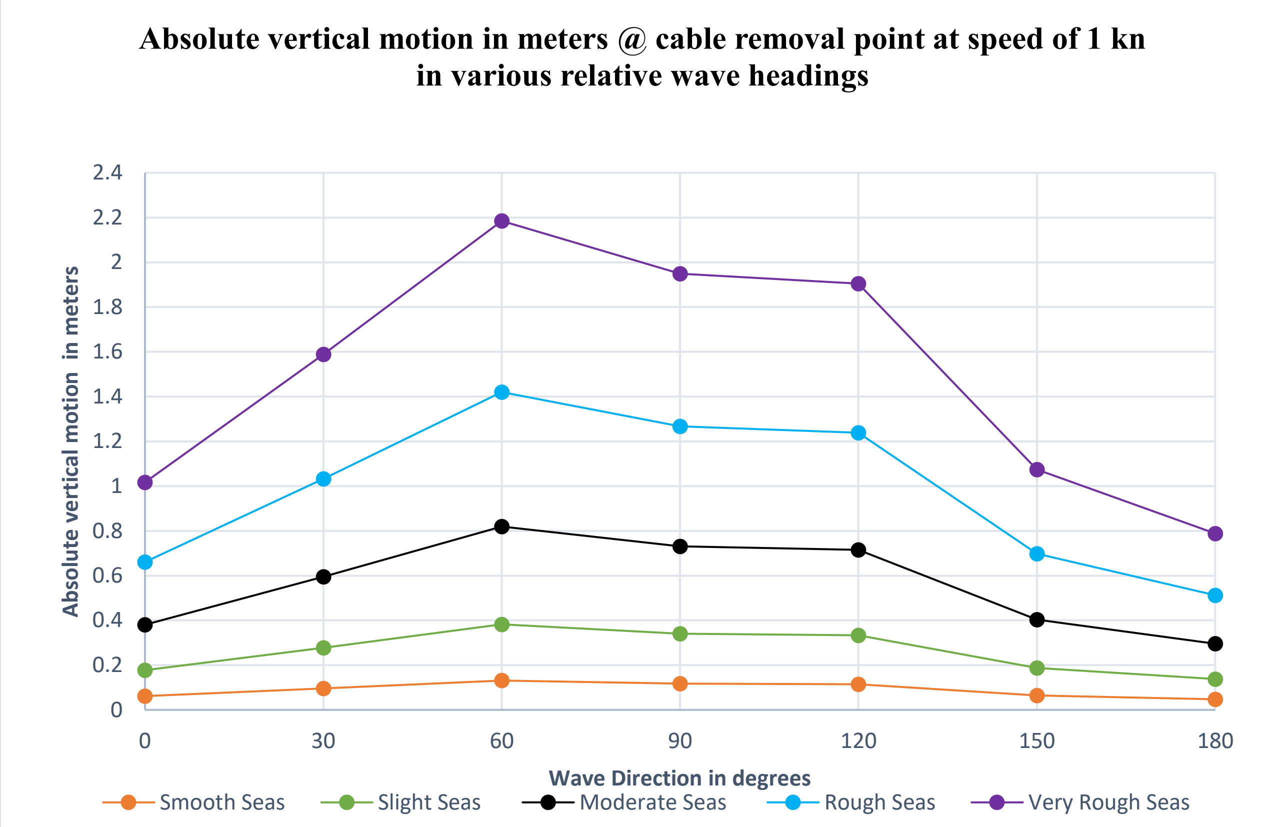


Figure 8-16 Comparison of absolute vertical motion during cable removal operation in various sea state

According to Figure 8-16, if the vessel has been encountered by rough seas and waves hitting the vessel from the beam side, the cable will be lifted by 1.27 m which is heave motion. In other words, the vessel's stern will be raised vertically by 1.27 m which the exerted tension may exceed the permissible tension and results in breaking of the cable.[79] The absolute vertical motion is one of the significant factors that will restrict the operation if it gets over the safe limit. However, the operation can be conducted under control. In this operation, always the winch operator has to be vigilant regarding the tension which is applied the winch. In addition to the winch tension sensor, it was proposed to install a load cell between the winch wire and the cable. So, the winch operator and also bridge team must be watchful to the indicators which shows the tensions. In case of extra tension, just the winch cable should be released which make the cable slack.

In addition to the heave, the pitch motion can exert tension to the cable too. This means that the cable moves upward and downward with the vessel pitch. Accordingly, the tension on the cable could happen if the right measures do not take place. However, the longitudinal movement is not significant, which could generate less tension on the cable.

[79] This happens in case the vessel is in a position of heave up phase. In the case of the heave down phase, the cable would have been in slack.

Based on Figure 8-17, the cable will move 5 cm in the forward direction and 5 cm in the aft direction if the vessel has been encountered by rough seas and the waves are hitting the vessel from the beam direction. The reference point for this movement is the chosen cable retrieval point, see Table 8-5.

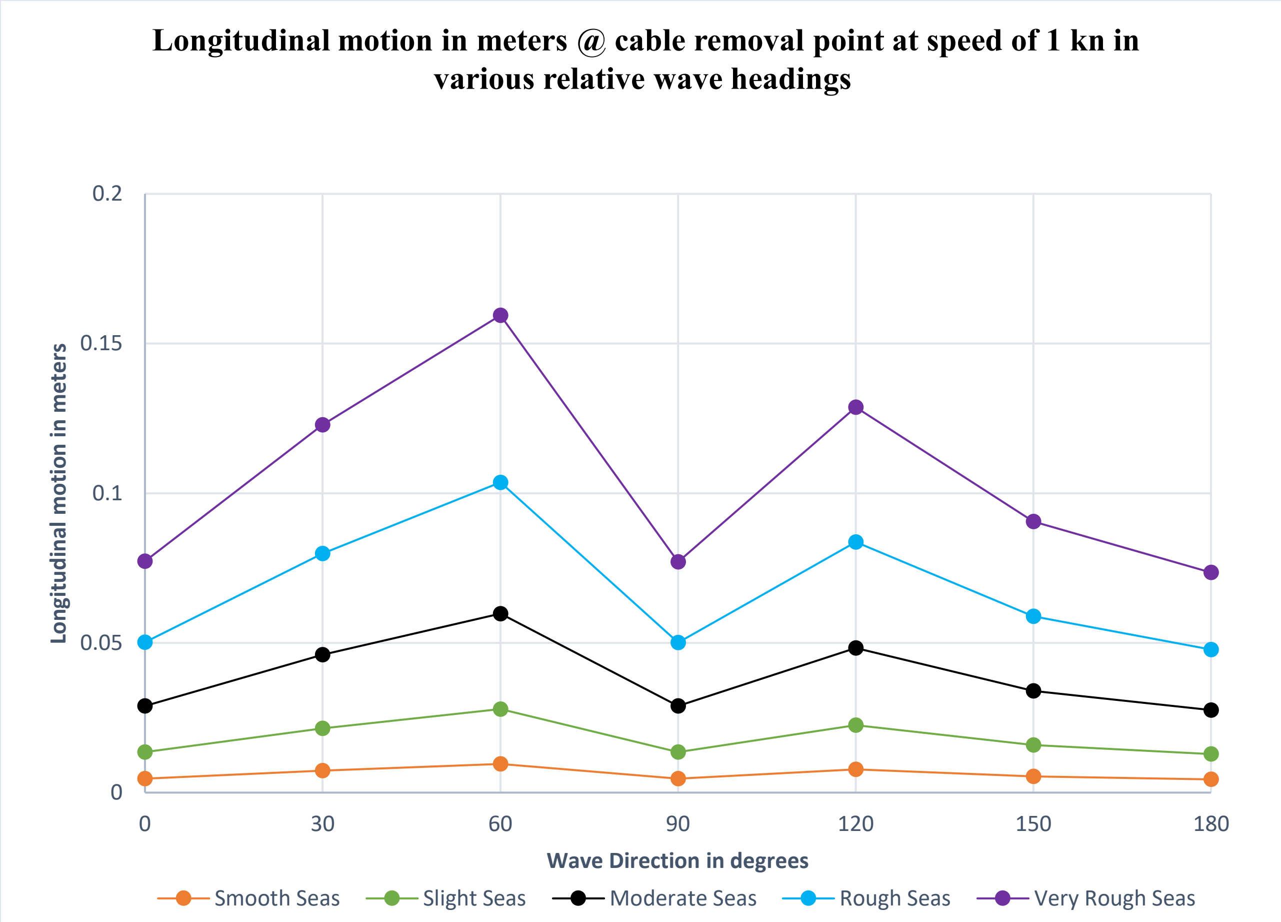


Figure 8-17 Comparison of longitudinal movement during cable removal operation in various sea state

The last motion which can affect the tension on the cable is roll motion. Throughout the cable removal operation, the cable could laterally move in the transverse direction. The rollers restrict the transverse movement of the cable. The movement of the cable inside the rollers depends on the interior width of roller which the cable is passing through. However, if the lateral motion was slightly large, a bending angle could happen to the cable in the transverse direction. The cable will touch the vertical roller, cause the cable to bend, and increase the tension on the cable. Consequently, careful selection of the roller can prevent exerting of extra tension to the cables.

Figure 8-18 compares the values of lateral motion in various sea states during various wave headings. According to Figure 8-18, if the vessel has been operated in rough seas and the waves hitting the vessel from the beam side, the lateral motion resulted from roll motion will be 1.5 meters.

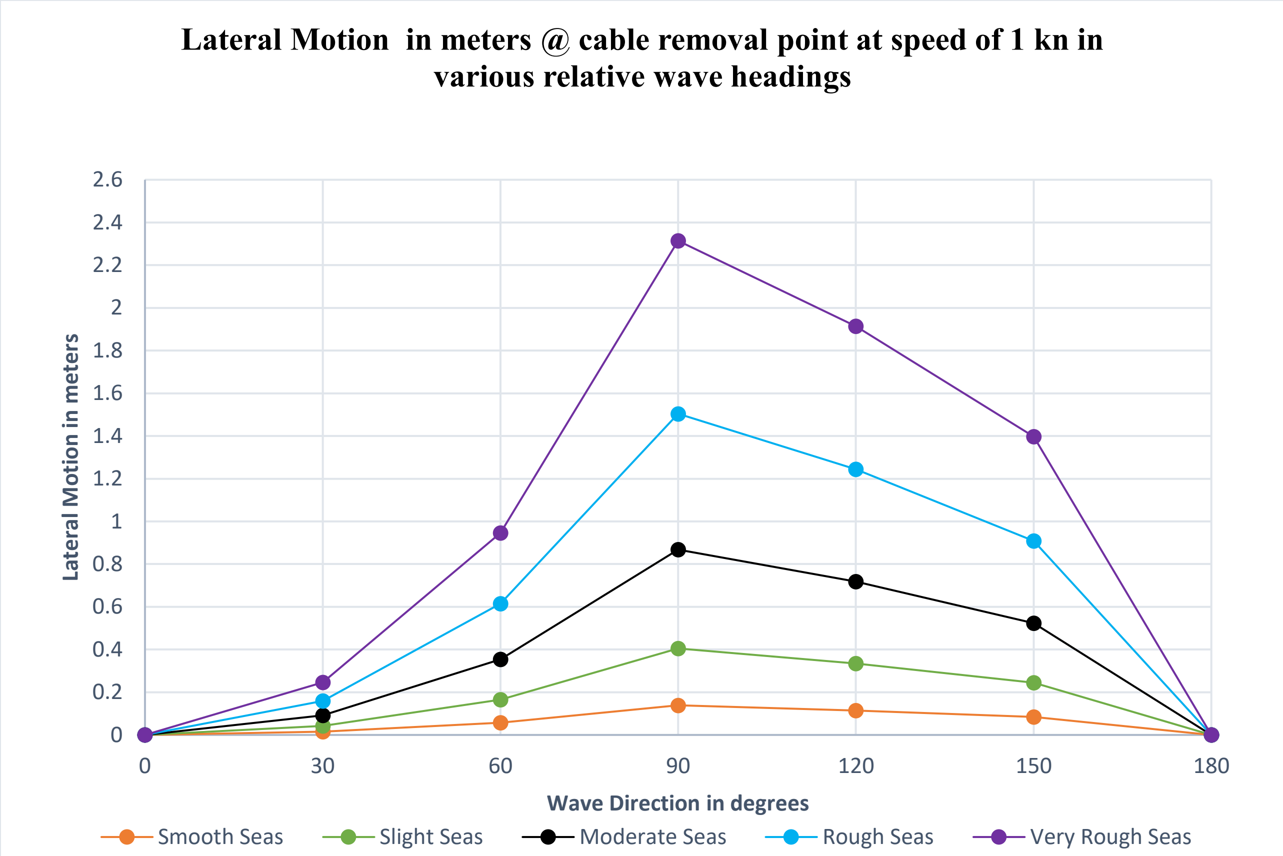


Figure 8-18 Comparison of lateral movement during cable removal operation in various sea state

8.13.2.1 Ship Motion in Irregular Seas During Cable Removal Operation

Figure 8-19 to Figure 8-25 shows the vessel response in irregular moderate seas at the vessel's centre of gravity. They demonstrate the magnitude of each motion during a period of 35 seconds. These figures represent the vessel motion in all chosen wave headings.

These figures give a broad outlook about how the vessel behave in several wave headings. Therefore, having these figures and knowing the response and reaction of the vessel deserving the chance for makings rational decision for the safe operation.

Also, Figure 8-19 shows the motions of the vessel when in the moderate sea state, irregular waves with heading of 180° hit the vessel.

In addition, Figure 8-20 shows the motions of the vessel when in the moderate sea state, irregular waves with heading of 150° strike the vessel.

Furthermore, Figure 8-21 shows the motions of the vessel when in the moderate sea state, irregular waves with heading of 120° strike the vessel.

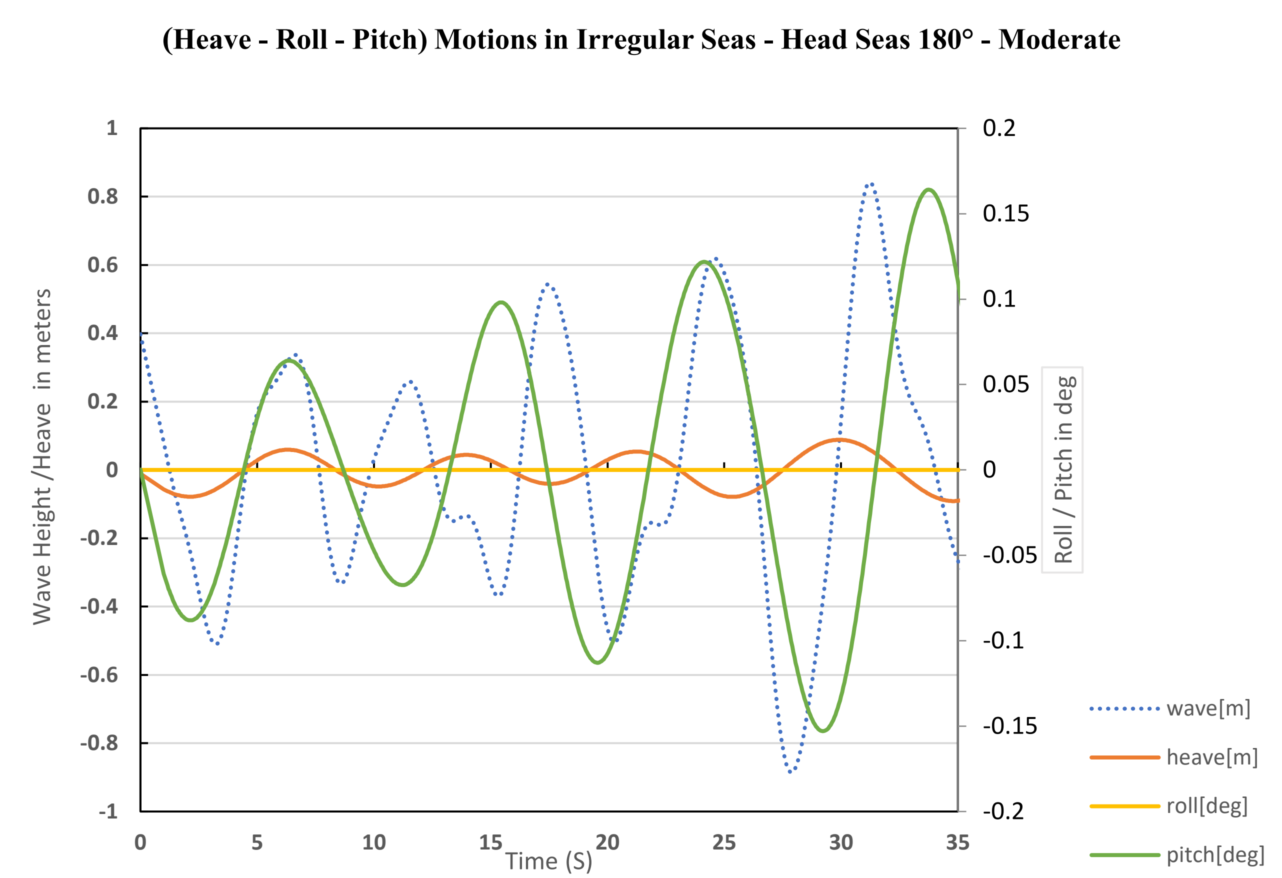


Figure 8-19 Motions in irregular head Seas – Moderate

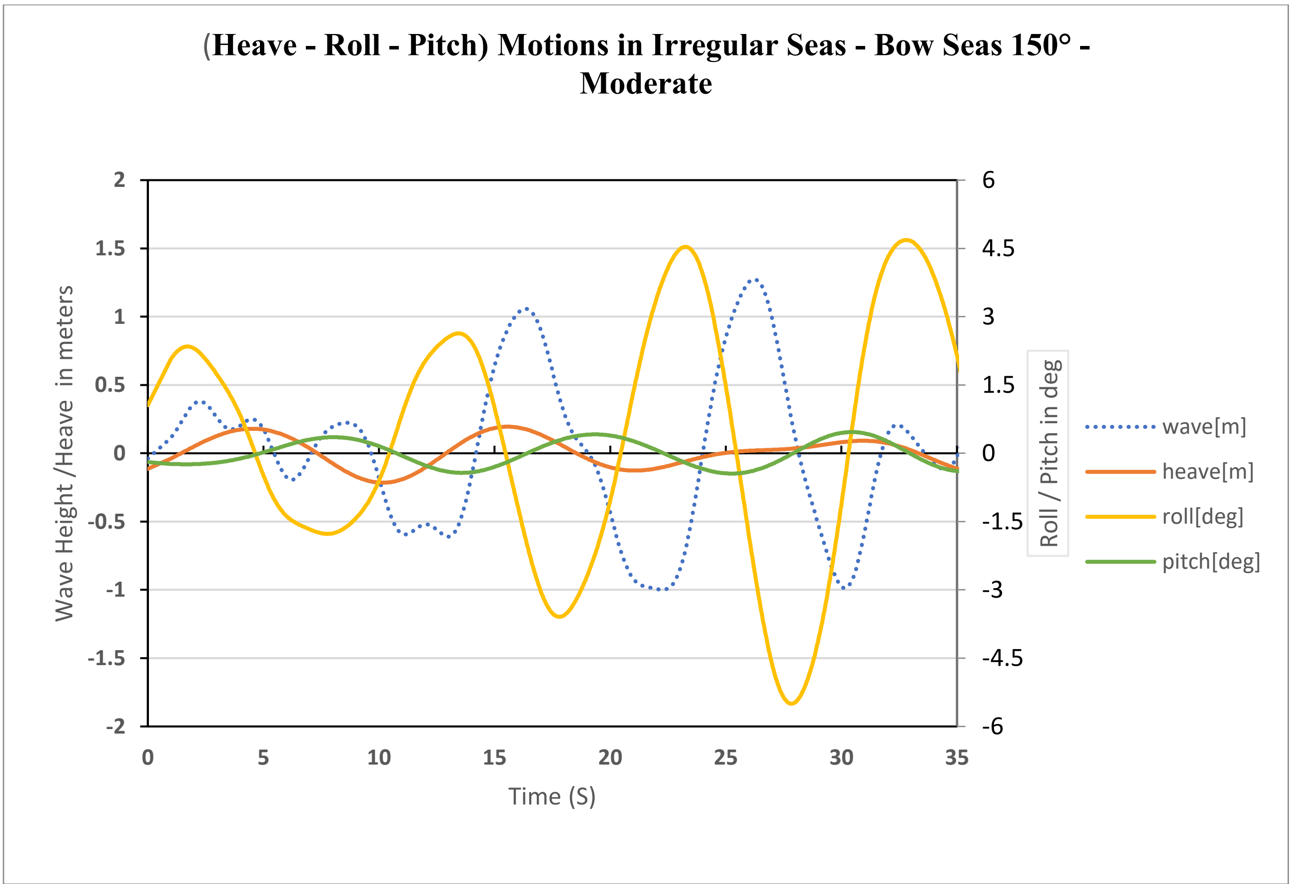


Figure 8-20 Motion in irregular bow seas 150° – Moderate

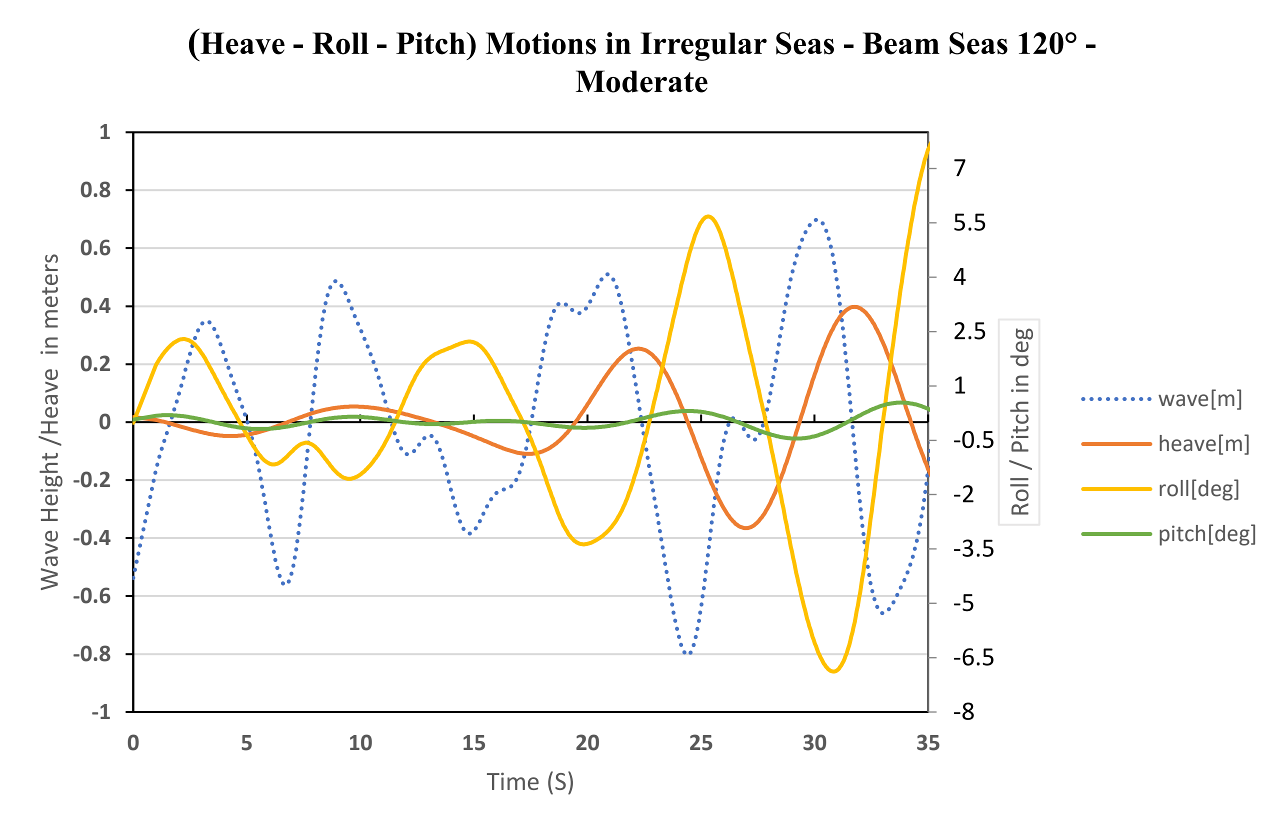


Figure 8-21 Motion in irregular beam seas 120° – Moderate

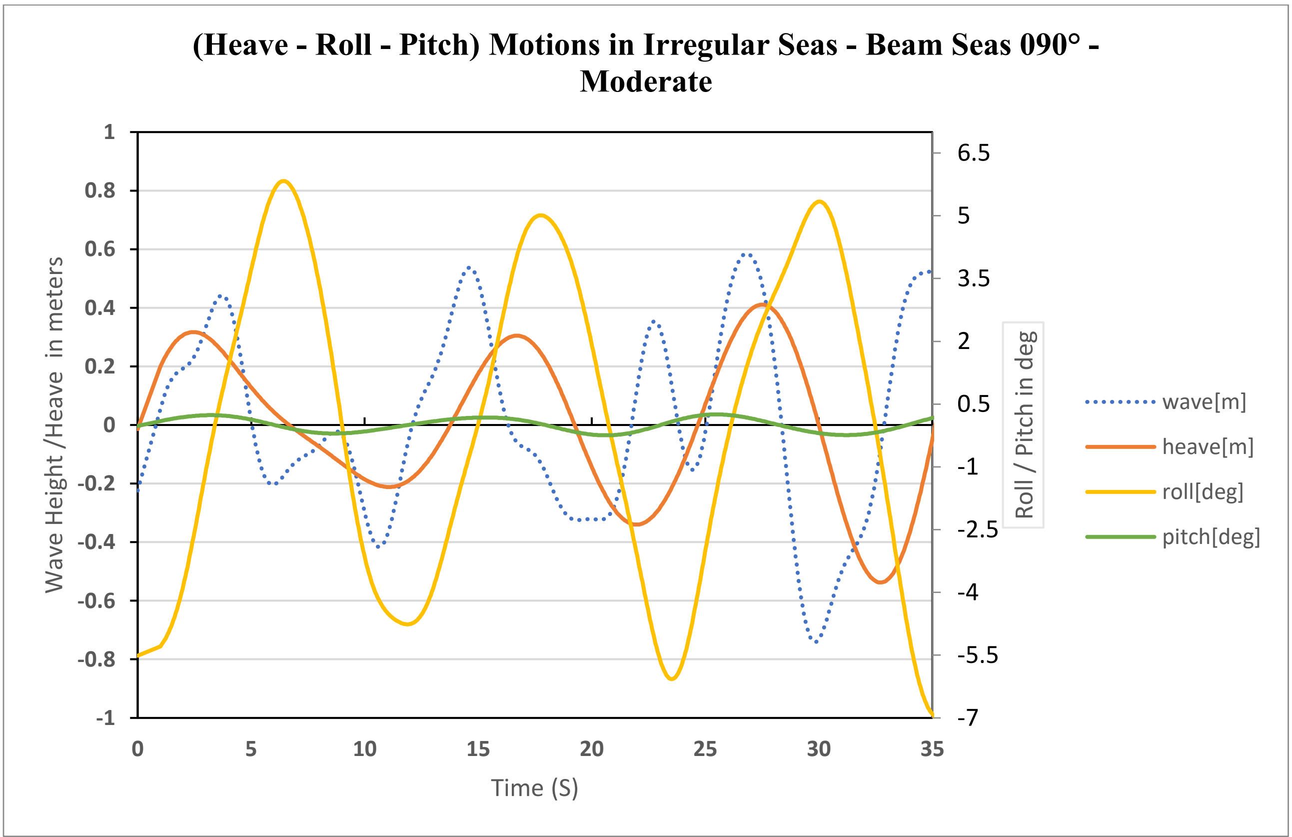


Figure 8-22 Motion in irregular beam seas 090° – Moderate

Figure 8-22 shows the motions of the vessel when in the moderate sea state, irregular waves with heading of 90° strike the vessel.

Figure 8-23 shows the motions of the vessel when in the moderate sea state, irregular waves with heading of 60° strike the vessel.

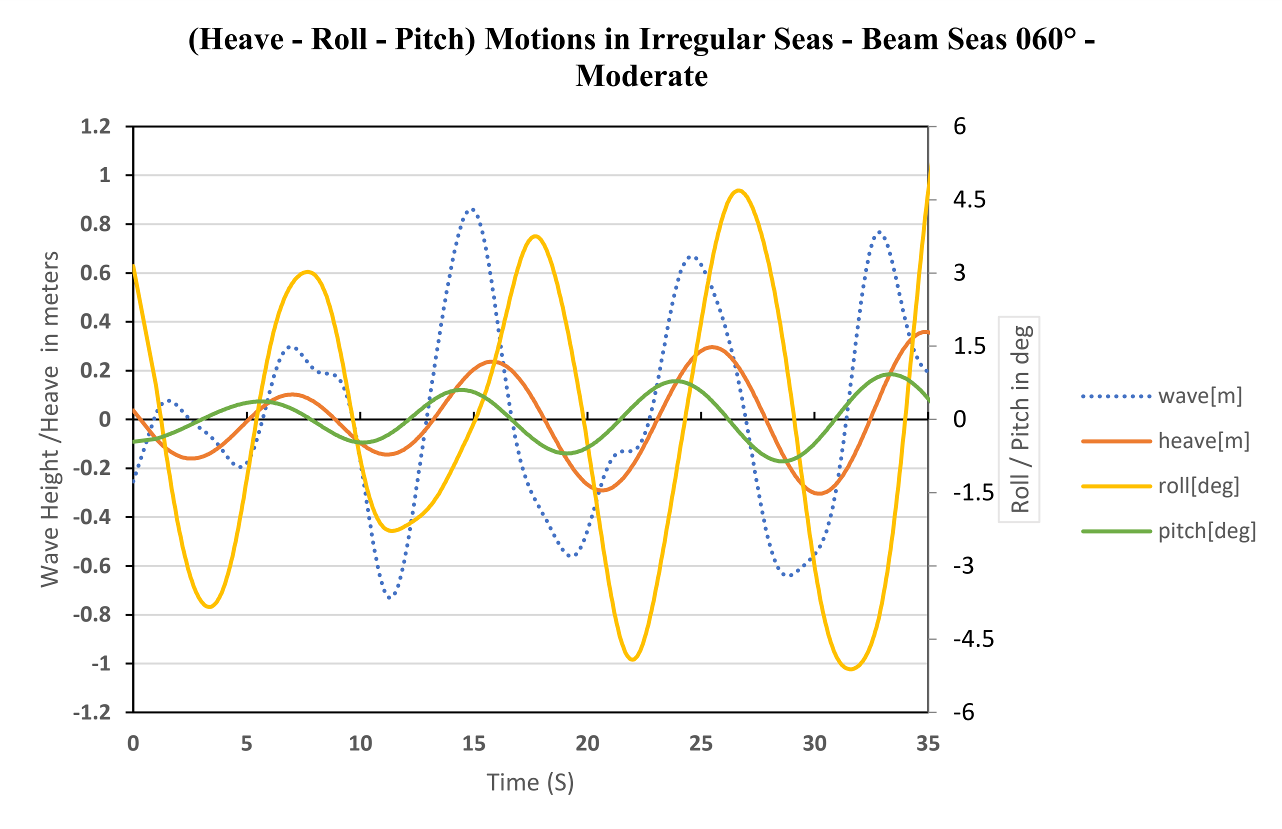


Figure 8-23 Motion in irregular beam seas 060° – Moderate

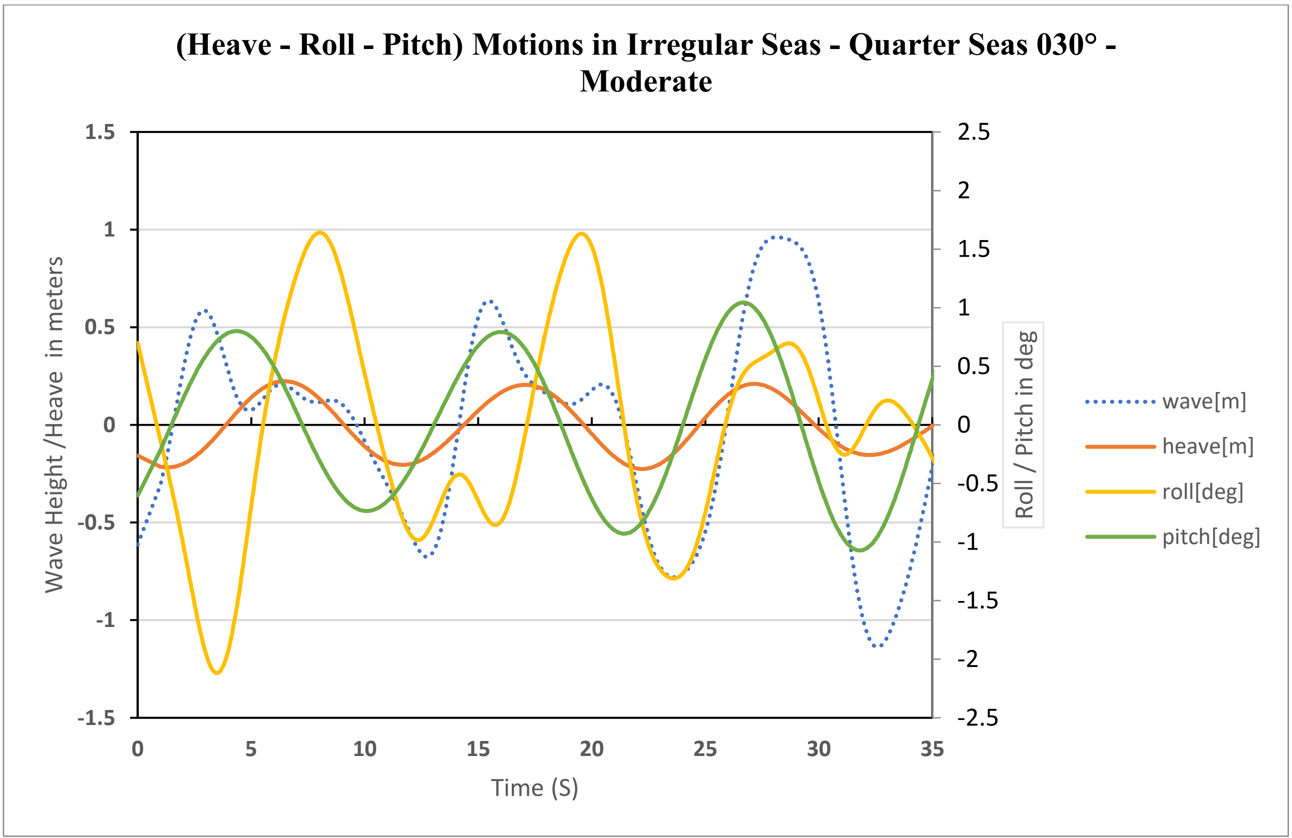


Figure 8-24 Motion in irregular following seas 030° – Moderate

Figure 8-24 shows the motions of the vessel when in the moderate sea state, irregular waves with heading of 30° strike the vessel.

Figure 8-25 shows the motions of the vessel when in the moderate sea state, irregular waves with heading of 00° hit the vessel.

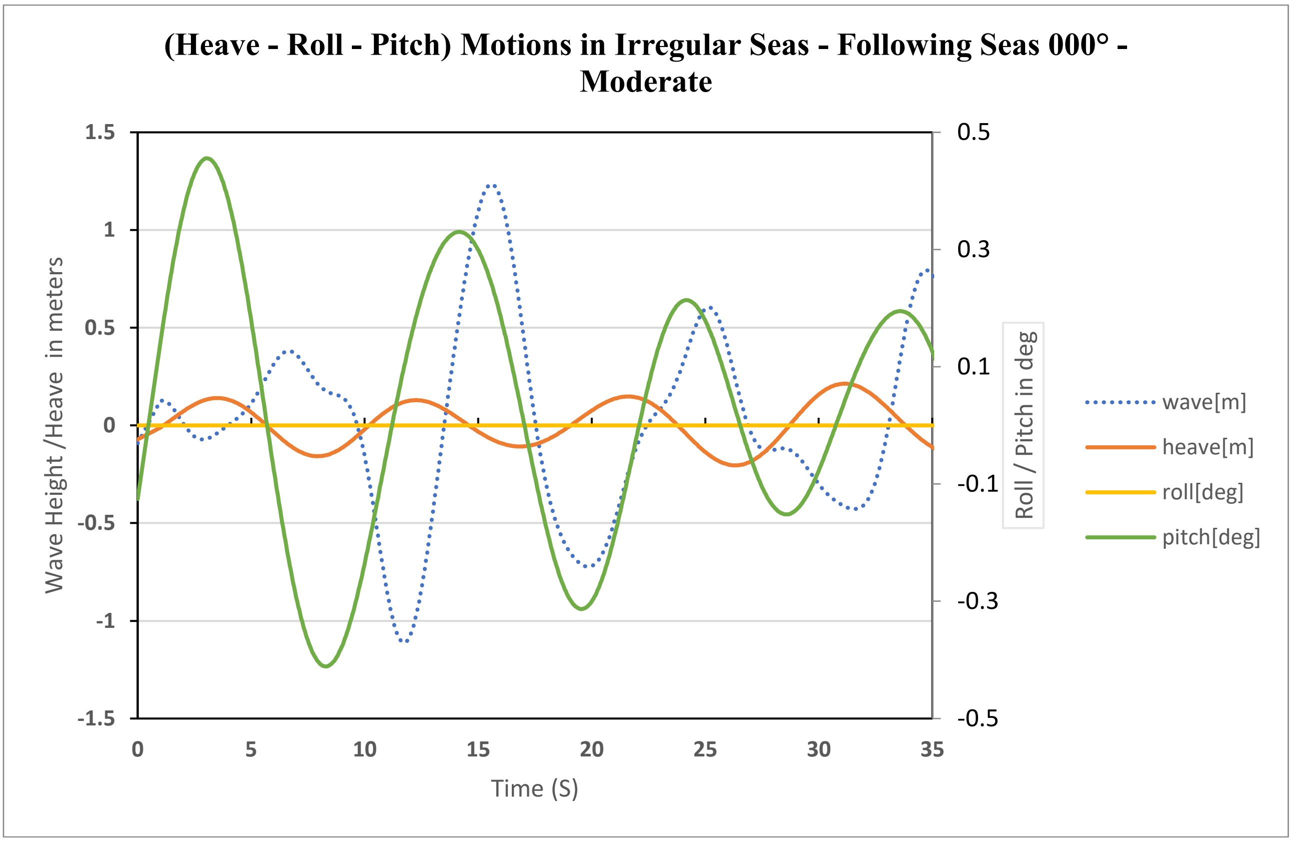


Figure 8-25 Motion in irregular following seas 000° – Moderate

8.14 Summary of the Vessel Motions at Glance

Remembering the above figures and making decision based on the above-described figures maybe is difficult. Normally the key personnel onboard the vessel such as master, construction superintendent, chief mate, MWS, TPAs and other involved decision makers can plan and judge the feasibility of the operation based on the values such as roll and pitch angle and heave motion. Having these figures in a good and clear format can provide reasonable and realistic chance for making right and rational decision. Therefore, a clear format is prepared which illustrates the motions of the vessel in various weather condition with respect to different vessel heading. As it stated before, the definition of sea states is described under Table 8-6. The last column which indicates the feasibility of the operations are based on authors stance. It is normal practice that site conditions may often warrant minor changes to offshore work plans.

During execution of the project in the offshore site, installation contractor reserves the right to utilize the superintendent's sole discretion regarding the safety of personnel and equipment on site, as well as expediting the work to best suit the prevailing site conditions. In other words, based on site condition, key personnel, in particular, the construction superintendent can override the approved procedure and plan.

Table 8-7 shows the motions of the vessel at its COG. This data can be used when the vessel has stationary position. The vessel has stationary position during disassembly of component with crane vessel, during cutting the transition piece and also when the vessel is in port, anchorage area or is at stand-by mode. At it shows, the vessel faces with 35 different scenarios which under seven scenarios, it cannot be operational. However, under that weather condition, if there is possibility to change the heading to 0° or 30°, the vessel experience less motions and capable to do the task. In other words, the workability of the vessel can be increased by changing the heading.

Table 8-7 Vessel Motions During Cargo Loading or Pile Extraction

Motions at COG of the Vessel (Gripping Operation, and or Cargo Loading Operation)					
Sea State	**Heading**	**Roll (deg)**	**Pitch (deg)**	**Heave (m)**	**Feasibility**
Smooth	0	0.000	0.036	0.012	Possible
	30	0.047	0.045	0.014	Possible
	60	0.221	0.061	0.039	Possible
	90	0.376	0.004	0.070	Possible
	120	0.218	0.056	0.042	Possible
	150	0.047	0.043	0.019	Possible
	180	0.000	0.034	0.016	Possible
Slight	0	0.000	0.105	0.035	Possible
	30	0.136	0.132	0.040	Possible
	60	0.645	0.179	0.113	Possible
	90	1.096	0.011	0.204	Depends
	120	0.635	0.164	0.123	Possible
	150	0.138	0.125	0.055	Possible
	180	0.000	0.099	0.047	Possible
Moderate	0	0.000	0.225	0.075	Possible
	30	0.292	0.282	0.085	Possible
	60	1.383	0.384	0.241	Depends
	90	2.349	0.024	0.436	Impossible
	120	1.360	0.351	0.263	Depends
	150	0.295	0.268	0.117	Possible
	180	0.000	0.212	0.102	Possible
Rough	0	0.000	0.391	0.129	Possible
	30	0.506	0.489	0.147	Possible
	60	2.397	0.666	0.418	Impossible
	90	4.072	0.041	0.756	Impossible
	120	2.358	0.608	0.456	Impossible
	150	0.512	0.464	0.202	Possible
	180	0.000	0.368	0.176	Possible
Very Rough	0	0.000	0.601	0.199	Possible
	30	0.779	0.752	0.227	Possible
	60	3.688	1.024	0.643	Impossible
	90	6.265	0.064	1.163	Impossible
	120	3.627	0.935	0.702	Impossible
	150	0.788	0.714	0.311	Depends
	180	0.000	0.566	0.271	Depends

Table 8-8 shows the vessels motion at gripper points. This study is of significant importance since the grippers are involved in two operations including transition piece removal as well as pile extraction. The motion analysis shows that this operation can be conducted in smooth, slight or more favourable weather conditions if either the vessel or gripper is not equipped with any compensation system. In other words, in order to increase the workability of the vessel, compensation system need to be designed for the grippers as well as vessel. The other method to increase the workability of the vessel with respect to the weather condition is to change the heading of the vessel since in the suite for pile extraction as well as transition piece removal there is not any obstruction for changing the heading. For the pile extraction operation, separate analysis and simulation should be conducted in order to see the feasibility of the operation. In that simulation, the interaction between the pile and the vessel needs to be analysed too. If the pile is enough stable, it avoids or reduce the movement of the stern of the vessel which may decrease the overall motion of the vessel.

Table 8-8 Vessel Motions at Grippers Point

Conducting Pile Extraction Operation - Motions at Gripper Point					
Sea State	**Heading**	**Lateral Motion(m)**	**Lon. Motion(m)**	**Vertical Motion(m)**	**Feasibility**
Smooth	0	0.000	0.014	0.066	Possible
	30	0.020	0.018	0.079	Possible
	60	0.036	0.024	0.105	Depends
	90	0.058	0.002	0.067	Depends
	120	0.057	0.022	0.097	Depends
	150	0.024	0.016	0.060	Possible
	180	0.000	0.012	0.044	Possible
Slight	0	0.000	0.040	0.192	Depends
	30	0.060	0.052	0.231	Impossible
	60	0.106	0.071	0.305	Impossible
	90	0.169	0.005	0.196	Impossible
	120	0.167	0.064	0.283	Impossible
	150	0.069	0.046	0.176	Depends
	180	0.000	0.035	0.129	Depends
Moderate	0	0.000	0.086	0.412	Impossible
	30	0.128	0.111	0.494	Impossible
	60	0.227	0.153	0.654	Impossible
	90	0.362	0.010	0.420	Impossible
	120	0.358	0.137	0.607	Impossible
	150	0.147	0.099	0.377	Impossible
	180	0.000	0.076	0.277	Impossible

Table 8-9 shows the motions of the vessel at the defined locations which is shown in the Figure 8-2. It shows even without including the compensation system, the vessel can carry our cable recovery in vast majorities of the weather conditions. To the best of our knowledge, the cable recovery operation even under the column of feasibility, the cells which shows depends can be performed.

Table 8-9 Vessel Motions at Cable Removal Point

Conducting Cable Removal Operation - Motions at Cable Removal Point					
Sea State	**Heading**	**Lateral Motion(m)**	**Lon. Motion(m)**	**Vertical Motion (m)**	**Feasibility**
Smooth	0	0.000	0.005	0.061	Possible
	30	0.015	0.007	0.095	Possible
	60	0.057	0.010	0.131	Possible
	90	0.139	0.005	0.117	Possible
	120	0.115	0.008	0.114	Possible
	150	0.084	0.005	0.064	Possible
	180	0.000	0.004	0.047	Possible
Slight	0	0.000	0.014	0.178	Possible
	30	0.043	0.021	0.278	Possible
	60	0.165	0.028	0.382	Possible
	90	0.405	0.013	0.341	Possible
	120	0.335	0.023	0.334	Possible
	150	0.245	0.016	0.188	Possible
	180	0.000	0.013	0.138	Possible
Moderate	0	0.000	0.029	0.381	Possible
	30	0.092	0.046	0.596	Possible
	60	0.355	0.060	0.819	Possible
	90	0.868	0.029	0.731	Possible
	120	0.718	0.048	0.715	Possible
	150	0.524	0.034	0.403	Possible
	180	0.000	0.028	0.296	Possible
Rough	0	0.000	0.050	0.661	Possible
	30	0.160	0.080	1.033	Depends
	60	0.615	0.104	1.420	Depends
	90	1.504	0.050	1.267	Impossible
	120	1.244	0.084	1.239	Depends
	150	0.908	0.059	0.698	Possible
	180	0.000	0.048	0.513	Possible
Very Rough	0	0.000	0.077	1.016	Depends
	30	0.245	0.123	1.589	Depends
	60	0.946	0.159	2.185	Impossible
	90	2.314	0.077	1.950	Impossible
	120	1.914	0.129	1.906	Impossible
	150	1.398	0.091	1.075	Depends
	180	0.000	0.074	0.789	Possible

8.15 Accelerations and forces

As stated earlier, heave, pitch, and roll induce a specific motion for any given point along the vessel such as absolute vertical motion, longitudinal motion, and lateral motion. Each of these motions have a specific acceleration: absolute vertical acceleration, longitudinal acceleration, and lateral acceleration. Accelerations (a) are used to calculate the forces that act in a specific point, for instance, gripper point, seafastening points, cable removal point, and so on.

Forces that act on the gripper are the most significant factors considered before designing the gripper and compensation system. In other words, in order to design the structure and motion compensation system of the gripper, the motion, acceleration and forces at gripper point should be identified. The sea state which delimits the operation of gripper need to ne discerned too.

Forces can be calculated by the following formula:

$$F_{(X,Y,Z)} = m.a_{(X,Y,Z)}$$

Where:

$F_{(X,Y,Z)}$: longitudinal, transverse and vertical forces. (kN)

m: mass of the unit. (ton)

$a_{(X,Y,Z)}$: longitudinal, transverse and vertical acceleration. (m/s^2)

The analysis is conducted at the gripper point since it is one of the most significant and critical operations that the Decom Tools vessel can have. Accordingly, accelerations data for the gripper point are presented on the following figures. See Figure 8-26, Figure 8-27, and Figure 8-28.

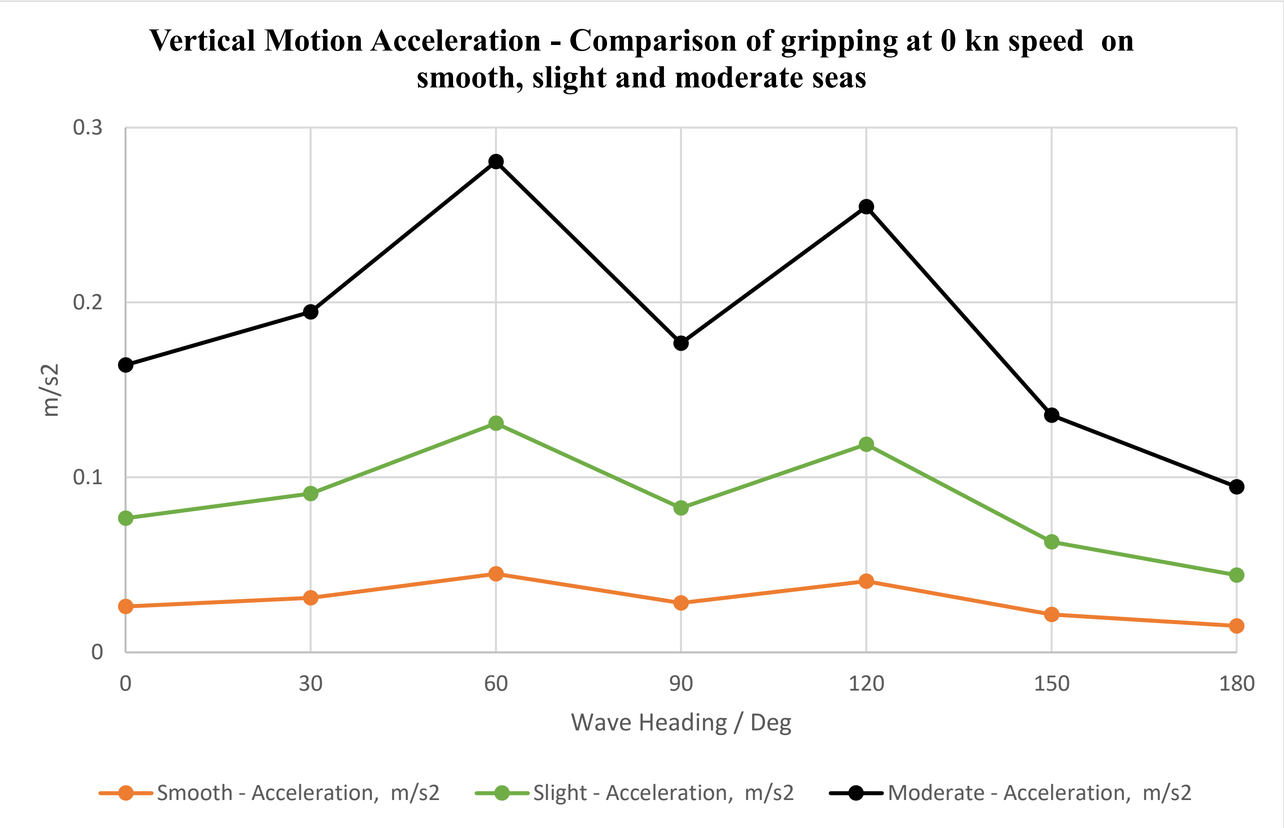


Figure 8-26 Absolute Vertical acceleration at Gripper point on three different Sea States

Figure 8-26 shows the vertical acceleration at the gripper point which happen due to heave motion. Accelerations find out on seven relative headings as well as three sea states condition.

Figure 8-27 shows the longitudinal acceleration at the gripper point which occur due to pitch motion. Accelerations find out on seven relative headings as well as three sea states condition.

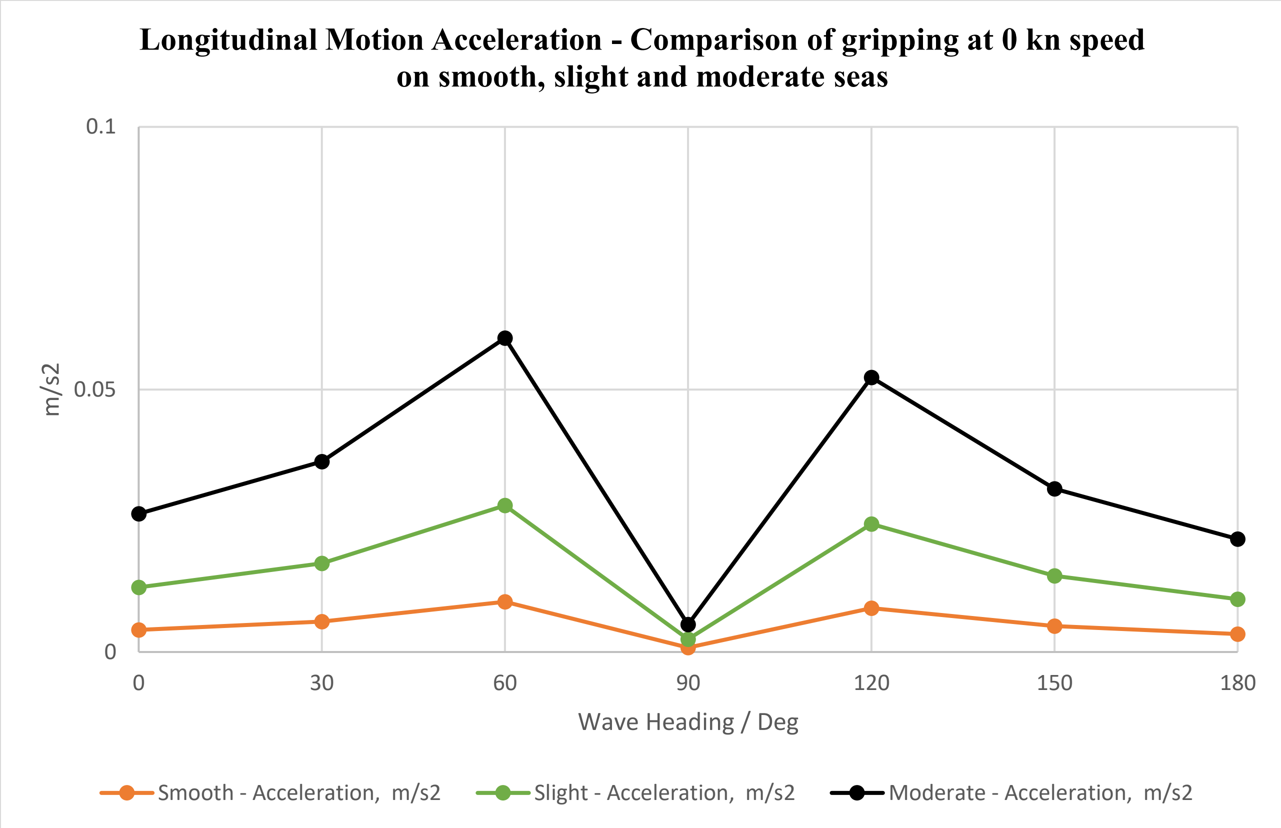


Figure 8-27 Longitudinal Motion Acceleration at Gripper point on three different Sea States

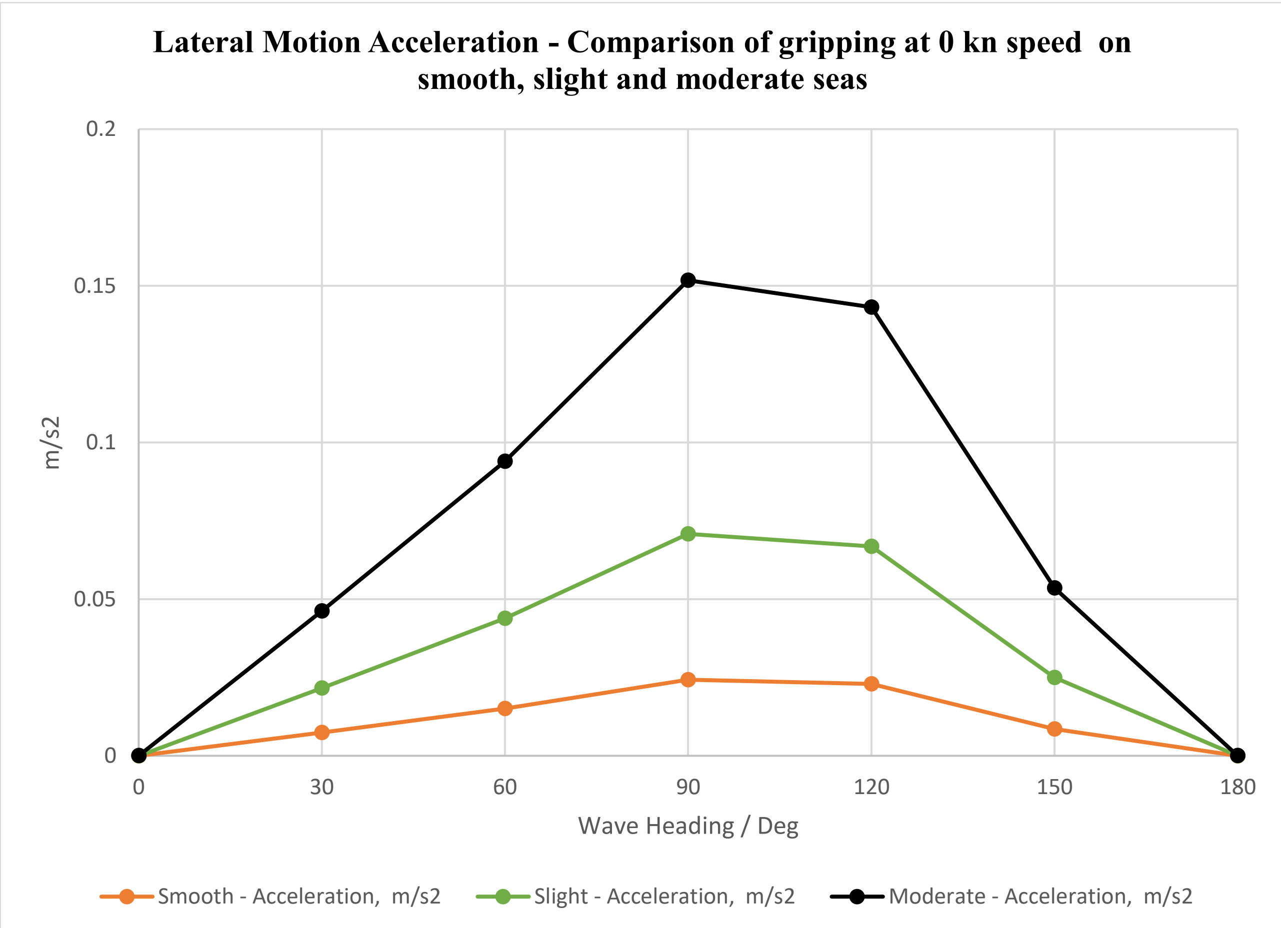


Figure 8-28 Lateral Motion Acceleration at Gripper point on three different Sea States

Figure 8-28 shows the lateral acceleration at the gripper point which happen due to roll motion. Accelerations find out on seven relative headings as well as three sea states condition.

Under section **Pile Extraction System** the procedure for pile extraction is explained. One of the major problems with pile extraction is that calculation of required forces for pile extraction is impossible due to changes of friction between soil and pile throughout the lifetime of the structure. Thus, it is not possible to assume the final forces for extraction of the monopile.

Regardless of shaft friction, during pile extraction, the lifting forces which is exerted by the Decom Tools vessel to the monopile is buoyancy of the vessel which is 33000 tons. Thus, the exerted force is considered equivalent to lifting capacity which is the result of ballasting and deballasting (extraction with changing the buoyancy).

Table 8-10 Accelerations and Forces that act on the Gripper

Sea State	Wave Heading	Vertical Acceleration m(/s²)	Longitudinal Acceleration (m/s²)	Lateral Acceleration (m/s²)	Vertical Forces (KN)	Longitudinal Forces (KN)	Lateral Forces (KN)
Smooth	0°	0.026	0.004	0.000	867.702	139.161	0.099
	30°	0.031	0.006	0.007	1027.521	191.400	244.200
	60°	0.045	0.010	0.015	1481.172	315.645	496.320
	90°	0.028	0.001	0.024	932.910	27.621	801.240
	120°	0.041	0.008	0.023	1345.113	276.012	755.997
	150°	0.022	0.005	0.009	715.539	164.010	283.008
	180°	0.015	0.003	0.000	499.488	113.718	0.099
Slight	0°	0.077	0.012	0.000	2530.770	405.900	0.330
	30°	0.091	0.017	0.022	2996.928	558.228	712.272
	60°	0.131	0.028	0.044	4320.063	920.634	1447.578
	90°	0.082	0.002	0.071	2720.949	80.553	2336.961
	120°	0.119	0.024	0.067	3923.205	805.035	2204.994
	150°	0.063	0.014	0.025	2087.019	478.335	825.462
	180°	0.044	0.010	0.000	1456.884	331.650	0.297
Moderate	0°	0.164	0.026	0.000	5423.055	869.814	0.660
	30°	0.195	0.036	0.046	6421.998	1196.217	1526.283
	60°	0.281	0.060	0.094	9257.292	1972.806	3101.934
	90°	0.177	0.005	0.152	5830.605	172.590	5007.750
	120°	0.255	0.052	0.143	8406.849	1725.075	4724.973
	150°	0.136	0.031	0.054	4472.193	1024.980	1768.833
	180°	0.095	0.022	0.000	3121.899	710.688	0.660

Table 8-10 shows the entire forces and accelerations that apply on gripper point on three different sea states, namely smooth, slight and moderate.

Table 8-10 provides a comprehensive overview about forces in three different axes (X, Y, Z), which will be used by ship's master, construction superintendent and other responsible to assess the working allowance as well as the overall safety of the operation.

As it sated before, these forces are calculated based on environmental loads. The resulting forces due to monopile extraction operation are not considered here. Therefore, another simulation and analysis need to be carried out to see what the final reaction of vessel and pile during extraction operation would be. To do this, the soil and pile should be modeled accurately in another software and dynamic analysis should be conducted.

8.16 Conclusion

The motion analysis has been performed for the Decom Tools vessel when the vessel has zero trim and has draught of 10.11 meters. Altering the trim or draught of the vessel influence the motion results. Additionally, the vessel centre of gravity will play a significant role in predicting the motion. In order to reduce the natural roll period which result in less motion and less acceleration, having higher VCG[80] and Lower GM[81] are preferred. Moreover, influences of wind are not considered in the analysis, therefore, result may change slightly, if it is included in the analysis.

The optimum wave heading for conducting the pile extraction with a minimum motion and accelerations is on head seas (180°) and then in following seas (00°). Furthermore, the optimum sea state is the slight seas or weaker. Additionally, it is not recommended to conduct such operation in waves that strike the vessel from direction other than following or head seas, as it proven that the vessel will not have rolling motion, See Figure 8-10. Despite the above analysis, if the Voith Schneider or other compensation system can reduce the motions and rolling of the vessel, the pile extraction operation can be executed in the rougher sea states and with different headings. It should be noted that during pile extraction, the vessel does not have manoeuvring limitation and can change the heading in the field to the desired heading.

Regarding cable removal operation, the operation under optimum wave heading is not always possible and it contingent on cable route. However, as it stated earlier, the winch operator can slack the wire of the winch and release the cable to avoid exerting of extra tension to the cable.

[80] VCG is the vertical distance between center of gravity and keel.

[81] GM is the metacentric height which is the distance between G and M.

Using the generating data from the motion analysis, the compensation system can be defined accordingly. However, for a comprehensive overview of figures and tables, it is suggested to look at the full report. Motion report have been attached to the CD.

9 Final Conclusion

Comprehensive research has been performed about involved fleets and offshore supply chain in installation and decommissioning of offshore wind parks. The finding revealed that lack of suitable cargo vessel in this industry compel the contractor to transport the wind farms' components with installation vessel. This logistic configuration which is coveted in this industry is not so efficient in terms of cost and environmental footprint, in particular, for the wind farm with large number of wind turbines, with long distance from shore and with deep water. This fact was proofed in the third chapter where the time-cost-emission analysis of various case studies explained. High charter rate of the installation vessel contributes to increase in the overall cost of decommissioning or installation, if the transportation of components performs with installation vessel. Thus, the authors strived to design a multi-function and multi-purpose green vessel in order to bring down the cost of decommissioning of offshore wind parks. Plausible explanations regarding the specification of the Decom Tools vessel are provided including the dimension, engines, onboard equipment, propulsion system, solar system and so forth. Moreover, the stability and motion analysis have been performed in the chapter 7 and 8 which shows the seaworthiness of the vessel in different situations and operations under different conditions and sea states.

Significantly, after establishing the proper procedures and describing the method statements regarding all phases of decommissioning including, disassembly of wind turbine, removal of transition pieces, extraction of foundation and recovery of submarine power cables, time-cost-consumption-emission analysis for all above-mentioned phases of decommissioning undertake. Time-cost-consumption-emission analysis for disassembly of wind turbine has been explained in chapter 3. The mentioned analysis for the transition piece removal, pile extraction and cable recovery have been described in chapter 6.

Offshore wind farm by the name of Hornsea 1 was the main case study in this document. The mentioned analysis for this wind farm for the phase of disassembly of wind turbines which includes dismantling of rotor, nacelle and tower, removal of transition pieces and extraction of monopile have be conducted. However, for recovery of out-of-service submarine cables, Anholt wind farm is selected as case study since more information and sources about this wind farm is available.

The time-cost-consumption-emission analysis has been conducted with two different scenarios.

The first analysis has been carried out based on base scenario which is execution of decommissioning reverse to the installation. In this case, the same vessels and logistic configuration has been selected for the analysis. Thus, in the first run of the analysis, the resulting cost, fuel consumption and emission are calculated with developed program for the base scenario. In the second run of the analysis, the analysis has been performed according to the proposed procedure and utilization of the Decom Tools vessel. This time, the logistic configuration and involved fleet of the decommissioning have been changed in order to reduce the offshore operation duration, project cost and mitigate the consumption and consequently the emission. The Decom Tools vessel is a multi-function and multi-purpose green vessel which can carry considerable number of wind turbine components. This capability led to reduction of the sailing time which lessen the fuel consumption and mitigate the CO_2 emission. Furthermore, the designed blade seafastening (blade rack) and designed cutting tools, enable to cut the blades into the small pieces without spread of small piece of blades material into the sea and environment which pave the way for easier and cheaper onshore materials handling, transportation and recycling.

Equally important, the designed hydraulic gripper at the stern of the vessel allows removal of transition pieces without deployment of construction vessel. Implementation of this tool onboard Decom Tools vessel eliminate utilization of construction vessel which has high charter rate, considerable fuel consumption and emission. The analysis of transition piece removal operation indicates that this innovative tool diminishes the cost and emission enormously.

Not only the hydraulic gripper tool can be used during transition piece removal but also it can be utilized for pile extraction. Pile extraction can be executed with hydraulic grippers and the potent buoyancy of the vessel. In general, one of the cost drivers of the installation or decommissioning operations is construction vessel which can be either jack up vessel or floating heavy lift vessel. The proposed method of pile extraction with the hydraulic gripper and vessel’s buoyancy eliminates the use of heavy lift vessel, the diving system and subsea operations such as subsea cutting tools.

The results of time-cost-consumption-emission analysis proofed that substantial saving in terms of time, cost and fuel consumption can be achieved if such tool and procedure can be executed.

The other innovation which was presented in this document is the design of cable hydraulic gripper as well as establishment of the procedure for the recovery of out-of-service submarine cables. It is demonstrated that recovery of out-of-service cables can be conducted with some widely available tools and without using cable laying vessel. The proposed procedure is discussed with specialist of this industry and they confirmed the feasibility of the procedure.

The results of time-cost-consumption-emission analysis verified that great saving in terms of cost and fuel consumption can be attained by the proposed procedure for cables recovery.

Table 9-1 shows the overall duration, cost, fuel consumption and emission of decommissioning of wind turbine, transition piece and monopile of Hornsea 1 wind farm and inter array and export cables of Anholt wind farm. The middle column demonstrates the time, cost, fuel consumption and emission, if the decommissioning take place reverse to the installation with the same fleet and logistic configuration. The right column depicts the duration, cost, fuel consumption and emission, if the decommissioning conduct with the Decom Tools vessel along with given procedures.

Table 9-1 Overall Time-Cost-Consumption and Emission Figures

Overall Figures of Decommissioning of Hornsea 1 WT, TP, MP & Cables of Anholt OWP		
Configuration / Parameters	**Reverse of Installation**	**Decom Tools Vessel**
Time (Day)	**817.03**	**466.06**
	Base Scenario	**-351**
		43%
Cost ($)	**$ 142,227,994.4**	**$ 51,461,247.1**
	Base Scenario	**$ (90,766,747.3)**
		63.82%
Fuel (Tones)	**16945.83**	**8887.38**
	Base Scenario	**-8058.44**
		48%
CO2 Emission (Tones)	**54328.32**	**25287.09**
	Base Scenario	**-29041.22**
		53%

Table 9-1 can be interpreted as following:

- ☑ From a duration stance, 43% saving in terms of time can be attained if decommissioning take place by using Decom Tools vessel and described procedure.
- ☑ From a cost perspective, decommissioning by proposed method and designed Decom Tools vessel results in cost-saving about 63% with respect to the base scenario which is reverse of installation.
- ☑ It can be argued that fuel consumption has correlation with duration of operation to some extent. However, the design of solar system, Flettner rotor and batteries improve the efficiency of the Decom Tools vessel and diminish the fuel consumption. Thus, from a fuel

consumption point of view, 48% fuel saving can be achieved if the same engines, speed and described procedure implement.

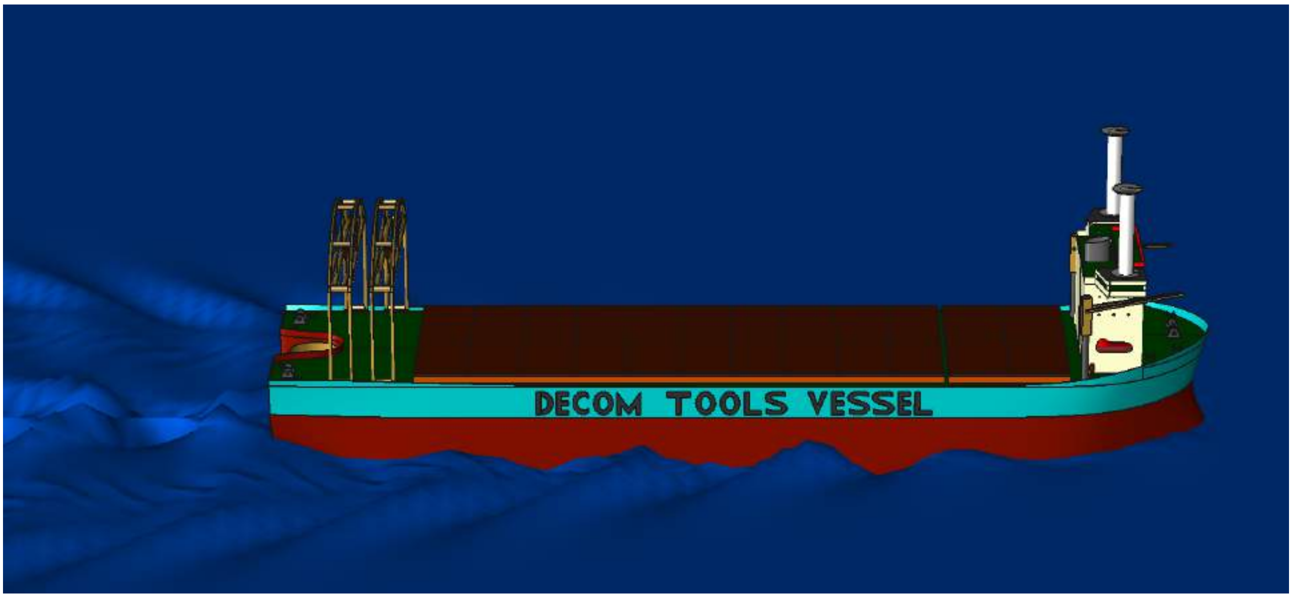
- ☑ The propulsion system of the Decom Tools vessels is discussed in the chapter 5 and the reason of selecting LNG as fuel was discussed in the chapter 4. The LNG fuel along with design of solar system, batteries and Flettner rotors contributed to 53% saving of CO_2 emission.

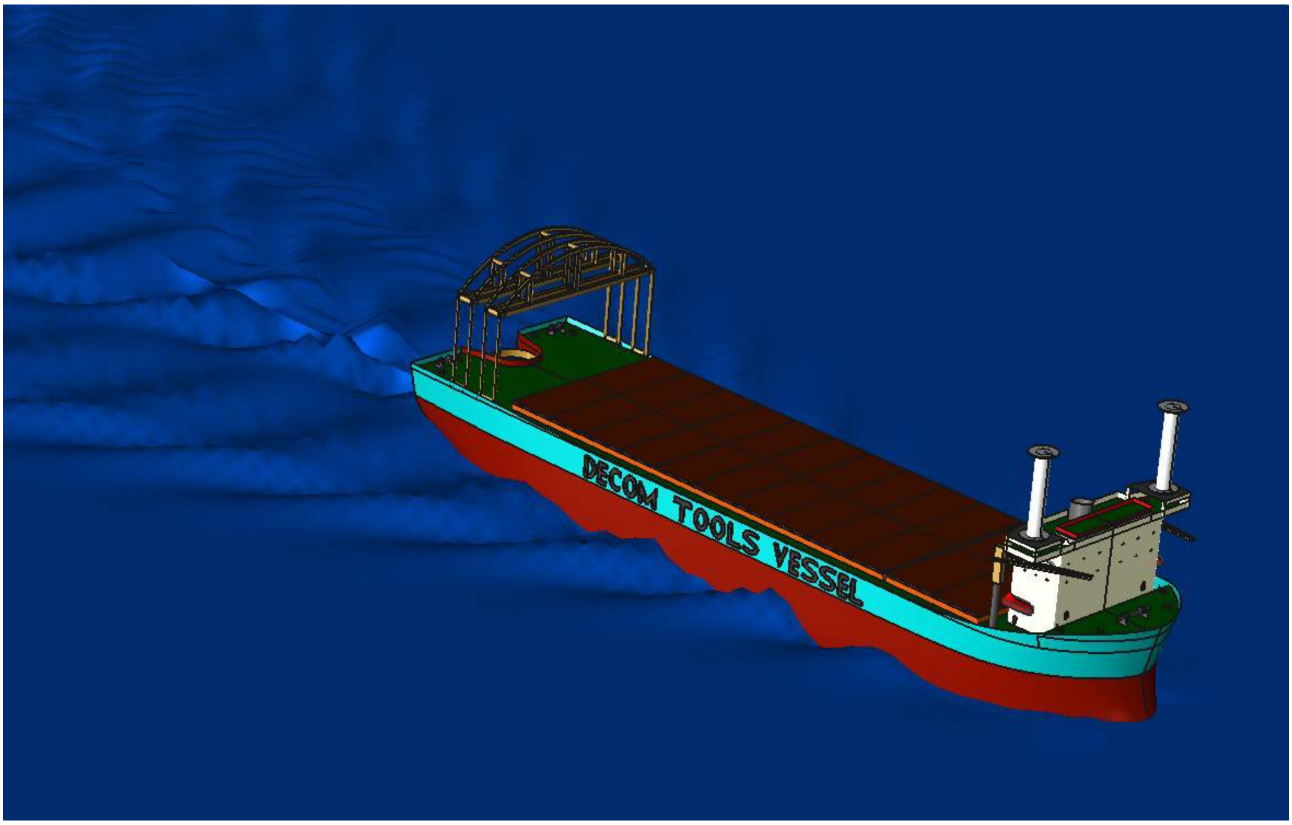
In a nutshell, construction and deploying of a vessel such as Decom Tools vessel as well as proposed procedure improve decommissioning cost, resources, and environmental footprint considerably.

10 Gallery


DECOM TOOLS VESSEL


DECOM TOOLS VESSEL


DECOM TOOLS VESSEL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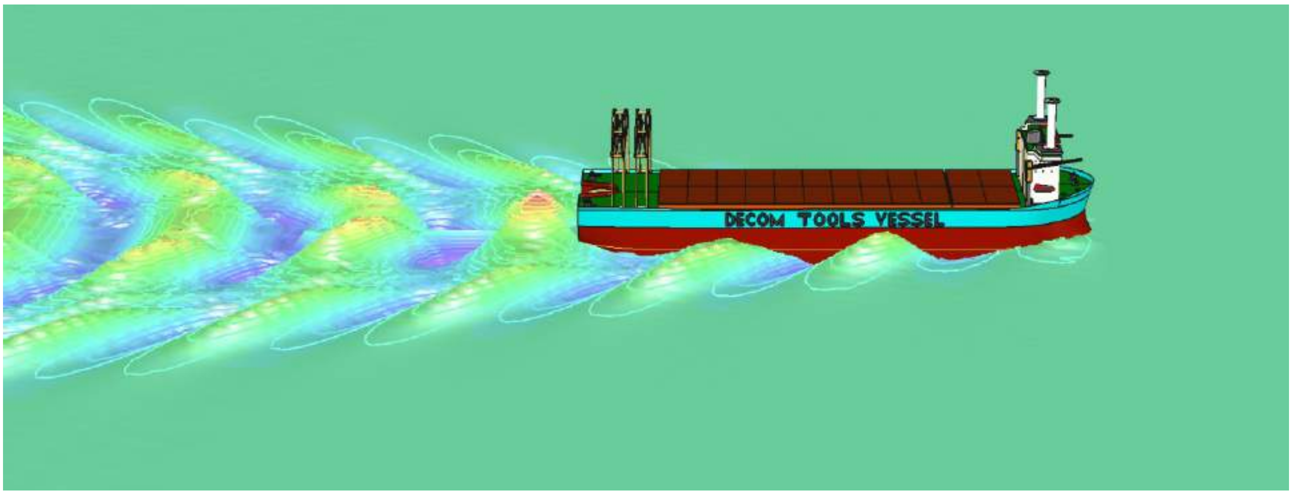
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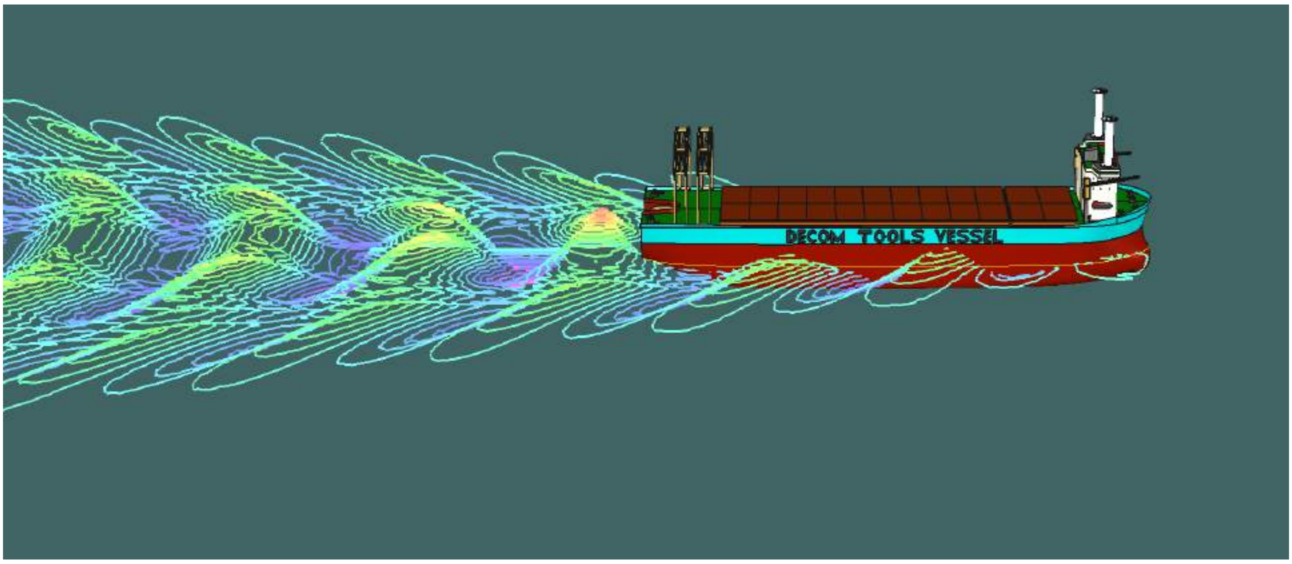
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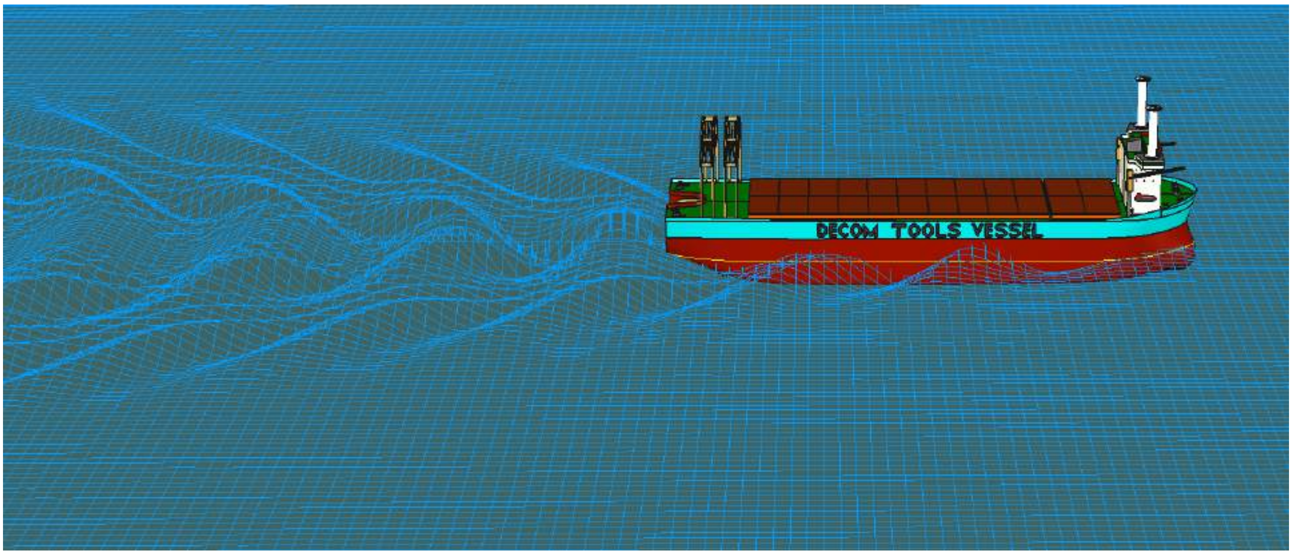
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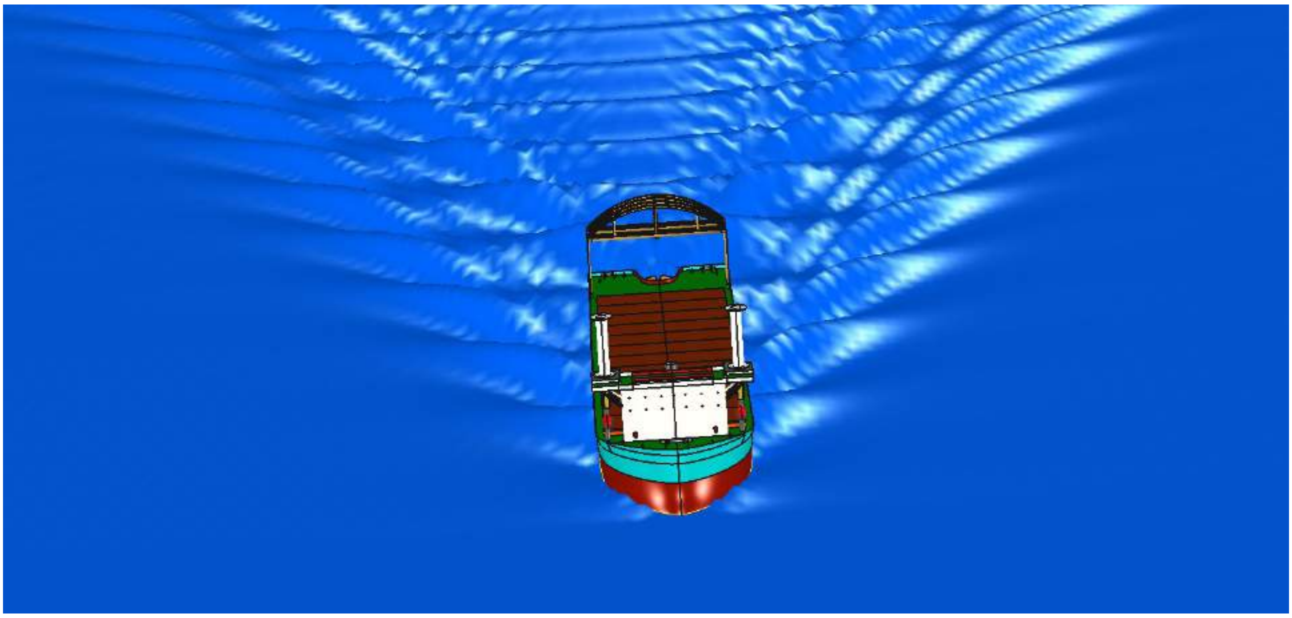

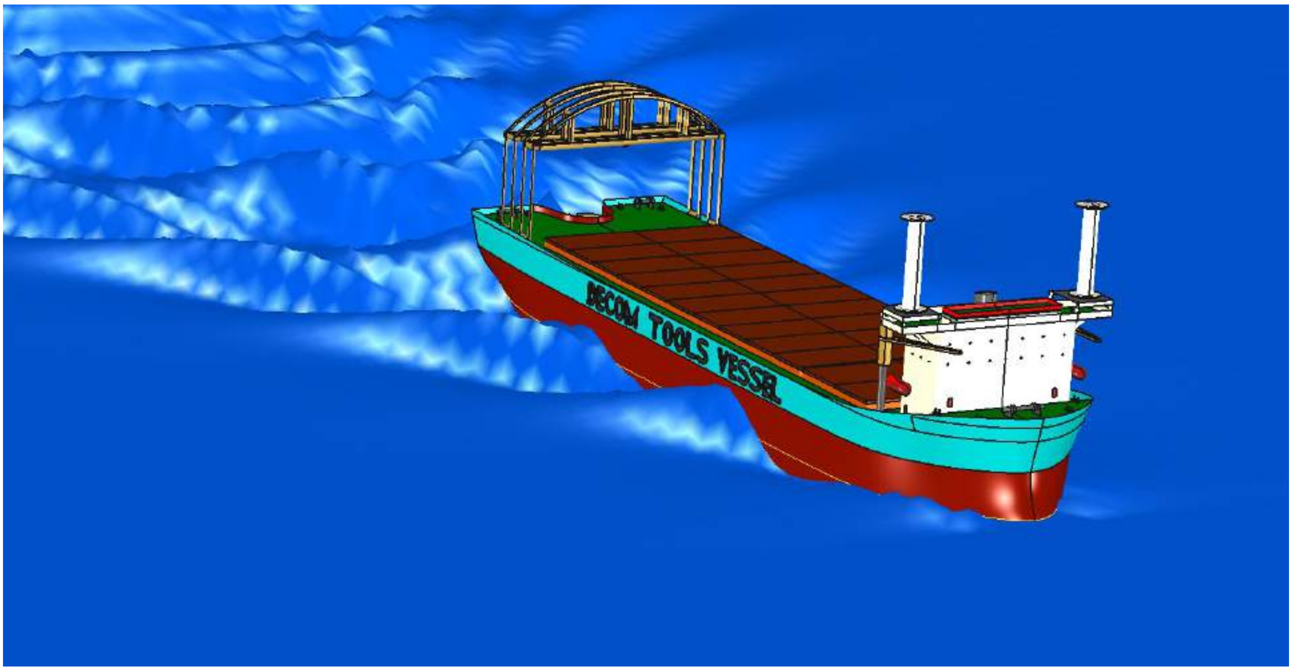
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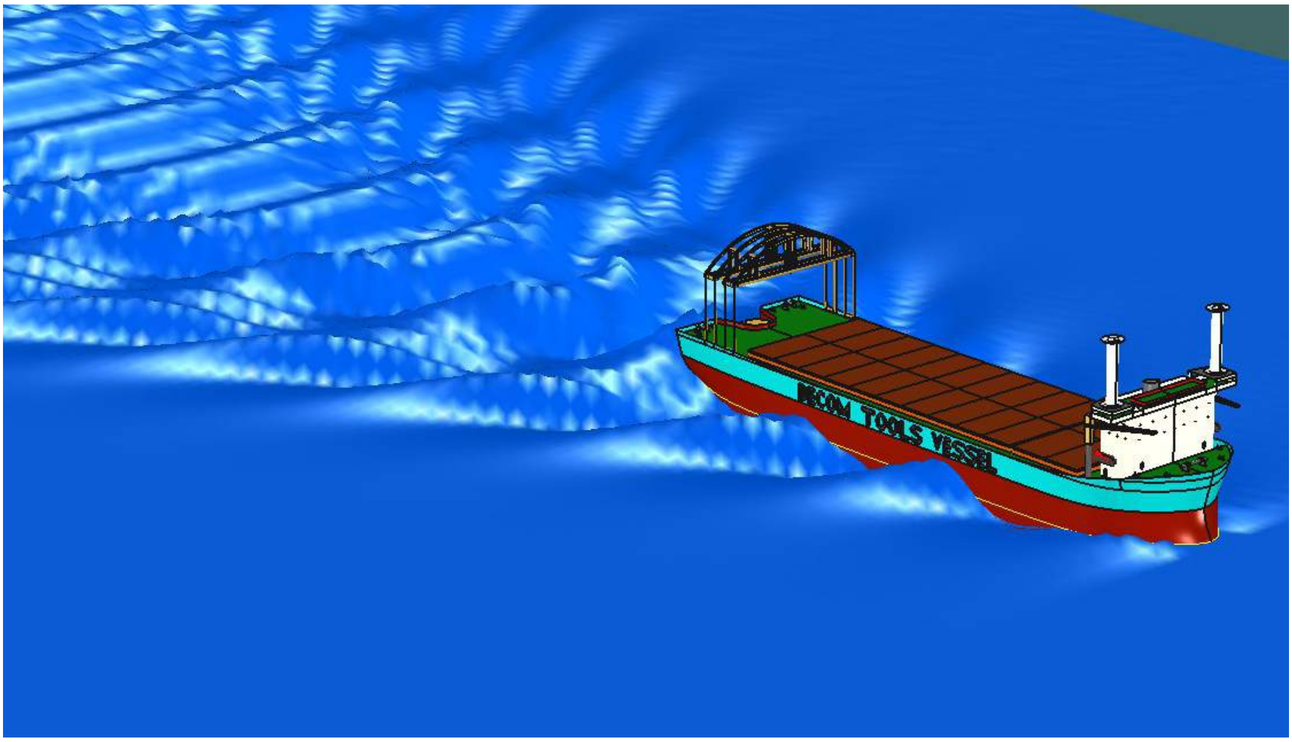
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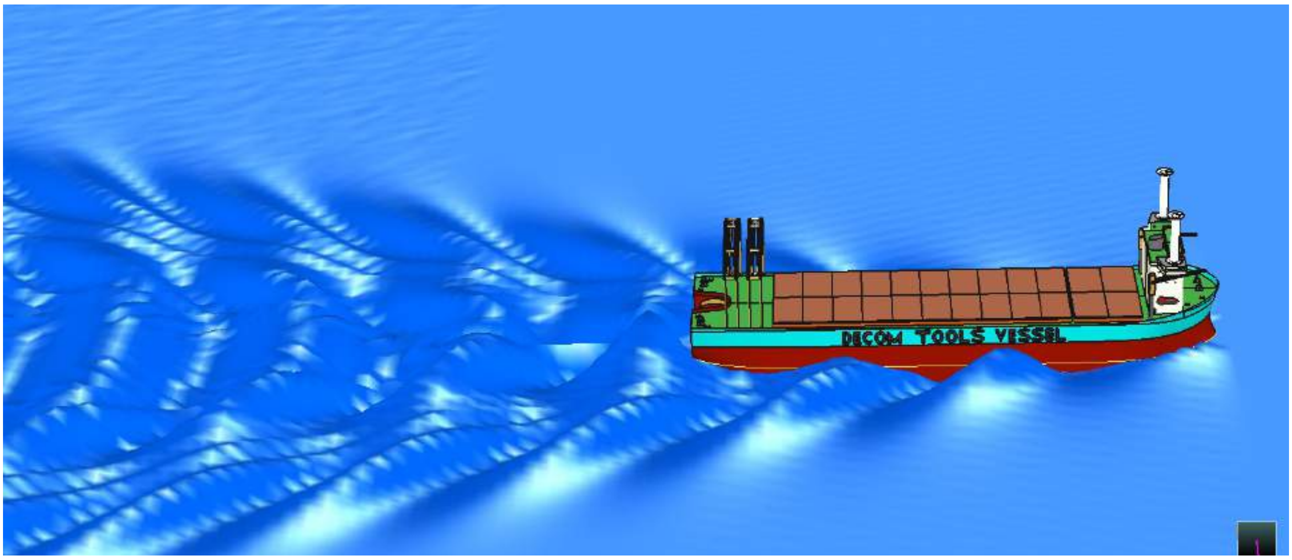
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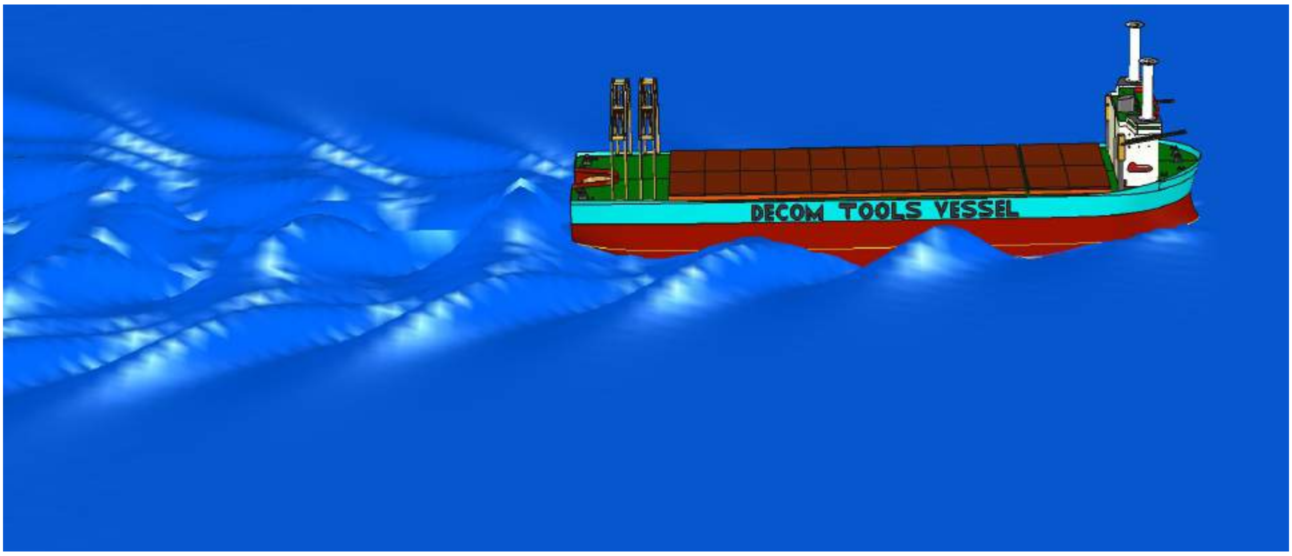
DECOM TOOLS VESSEL

11 Decom Tools Vessel Particular

Specification of Multi-Purpose and Multi-Function Green Decom Tools Vessel		
Vessel Name	Decom Tools Vessel	
Type	Cargo Vessel (C/V) Or Heavy Lift Carrier (HLC)	
Dimensions		
Length overall (M)	195	
Breadth overall (m)	48	
Moulded depth (m)	26.5	
Summer Draught (m)	19.762	
Summer Freeboard (m)	6.738	
Figures of Hatches and Holds		
Number of Holds	2	
Dimension of Hold 1 (m)	L= 25 B=43 H=16.5	
Dimension of Hold 2 (m)	L=109 B=43 H=23	
Dimension of Tween Deck (m)	L=108.7 B=21	
Tween Deck Total Area (m^2)	4565.4	
Hold Space Total Area (m^2)	Hold No 1= 1055 Hold No 2= 4599.8	
Hatch cover Total Area (m^2)	Hatch Cover No 1= 1075 Hatch Cover No 2= 4687	
Main Deck Total Area (m^2)	2978	
Hatch Cover Types	Hatch Cover No 1 Hatch Cover No 2	Pontoon
Tween deck type (Only hold No 2)	20 Panels L=10.87 B=21 H= 0.4	10 Pontoon Panels on Each Side
Vessel Tonnage		
Lightweight (Tons)	20741.78	
Summer Deadweight (Tons)	132322.2	
Summer Displacement (Tons)	156064	
Propulsion System		
First Engine Model	2 x Wärtsilä 6L34DF	Dual Fuel (LNG+ MGO)
Second Engine Model	2 x Wärtsilä 12V34DF	Dual Fuel (LNG+ MGO)

Specification of Multi-Purpose and Multi-Function Green Decom Tools Vessel		
Propulsion Type	Self-propelled	Voith Schneider
Maximum Speed	12.62 knot @ draft 6	9.54 @ draft 19.7
Bow Thrusters	2 X 1000 kW	
Voith Thrusters	3 x 3900 kW	
Positioning	DP and Mooring	
Reference systems	DGPS/tautwire/H.P.R./	Fanbeam/Glonass
Mooring system	8 Mooring Winch	
Power System		
Main Fuel System	LNG	
Wind Assisted Propulsion System	2 x Tiltable Flettner Rotor	Diameter 3m & Height 18m
First Solar Panels	Fixed Panel (Trina Solar 605 Wp)	Model: Vertex TSM DE20
Second Solar Panels	Rollable Solar Panel (Global Solar 300 Wp)	PowerFLEX^{TM} BIPV 300W
Battery Types	Lithium – ion	7 numbers (in overall 1 TWh)
Emergency Generator	1 x 500 KW	
Accommodation		
Accommodation	90 Persons	
Major Equipment and Machineries		
Main Cranes	2 x Gantry Crane	Each 750 tons
Provision Cranes	2 x pedestal Crane	Each 50 tons
Pile Extraction System	Hydraulic Grippers	Extract with Vessel buoyancy
Pile Cutting System	Oxy Fuel	
Cable Recovery System	Winches and rollers	Holding with Hydraulic clamp
Cable Cutting System	Hydraulic shear Cutter	
Water Desalination System	2 x AQUA Blue C100	50 m^3/day (each average 25 m^3/day)
Fuel Consumptions		

Specification of Multi-Purpose and Multi-Function Green Decom Tools Vessel		
Sailing at 7.57 knots	14.8 Tons LNG excluding Pilot Fuel	38% Improved by Flettner rotors, Solar System and Batteries
Sailing at 1 knot	0.1 Tons LNG excluding Pilot Fuel	95% Improved by Solar System and Batteries
Stand-by	0.1 Tons LNG + Pilot Fuel	91% Improved by Solar System and Batteries
Operation on DP mode	51.34 Tons LNG excluding Pilot Fuel	7% Improved by Solar System & Batteries
Operation on PAW	9.4 Tons LNG excluding Pilot Fuel	30% Improved by Solar System & Batteries
Operation when tie up to construction vessel	1 Tons LNG excluding Pilot Fuel	81% Improved by Solar System & Batteries
Operation While Cutting TP &MP	14.4 Tons LNG excluding Pilot Fuel	20% Improved by Solar System & Batteries
Pile Extraction/cable recovery	32.7 Tons LNG excluding Pilot Fuel	10% Improved by Solar System & Batteries
Port Mode	1.5 Tons LNG excluding Pilot Fuel	73% Improved by Solar System & Batteries
Cargo Loading Scenarios		
Loading Arrangement 1 Figure 6-27	12 MW Wind Turbine	8 Nacelle + 8 Towers + 24 Blades
Loading Arrangement 2 Figure 6-45	TP diameter 10.2 m & height 25m above	20
Loading Arrangement 2 Figure 6-110	TP diameter 10.2 m & height 9.5m above	56
Loading Arrangement 3 Figure 6-33	MP with 10m diameter & 100m length + TP with 10.2 m diameter and 25m height	12 MP + 4 TP

Specification of Multi-Purpose and Multi-Function Green Decom Tools Vessel		
Loading Arrangement 4 Figure 6-31	MP with 10m diameter & 100m length + TP with 10.2 m diameter and 25m height	11 MP + 11 TP
Loading Arrangement 5 Figure 6-48	12 MW Blades 107M, 5.5m, 55tons	24 Blades
Loading Arrangement 6 Figure 6-49	12 MW Towers, diameter 10 m, 2 segments (68m+68m)	24 Towers
Loading Arrangement 7 Figure 6-51	12 MW Nacelle 29m x 11m x 10x5 m	26 Nacelles
Loading Arrangement 8 Figure 6-38	5 MW Wind Turbine	24 Nacelle + 24 Towers + 72 Blades
Loading Arrangement 9 Figure 6-42	3.6 MW Wind Turbine	33 Nacelle + 33 Towers + 99 Blades
Possible Loading Arrangement 10	MP diameter of 9 to 10 m	1488 meters, one tier on the hatch cover
Loading Arrangement 11 Figure 6-166	MP diameter of 8,1 meters	1560 meters, one tier on the hatch cover
Possible Loading Arrangement 12	MP diameter of 7 meters	2280 meters, one tier on the hatch cover
Possible Loading Arrangement 13	MP diameter of 6 meters	3156 meters, one tier on the hatch cover
Possible Loading Arrangement 14	MP diameter of 5 meters	4080 meters, one tier on the hatch cover

12 Reviewed Vessel

As it stated before, for the design of the Decom Tools vessel, the specifications, images and documents of many vessels are reviewed. Table *12-1* shows the list of reviewed vessels. Also authors worked onboard several vessels which the name of them are not listed in the following tables.

Table 12-1 List of Reviewed Vessels

No	Name of the Vessel	Type of Vessel	Owner	Source
1	Boka Tiamat	Multipurpose DP2 Construction Vessel	Boskalis	Link
2	Bokalift 1	Transportation & installation vessel	Boskalis	Link
3	Ndurance	Cablelaying / multipurpose vessel	Boskalis	Link
4	Boka Constructor	Cable lay barge	Boskalis	Link
5	Boka Falcon	Multipurpose DP2 Offshore Construction vessel	Boskalis	Link
6	Ndeavor	Cable - laying / multipurpose vessel	Boskalis	Link
7	Spirit	Cable - laying vessel	Boskalis	Link
8	Boka Falcon	Multipurpose DP2 Offshore Construction vessel	Boskalis	Link
9	Taklift 4	Floating Sheerleg	Boskalis	Link
10	Asian Hercules	Floating Sheerleg	Boskalis	Link
11	Asian Hercules	Floating Sheerleg	Boskalis	Link
12	Taklift 7	Floating Sheerleg	Boskalis	Link
13	Smit Borneo	Crane and accommodation Barge	Boskalis	Link
14	Gaint 7	Multipurpose barge	Boskalis	Link
15	Boka Vanguard	Heavy transport vessel	Boskalis	Link
16	Blue Marlin	Heavy transport vessel	Boskalis	Link
17	White Marlin	Heavy transport vessel	Boskalis	Link
18	Black Marlin	Heavy transport vessel	Boskalis	Link
19	Triumph	Heavy transport vessel	Boskalis	Link
20	Trustee	Heavy transport vessel	Boskalis	Link
21	Mighty Servant 1	Heavy transport vessel	Boskalis	Link
22	Mighty Servant 3	Heavy transport vessel	Boskalis	Link
23	Forte	Heavy transport vessel	Boskalis	Link
24	Transshelf	Heavy transport vessel	Boskalis	Link
25	Target	Heavy transport vessel	Boskalis	Link
26	Gaint 5	Semi-Submersible barge	Boskalis	Link
27	Gaint 6	Semi-Submersible barge	Boskalis	Link

No	Name of the Vessel	Type of Vessel	Owner	Source
28	Bokabarge 77	Flat top pontoon	Boskalis	Link
29	Smitbarge 14	Pontoon CC	Boskalis	Link
30	Smitbarge 12	Pontoon CC	Boskalis	Link
31	Smitbarge 11	Pontoon CC	Boskalis	Link
32	Smitbarge 10	Pontoon CC	Boskalis	Link
33	Smitbarge 2	Pontoon CC	Boskalis	Link
34	Bokabarge 9	Pontoon CC / SUB	Boskalis	Link
35	Bokabarge 8	Pontoon CC / SUB	Boskalis	Link
36	Bokabarge 7	Pontoon CC / SUB	Boskalis	Link
37	Bokabarge 6	Pontoon CC / SUB	Boskalis	Link
38	E1506	Pontoon CC / SA / TA	Boskalis	Link
39	E3505	Pontoon CC / RoRo	Boskalis	Link
40	E3004	Pontoon CC / TA	Boskalis	Link
41	Aeolus	Offshore installation vessel	Vanoord	Link
42	Svanen	Heavy lift vessel	Vanoord	Link
43	Nexus	cable lay vessel	Vanoord	Link
44	Stingray	Shallow water pipe lay barge	Vanoord	Link
45	Sleipnir	Semi-Submersible Crane Vessel	HMC	Link
46	Thialf	Semi-Submersible Crane Vessel (SSCV)	HMC	Link
47	Balder	Semi-Submersible Crane Vessel (SSCV)	HMC	Link
48	Aegir	Fast sailing Heavy Lift Vessel	HMC	Link
49	H-302	Cargo Barges	HMC	Link
50	H-405	Cargo Barges	HMC	Link
51	H-406	Cargo Barges	HMC	Link
52	H-407	Cargo Barges	HMC	Link
53	H-408	Cargo Barges	HMC	Link
54	H-591	Cargo / Launch Barges	HMC	Link
55	H-627	Cargo / Launch Barges	HMC	Link
56	H-541	Float-over / Launch Barges	HMC	Link
57	H-542	Float-over / Launch Barges	HMC	Link
58	H-851	Float-over / Launch Barges	HMC	Link
59	Pioneering Spirit	Heavy lift vessel	All Seas	Link
60	Fortitude	Multipurpose offshore construction vessel	All Seas	Link

No	Name of the Vessel	Type of Vessel	Owner	Source
61	Oceanic	Offshore construction vessel	All Seas	Link
62	MV Lone	Heavy lift vessel	SAL	Link
63	MV Svenja	Heavy lift vessel	SAL	Link
64	FLY-JIB	Heavy lift vessel	SAL	Link
65	MV Regine	Multi-purpose dry cargo ship	SAL	Link
66	MV Trina	Multi-purpose dry cargo ship	SAL	Link
67	MV Anne-Sofie	Multi-purpose dry cargo ship	SAL	Link
68	MV Frauke	Multi-purpose dry cargo ship	SAL	Link
69	MV Maria	Heavy lift vessel	SAL	Link
70	MV Annette	Heavy lift vessel	SAL	Link
71	Happy Star	Heavy lift vessel	BigLift	Link
72	Happy Sky	Heavy lift vessel	BigLift	Link
73	Happy Buccaneer	Heavy lift vessel	BigLift	Link
74	Happy R-Type	Heavy lift vessel	BigLift	Link
75	Happy D-Type	Heavy lift vessel	BigLift	Link
76	Spliethoff P-type	Heavy lift vessel	BigLift	Link
77	CY-Class	Heavy lift vessel	BigLift	Link
78	BRAVE TERN	Jack-Up Installation Vessels	Fred. Olsen Windcarrier	Link
79	BOLD TERN	Jack-Up Installation Vessels	Fred. Olsen Windcarrier	Link
80	BLUE TERN	Jack-Up Installation Vessels	Fred. Olsen Windcarrier	Link
82	Jill	Jack-Up Vessel	Fred. Olsen Windcarrier	Link
83	Apollo	DP2 installation vessel	DEME	Link
84	Goliath	DP2 installation vessel	DEME	Link
85	Gulliver	Heavy lift vessel	DEME	Link
86	Innovation	DP2 installation vessel	DEME	Link
87	Living Stone	DP3 cable installation & multipurpose vessel	DEME	Link
88	Neptune	Heavy Lift DP2 Jack-up Vessel	DEME	Link
89	Orion	Heavy Lift DP3 Installation Vessel	DEME	Link
90	Rambiz	Heavy lift vessel	DEME	Link
91	Sea Challenger	DP2 installation vessel	DEME	Link
92	Sea Installer	DP2 installation vessel	DEME	Link
93	Thor	DP2 installation vessel	DEME	Link

No	Name of the Vessel	Type of Vessel	Owner	Source
94	Vagant	Jack-up platform	DEME	Link
95	Isaac Newton	DP2 Cable Laying / Trenching Support Vessel	JDN	Link
96	Willem de Vlamingh	DP2 Cable Laying / Trenching Support Vessel	JDN	Link
97	Connector	DP3 Multipurpose, Flex-Lay Subsea Construction Vessel	JDN	Link
98	Voltaire	Jack-up Installation Vessel	JDN	Link
99	Vole au vent	Jack-up Installation Vessel	JDN	Link
100	Taillevent	Jack-up Installation Vessel	JDN	Link
101	Oceanic-5000	Multi-Purpose Vessel	OMC	

13 Declaration of Authorship

Declaration of Authorship

Bremen, 15.09.2021

We hereby declare that we, the undersigned, are the sole authors of this document. All sources consulted for this document have been listed; all quotations from and references to these sources have been properly cited and included in chapter notes and in the list of references. The parts that have been prepared by one of us, are indicated accordingly. No version of this document has been used to achieve an academic degree or any other examination.

Hamed Askari | Ahmad Halimah

Signature: | Signature:

14 Responsibilities

This paper has been written by two students Hamed Askari and Ahmad Halimah.

Each student was responsible for different part. Below are the responsibilities

Hamed Askari

Chapter 1

Chapter 2

Chapter 3 excluding 3.4.1 to 3.7

Chapter 4

Chapter 5.17 to 5.29

Chapter 6.1 to 6.6

Chapter 6.13 to 6.21

Chapter 9

Chapter 11

Ahmad Halimah

Chapter 3.4.1 to 3.7

Chapter 5.1 to 5.16

Chapter 6.7 to 6.12

Chapter 7

Chapter 8

Chapter 10

Chapter 11

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