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MASTER'S THESIS

Technical Feasibility of Decomtools Vessel Monopile Extraction System

Prince Paa Tawiah Ankrah (595080)

Master in Maritime Operations, Offshore and Subsea Operations Profile

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Supervisor: Prof. Andrés Franklin Olivares Lopez

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TECHNICAL FEASIBILITY OF DECOMTOOLS VESSEL MONOPILE EXTRACTION SYSTEM

WESTERN NORWAY UNIVERSITY OF APPLIED SCIENCES

MASTER THESIS (MSc MARITIME OPERATIONS)

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PREFACE

This Master's thesis was produced as part of the requirements for the award of a Master of Science degree in Maritime Operations with specialization in Offshore and Subsea Operations from Western Norway University of Applied Sciences in Haugesund, Norway. The program, which is a joint master's degree undertaken by a collaboration between Western Norway University of applied sciences (HVL) and Hochschule Emden/Leer in Germany, draws on the expertise of both institutions in the maritime field.

As part of the EU-funded Decomtools project for offshore wind farm decommissioning, the thesis set out to evaluate the technical feasibility of the monopile extraction system of the concept eco-innovative Decomtools vessel design. The thesis evaluates the design feasibility of the gripper support beams in terms of the capacity to withstand the maximum design forces. It further evaluates the cutting method and equipment proposed as part of the extraction system, as well as the crane system and estimates their respective footprints to aid further development and improvement of the vessel during the detailed design phase.

Professor Andrés Franklin Olivares Lopez, my internal supervisor and the research topic's originator, has provided invaluable academic assistance and insight into the project's scope.

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ABSTRACT

Offshore wind power offers potential as a carbon neutral source of energy generation. For decades now, offshore wind technology has developed steadily, and Europe particularly has accelerated development and construction of wind farms off its coasts. Offshore wind structures have a finite design life, and, like the well-established oil and gas industry, offshore installations require sustainable decommissioning at the end of their life cycles. Many global institutions have set out to address the unintended risks this process may pose to the environment by researching and providing innovative solutions. Interreg North Sea (NSR) with its DecomTools project seeks to achieve two main objects which include reducing decommissioning cost and reducing carbon emission during the process significantly. As part of the project, a concept decomtool vessel design was developed to perform installation and decommissioning of offshore wind structures.

The aim of this thesis is to assess the technical feasibility of the monopile extraction system of the Decom Tools concept vessel for the decommissioning of offshore wind farms. The work initially presents a literature review of the current decommissioning operations for the offshore wind industry including current techniques developed for extracting monopile foundations. It subsequently addresses the aim of the research by assessing the technical feasibility of the concept decomtool vessel's extraction system, focusing on the mechanical behavior of the support beam members of the gripper in response to the shear load during removal of the monopile from the seabed. It also assesses the Oxy-fuel cutting method and equipment for its suitability in terms of ease of use, ability to cut the steel monopile structure, estimated time for cut operation, and the minimum equipment space required. Finally, the vessel cranes' technical design parameters are evaluated for operational propriety under the present offshore wind decommissioning needs. The Horns Rev 1 wind farm monopile foundation was used as case study for estimations such as the cut time for monopile and crane capacity.

The finding of this research reveal that the gripper system support beams are unable to sustain the working loads during the extraction process, necessitating further research work to develop suitable support mechanism for the grippers. It also estimates the cutting time for a monopile and provides the footprints of the cutting equipment and gantry cranes.

DEDICATION

To God Almighty, my wife, mother, grandmother, and siblings

ACKNOWLEDGEMENT

This thesis was prepared as part of the pre-requisite for the master's in Maritime Operations degree program, jointly offered by Western Norway University of Applied Sciences and University of Applied Science Emden/Leer.

First and foremost, I would like to express my gratitude to Prof. Andrés Franklin Olivares Lopez, my internal supervisor, for his invaluable inputs, and guidance towards the completion of this project, and for introducing me to the decomtools projects. I have gained considerable insight into the offshore wind industry through this project. I also want to acknowledge the entire department staff and lecturers of both universities for the academic impact and knowledge gained throughout the course of the program.

Finally, to all my colleagues of the program I say thank you. The numerous brainstorming sessions was worth it in the end. Wish you all the very best.

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ABBREVIATIONS

AWJ	Abrassive Water Jet
DNV	Det Norske Veritas
DP	Dynamic Positioning
ELT	External Lifting Tool
EU	European Union
FEA	Finite Element Analysis
GBF	Gravity Based Foundation
HAZ	Heat Affected Zone
HLV	Heavy Lift Vessels
HyPE-ST	Hydraulic Pile Extraction Scale Tests
IMO	International Maritime Organization
LEC	Leg Encircling Crane
NSR	North Sea Region
OEM	Original Equipment Manufacturer
OSPAR	Convention for the Protection of the North-East Atlantic Marine Environment
OWF	Offshore Wind Farm
OWT	Offshore Wind Turbine
ROV	Remotely Operated Vehicle
SWL	Safety Working Load
TLP	Tension Leg Platform
UB	Universal Beam
UK	United Kingdom
UNCLOS	United Nations Convention on the Law of the Sea
WTIV	Wind Turbine Installation Vessels

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NOMENCLATURE

CO_2	Carbon Dioxide
F	maximum breakout resistance
$F_{s,r}$	Total shaft resistance
$F_{int.wall}$	Internal shaft resistance
$F_{ext.wall}$	External shaft resistance
W_{mp}	Weight of Monopile
L_{max}	Maximum extractable length per attempt
$\nabla\ draft$	Maximum and minimum draft difference
∇W	tonnage of ballast pumped out
F_{lift}	lifting capacity
F_{beam}	acting on each beam
F_y	Yield Strength
F_u	Ultimate Strength
F_a	Allowable shear stress of a beam
τ_{beam}	Induced Shear stress
Ω_{v}	Safety factor
M_x	Induced moment
$M_{c,Rd}$	Maximum moment capacity
M_{pl}	Plastic bending moment
W_{pl}	Plastic section modulus
y_{mo}	Partial factor
L_{beam}	Length of beam
$\varnothing_{cyl}$	Diameter of Cylinder
$\rho_{c,max}$	Maximum Pressure of Cylinder
A_{cyl}	Area of Cylinder
V_{cyl}	Velocity of Cylinder
Q_{cyl}	Volumetric flow rate in Cylinder
Q_t	Total Volumetric flow rate
P	hydraulic power in watts
P_{eff}	Electric Power required
L_{cut}	Length of cut

r	Outer radius
D	Outer diameter
t_{cut}	Cutting Time
S_{cut}	Hand Cut Speed
$t_{cut,monopile}$	cutting time for 1 complete monopile
C_{oxy}	Oxygen consumption
$C_{acetylene}$	Acetylene consumption
m	Meter
mm	Millimeter
ton	Tonnes
psi	Pound Per Inch
Pa	Pascal
kPa	Kilo Pascal
Mpa	Mega Pascal
s	Seconds
min	Minutes

1.0 INTRODUCTION

1.1 Background

Many international institutions have made a concerted effort to minimize greenhouse gas emissions in recent decades. As a result, renewable energy sources have emerged as an essential and realistic alternative to traditional fossil energy sources in order to meet worldwide objectives for greenhouse gas emissions while maintaining energy security. Wind energy is a key element of this green revolution, accounting for a considerable share of total renewable energy and continuing to develop as a particularly appealing form of clean energy [1]. According to Premalatha et al [2], wind energy makes up about 1.8% of the world's total electricity demand and is estimated to rise to about 20% by 2050. This will necessitate a greater number of wind farms being built to fulfill future demand.

Currently, onshore and offshore wind energy production represents two different alternatives. Although onshore wind energy has been utilized for a relatively long time, it was only in 1991 when the world's first offshore wind farm was commissioned by Orsted at Vindeby in Denmark [3]. Offshore wind installations have a design life of approximately 20 – 25 years, after which the turbines have their accredited operational lifetime extended or decommissioned according to current laid down regulations [4]. Decommissioning of offshore wind structures involves the dismantling of the wind turbine and its support structures including its foundation or base structures. The monopile is the most popular foundation for an offshore wind turbine (OWT), and largely applicable for water depths below 30 meters [5]. The monopiles are currently decommissioned by cutting the structure from the inside out a few meters below the seabed (mud line) after the topsoil layer is dredged. The disadvantages of this strategy include the possibility of repowering being restricted by leaving a portion of the pile below the seabed, as well as the potential hazard posed to the marine ecosystem.

Until date, the decommissioning procedure for offshore wind turbines has lagged behind and lacked knowledge and know-how. The Interreg North Sea (NSR) nations launched the Decomtools project to bridge the gap by inventing and implementing ecoinnovative concepts. It seeks to lower the cost of decommissioning by 20% and the environmental footprint by 25% (measured in CO_2 equivalents). It also aims to improve the knowledge and competence of NSR stakeholders that are participating [6].

One concept developed under the demtools project, "DecomTools Vessel Design – Presenting an Eco-Sustainable Approach to decommission Offshore Wind Park by designing a New Ship, New Tools and efficient and reliable procedures", aims to fill the knowledge gaps of the offshore wind industry that exists between wind manufacturers, transportation, and installation contractors. It entails the design of a concept multi-function, multi-purpose green vessel, new concept tools, and efficient, reliable, and safe procedures for both installation and decommissioning of offshore wind parks. The vessel is fitted with a monopile extraction technology for decommissioning, which will allow the complete monopile to be extracted from the seabed [7].

1.2 International Regulatory Framework for Offshore Structures Decommissioning

The offshore industry's decommissioning process is currently poorly regulated and lacks appropriate guidelines on recommended procedures [8]. One of the current challenges in dealing with offshore platform decommissioning is the lack of a clear legal definition of what constitutes decommissioning. This is not a problem exclusive to offshore wind projects; it also impacts others such as that in oil and gas.

The term "decommissioning" is absent from the Geneva Convention on the Continental Shelf of 1958, the 1982 United Nations Convention on the Law of the Sea (UNCLOS), and the 1989 International Maritime Organization (IMO) Guidelines and Standards [9]. It is also not described under the 1992 Convention for the Protection of the North-East Atlantic Marine Environment (OSPAR) [10] or other regional accords dealing with marine pollution. Despite the fact that they are not specified, all of the above-mentioned international treaties highlight the necessity to remove offshore installations that are no longer in operation.

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) established international obligations to decommission abandoned facilities. To guarantee navigational safety, this necessitates the removal of abandoned or unused infrastructure or installations, in accordance with generally recognized international standards such as the International Maritime Organization (IMO) standards issued in 1989. On the Continental Shelf and in the Exclusive Economic Zone, the IMO-approved resolution establishes norms and criteria for the removal of offshore equipment and structures, such as wind farms. These recommendations compel state parties to remove any abandoned and unused offshore installations on any continental shelf or in any exclusive economic zone, unless non-removal or partial removal is permissible under the requirements [11]. Any

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decision to leave some or all of an offshore structure or installation on or in the seabed will be based on a case-by-case assessment of a variety of factors, including, where appropriate:

- potential impact on subsurface or surface navigation safety;
- potential impact on other uses of the ocean;
- potential impact on the marine environment;
- total cost of removal;
- risks of personnel injury associated with removal.

[12]

However, in other scenarios, the IMO regulations require that an installation or structure be completely dismantled, with no exception. These are "approaches to or in straits used for international navigation or routes used for international navigation through archipelagic seas, in customary deep draught sea lanes, or in, or immediately adjacent to, routing systems established by the Organization.". Relevant work has also been done under the OSPAR Convention, a regional treaty only applicable in Europe, which directs international collaboration on the conservation of the North-East Atlantic maritime environment. OSPAR Decision 98/3, on the Disposal of Disused Offshore Installations, establishes legally enforceable standards for the disposal of decommissioned offshore oil and gas installations. While there is no analogous Decision for offshore renewable energy plants, OSPAR has issued offshore wind farm guideline documents that include proposals for decommissioning [12].

Januario et al. [13] in their paper, “Offshore Windfarm Decommissioning: A proposal for guidelines to be included in the European Maritime Policy”, provide an initial summary of the legislation governing the decommissioning of offshore wind turbines. The authors emphasize the need of developing guidelines as part of the European Maritime Policy and advocate for the entire removal of any offshore station, unless there are compelling reasons not to.

1.3 Offshore Turbine Foundation

The bulk of offshore wind farms are situated on the continental shelf, around 10 kilometers off the coast, in sea depths of about 10 meters [1]; however since 2019, the average water depth and distance to shore of offshore wind farms constructed specifically in Europe are 33 meters and 59 kilometers respectively [14]. The support structures must support the wind turbines by absorbing all stresses and loads, as well as providing a secure and sturdy foundation. Wind turbines with permanent foundations, such as gravity base, monopile, tripod, and jacket foundations, are commonly found in sea depths of less than 50 meters in existing offshore wind turbines. Because the wind resource is large for sea depths more than 50 meters, bottom-fixed offshore wind turbines are becoming a less economically viable option for resource extraction. [15].

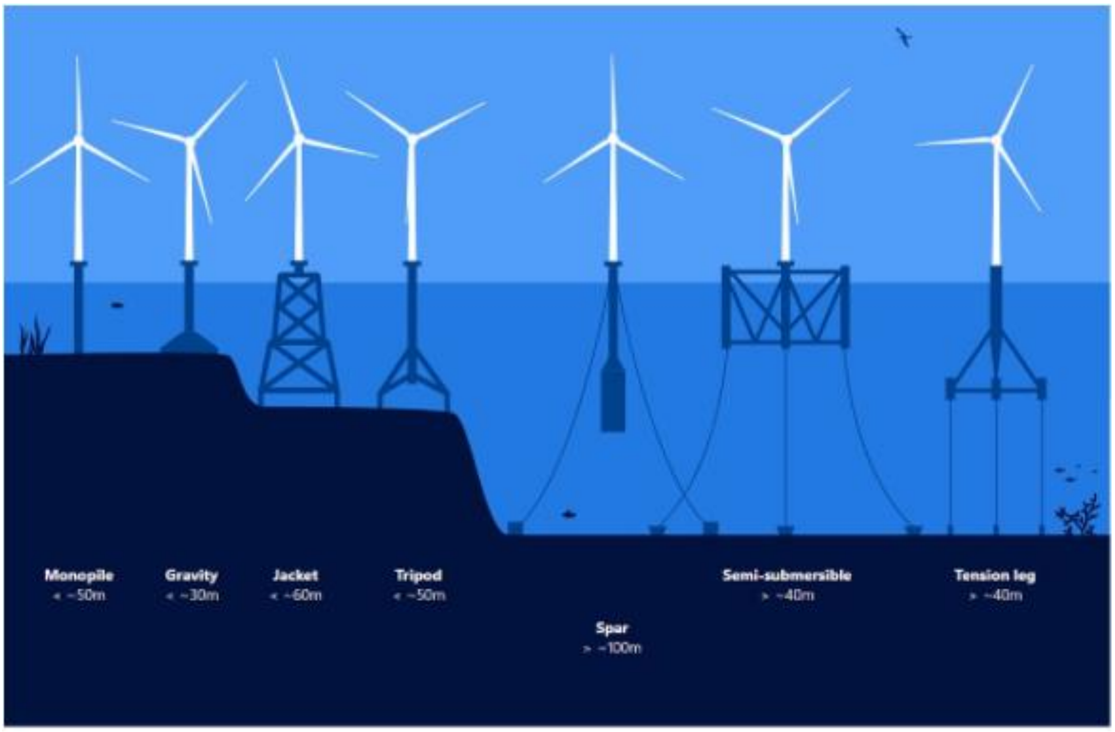

Fig. 1 Offshore wind foundations, from [16]

According to inventory statistics, the cost of foundations accounts for 20% to 30% of the cost of a typical offshore wind farm. This explains why offshore wind turbines are more costly than onshore wind turbines [1]. As a result, selecting the proper foundation type for offshore wind turbines is critical to making the most of the technology. There are many options for foundations that can be utilized for this purpose, and Fig. 1 depicts a schematic layout of some common foundation systems for permanent offshore wind turbines.

The overall installed capacity of Europe's offshore wind turbines is expected to expand dramatically. The rapid development of the industry has resulted in an increase in size and capacity of these structures. Bringing into focus the foundation support systems and the accompanying installation and decommissioning challenges. As Table 1 indicates, installed offshore wind turbines in the European continental shelf employ a variety of foundation supports. Foundation options will be explored in a bit more details.

Table 1 some offshore wind installation and foundations in Europe, from [14]

COUNTRY	WIND FARM	CAPACITY CONNECTED IN 2019 (MW)	NUMBER OF CONNECTED TURBINES	FOUNDATION TYPE
UK	Hornsea One	1,218	174	Monopile
	Beatrice 2	315	45	Jacket
	East Anglia Offshore Wind 1	231	33	3-leg Jacket
Germany	EnBW Hohe See	497	71	Monopile
	Deutsche Bucht	260.4	31	Monopile
	Merkur Offshore	252	42	Monopile
	Trianel Windpark Borkum 2	101.3	16	Monopile
Denmark	Horns Rev 3	373.5	45	Monopile
Belgium	Norther	369.6	44	Monopile
Portugal	Windfloat Atlantic Phase 1	8.4	1	Semi-sub

1.3.1 Gravity Based Foundation (GBF)

The gravity base foundation is a form of reinforced concrete tube construction that has a limited load bearing capability. As shown in Fig. 2, they are designed largely for self-weight, which must be strong enough to resist high overturning moments while leaving support structures standing upright on the seabed, and are appropriate for light environmental loads, such as minor waves with considerable dead load, or where extra ballast can be easily delivered at a low cost [17] [1].

Gravity-base foundations are the second most common type of support system [18]. They have mostly been utilized to sustain smaller turbines in shallow seas close shore with a rough bottom, where piling is exceedingly difficult and expensive. Gravity base foundations are more ideal for seabeds formed of rock, sandy soil, and compacted clay because they require sufficient load bearing capability to sustain the self-weight, service loads, and environmental pressures acting on the structures of the foundation. This foundation is often found in water depths of less than 10 meters [17].

Fig. 2 gravity base foundation (GBF) for Blyth offshore wind farm, from [19]

1.3.2 Tripod

A tripod is a steel tube that protrudes from the surface of the water. The foundation comprises a three-legged foundation exists under the water's surface; each "leg" terminates in a pile sleeve, where an anchor pile is sunk into the seabed to secure the foundation [20]. A tripod truss can sustain top loads applied to the tower and transfer stresses and moments to the prefabricated three steel piles unit. The tripod foundation is solid, light, and appropriate for use in water depths ranging from 10 to 35 meters. The benefit of the tripod is that, despite the area entering the wave zone is as small as a monopile, it is stretched out like a camera tripod (see Fig. 3) on the seabed. As a result, it offers tremendous resistance to bending moments [1] [20].

Fig. 3 Tripod foundations for Global Tech I., North Sea, Germany, from [21]

1.3.3 Jacket

A jacket foundation as shown in Fig. 4, is made up of a space frame construction made up of steel tube elements that are normally welded together on land in preparation. After that, the jacket is delivered to the location (Fig. 5), and placed onto the seafloor. In terms of steel consumption, jacket foundations are very inexpensive, however, its storage, shipping, and installation can be costly, significantly increasing the total cost [1]. The jacket's advantage is that, given its size and water depth, it is rather light. It is only utilized at large water depths, where it is the preferable solution [20]. The jacket, like the tripod, has corner pile sleeves through which anchor piles are pushed to maintain the jacket in place. According to Wu et al [1] jacket foundations have been utilized extensively in intermediate water depths ranging from 5 to 50 meters to date. Despite the fact that the three-legged idea is commonly employed in the offshore oil and gas business, practically all jacket substructures used in the offshore wind industry now have four legs [22].

Fig. 4 Installation of jacket foundation for Aberdeen Offshore wind farm, from [23]

Fig. 5 Transportation of jacket foundation for Seagreen, Scotland by Seaway 7

1.3.4 Floating

There are three primary types of foundation ideas and mooring techniques utilized for floating offshore wind substructures or foundations namely the Tension Leg Platform (TLP), Semisubmersible (Semi-sub), SPAR [24].

Tension Leg

The tension leg platform (Fig. 7) is a moored floating structure with tendons linking it to anchors on the seabed. Its position is maintained in terms of tendon tension caused by the floating structure's high buoyancy.

Fig. 7 Tension Leg Platform concept, SBM, from [24]

Fig. 6 Semi-submersible, Principal Power, from [24]

The elastic elongation of the bracing will also restrict the vertical movement of the platform due to waves. This foundation generally has a characteristic feature of having a small dynamic response to external forces, and is particularly adapted for great depths in the water [24]

Semi-Submersible

Typically consisting of multiple columns and pontoons, the semi-submersible foundation is partly submersed to provide station keeping and stability. The stability is accomplished by the restoring moment of the columns, while the pontoons provide additional buoyancy [25]. A mooring system, consisting of catenary or taut spread mooring lines and suction anchors, keeps the floating structure in place. The semi-sub has the advantage of avoiding significant wave loads due to the smaller tubulars in the splash zone. Various unique floating wind semi-submersibles have been built by various floating wind prototype designers to optimize the foundation design and achieve wind turbine stability [25]. Principle Power's WindFloat (Fig. 6) for example, comprises three big diameter columns with smaller diameter steel bracing.

SPAR

A SPAR is a vertically floating cylinder containing ballast tanks in portions of the cylinder volume, making the construction less susceptible to current, wave, and wind [24]. As seen in Fig. 8, the spar foundation is held in place by catenary or taut spread mooring lines with suction anchors, similar to semi-submersibles.

Its main advantages are that the structure configuration is usually simpler than semi-submersible and tension leg platform; it is more stable than semi-submersible due to its deep draft design; and the anchoring mechanism is less expensive than TLP. Due to the tall hull construction of the spar, however, it can only be used at water depths more than 100 meters [25].


Fig. 8 Illustration of the Hywind Tampen array with the spar buoy foundation, source Equinor

1.3.5 Monopile

A monopile foundation (Fig. 9) consists of a single steel tube pile with a typical diameter of 3 to 8 meters, although larger diameters are currently designed and manufactured for new offshore wind projects. Monopiles are situated at shallow water depths ranging from 20 to 40 meters, and the depth of water at which these foundations become uneconomic is unknown [1]. Monopiles can be erected offshore using vibratory drive or impact hammers on seabed with clay, sand, or chalk stratigraphy. Drilling and drilled pile procedures are widely used on a rocky seafloor. It is able to stand upright due to the friction of the seabed on the sides and the lack of vertical ground pressure on it [20]. The monopile has been used for offshore wind turbine foundations all around the world due to its ease of fabrication, low cost, and controllable construction [1].

Fig. 9 Monopile foundation, from [26]

1.4 Aim and Research problem

Topham et al [27] in their research "Challenges of decommissioning offshore wind farms: Overview of the European experience" outlined lack of regulation, unavailability of suitable vessels, process planning, and impact on the environment as the four key issues confronting offshore wind farm decommissioning. The unavailability of suitable vessels to tackle this relatively new offshore activity has a significant adverse impact on the environment by increasing project duration, and its subsequent consequence on environmental footprint (measured in CO_2 equivalents). A novel design of a vessel under the Decomtool project aims to address this problem, providing a specialized vessel that will drastically reduce decommissioning time while also addressing the current offshore wind monopile decommissioning processes, which involve cutting and leaving a portion of the pile in situ.

This thesis aims to assess the technical feasibility of the monopile extraction system of the Decom Tools concept vessel for decommissioning offshore wind monopile foundation proposed under the Decomtools project. It evaluates the three main components of the extraction system namely the gripper system, where it focuses on the gripper support beams and hydraulic unit; the cutting tool and method, where it focuses on the cutting time and footprint of the cutting equipment on the vessel deck; and the crane and lift system, where its focus is on the suitability of equipment design characteristics in relation to the operations and availability of similar profile cranes on the market.

The thesis answers the following questions on each sub-system:

1. Gripper system
    - What are the forces that the beams must support?
    - What is the failure mode for the support beams?
    - Will the design of the support beam system fail?
    - What is the hydraulic unit capacity requirements for the gripper system design?
    - What is the vessel deck space requirement for the hydraulic unit?
2. Cutting tool and method
    - Does the oxy-fuel cutting equipment have the capacity to cut the monopile?
    - What is the expected cut time for the monopile?
    - What is the vessel deck space requirement for the oxy-fuel equipment?
3. Crane and lifting system
    - What is the expected maximum load to be supported by crane?
    - What is the estimated footprint of the gantry cranes?
    - What are the available options on the market

1.4.1 Methodology

Various methodologies were used to address the research questions given in the preceding section. They typically consisted of desktop research for literature review, a design analysis tool, and basic engineering calculations. Chapter 3 contains a more extensive discussion of the techniques employed.

1.4.2 Outline of Thesis

The structure of the thesis is as follows:

Chapter 1. Introduction:

The research criteria and scope of study are presented in this section. It contains background research that is relevant to the work's goal and purpose, as well as a summary of methodology and a thesis outline.

Chapter 2. Literature Review:

This chapter provides a quick summary of prior research projects' literatures. A broad overview of the offshore wind farm sector, with a focus on decommissioning, was provided. A look at vessel requirements, equipment, and offshore wind turbine components in relation to decommissioning activities, as well as developing monopile foundation decommissioning solutions, were also addressed.

Chapter 3. Data and methods:

This chapter provides an in-depth explanation of the data collection and methodology employed in this work.

Chapter 4. Decomtools design vessel monopile extraction system:

The Decomtool design vessel is introduced and described in this chapter, followed by a brief discussion of the Horns Rev1 wind farm monopile foundation. It subsequently assesses the gripper support beams for design feasibility, as well as an assessment of the Oxy-Acetylene cutting method and equipment. Finally, the gantry cranes of the vessels analysed in terms of load capacity as compared to available vessel deck gantry cranes of similar capacity.

Chapter 5. Discussion:

Outcome of the research will be discussed in this chapter.

Chapter 6. Conclusion and Future Works:

This section provides conclusion remarks and proposal for future works.

2.0 LITERATURE REVIEW

2.1 Offshore Wind Turbine Decommissioning

The development of offshore wind energy lags behind that of onshore wind energy [8]. However, the offshore wind industry is developing rapidly. As more offshore wind turbines reach the end of their design lives, end-of-life management will become increasingly important for the industry's long-term viability. The projected operating life of an offshore wind farm (OWF) is 20-25 years [4], [8], which raises the question of what happens after its design life.. There are currently three main options namely Life extension, which involves maintaining the windfarm in its present state; repowering, which entails replacing older components with modern equivalents to improve overall efficiency and performance; and decommissioning, which refers to dismantling and removal of the structure [28]. In the North Sea Region in Europe for example, the annual number of wind turbines scheduled to be decommissioned is shown in Fig. 10.

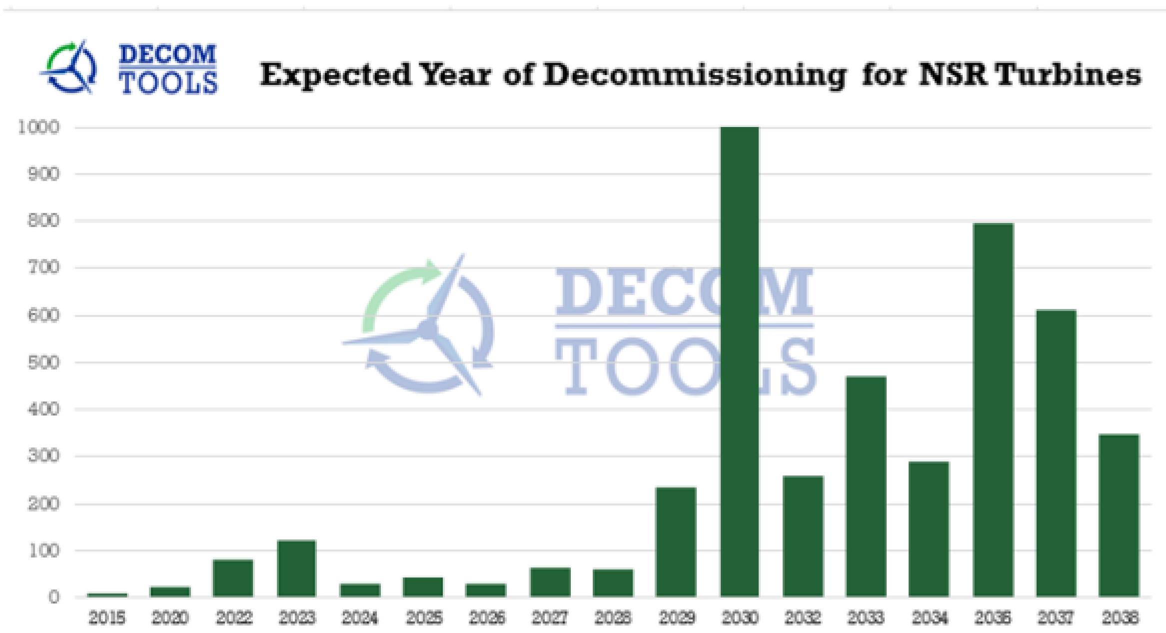

Fig. 10 Schedule of annual decommissioning of wind turbines in the NSR, from [29]

Although fully decommissioning an offshore wind farm is the least cost-effective option for project owners nearing the end of their life cycle, all windfarms will eventually reach a point where the cost of maintenance or repowering is no longer commercially viable when compared to the cost of decommissioning. [28], [30]. Decommissioning of an offshore wind farm may be divided into three phases: preparatory work to produce comprehensive designs and permits, operative work to remove the turbines and their foundations, as well as other offshore structures and cables, and monitoring [31]. Table 2 displays a list of decommissioned offshore wind farms in Europe that are no longer economically viable to maintain.

Table 2 Removed Offshore Wind Farms [8], [31]

Wind Farm	Country	Number x Size	Foundation	Built	End of Service	Removed
Nogersund/Blekinge/Svante	Sweden	1x220 kW	Tripod	1991	2004	2007
Yttre Stengrund	Sweden	5x2 MW	Drilled MPs	2001	2015	2015
Utgrunden I	Sweden	7x1.5 MW	MP	2000	2018	2018
Robin Rigg (2 of 60)	UK	2x3 MW	MP	2010		2015
Blyth	UK	2x2MW	MP	2000	2013	2019
WindFloat	Portugal	1x2 MW	Floating	2011	2016	2016
Hooksiel	Germany	1x5 MW	Tripile	2008	2011	2016
Lely	Netherlands	4x500 kW	MP	1994	2014	2016
Vindeby	Denmark	11x450 kW	GBS	1991	2016	2017

2.1.1 Decommissioning Wind Turbine and Tower

The turbine is anticipated to be removed in the same way it was installed, commonly referred to as reverse installation, with a crane aboard a jack-up vessel removing the blades, nacelle, and tower individually. The vessel used for installation and, thereafter, any major component changes during the turbine's operating life will most likely also be used to deconstruct it for a certain turbine size and location [31]. The preparation of the site is the initial step in the decommissioning process. This is expected to include; developing an approved lift plan and safe system of work for the decommissioning of the main components prior to any onsite operations; inspecting hook on points and any other safety related equipment; removing all loose items from the structure; hot bolting key bolts to aid the dismantling process or decreasing the torque and tension of components [32]. The operations then begin with liquids such as gear or motor oils, as well as any other chemicals that may be present, are either collected and extracted from the turbine for later suitable treatment after the turbine has been de-energized, or they can be kept inside the nacelle to reduce spillage risk and collected once ashore. Bolts fastening joints are removed by normal methods or with cutters and angle grinders if the initial option proves impossible [33].

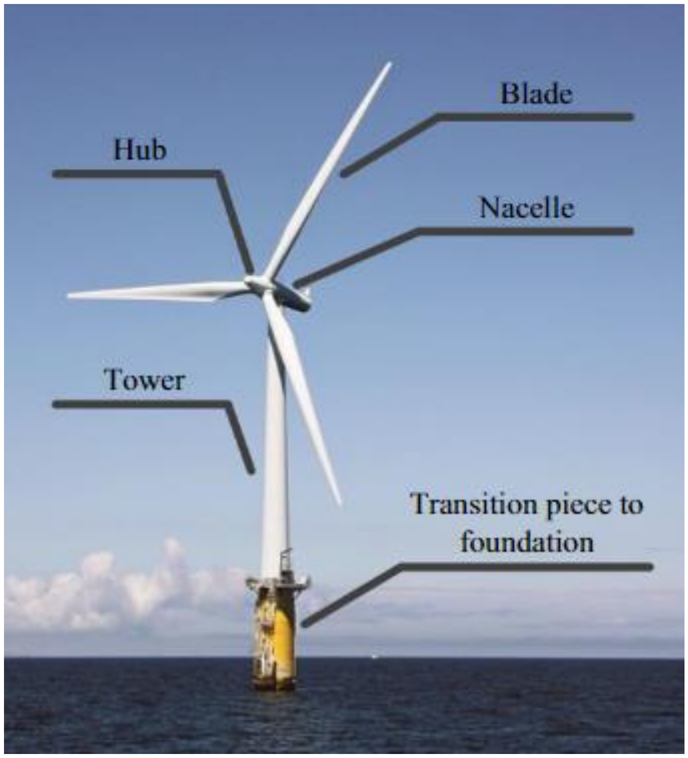

Fig. 11 Major components of an OWT, from [34]

Other activities during the decommissioning are disconnection of power and signal cables between the power and nacelle, removal of rotor blades one at a time, removal of tower and nacelle, and effecting and safe lifting of these parts onto the vessel. The optimal decommissioning approach will have a reasonable operating duration, low personnel risk, and be cost-effective to implement [8], [32]. The major parts of an offshore wind turbine with support structure is illustrated in Fig. 11.

2.1.2 Decommissioning Foundations

The process for dismantling the turbine foundations varies depending on the foundation type (Fig. 12). The most common form of foundation is a monopile foundation, which consists of steel cylinders called piles that are driven into the seafloor. The prevailing decommissioning process for these piles may be to cut and removed, generally approximately 1m below the ocean level

Gravity-based foundations, which are often enormous concrete buildings filled with ballast, can be refloated by removing the ballast and towing or lifting them onto a vessel [8].

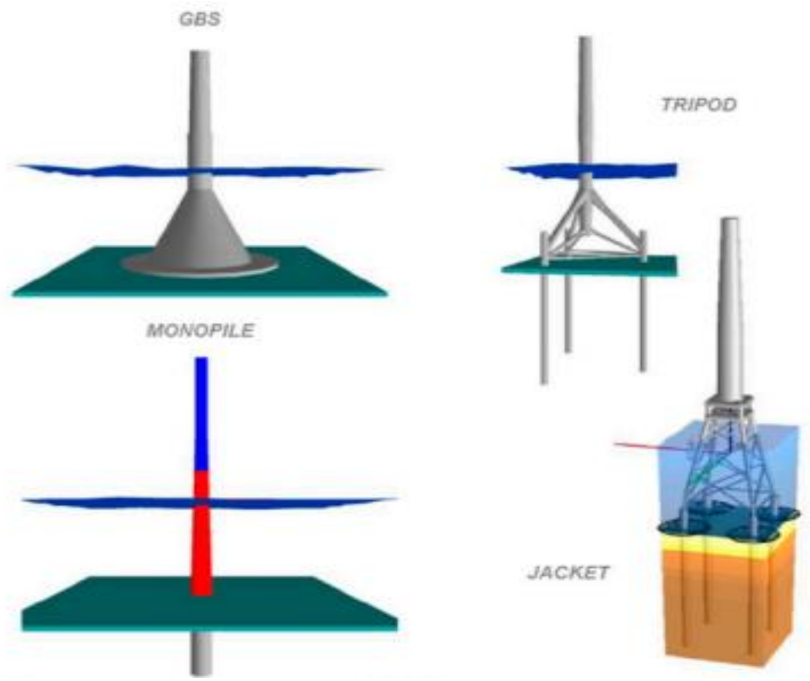

Fig. 12 Offshore wind turbine foundation types, from [35]

The jacket foundation is currently decommissioned by cutting through each of its legs at a significant depth below the bottom; the structure may be hoisted in a single lifting operation. The legs, usually consisting of a stub pipe installed at the bottom of the structure, a pile driven into the seabed, and grout used to fill the space between them. Before the legs are cut, often with a diamond-wire cutting tool and the assistance of ROVs, lift rigging must be erected from the jacket to the crane vessel. The structure can be totally raised and placed into a transportation vessel once the four legs have been severed [36]. For a bucket or suction foundation, a pump mechanism is utilized to apply pressure inside the buckets, allowing the foundation to be released and extracted from the bottom. Pumping saltwater or ballast from within the foundation makes the structure buoyant, making it easier to capture and load into a ship for subsequent transfer [37].

2.1.3 Decommissioning Transition Piece

Together with the monopiles, the transition pieces (shown in Fig. 13) constitute the base of the turbines. The transition piece serves a variety of purposes, including access for maintenance, a cable connection for the turbine's energy, and corrosion protection for the entire foundation [38]. The cables linking the turbine's tower to the foundation will be severed and cut, allowing the lifting operation to take place. While the J-tubes are being cut, a cutting tool must be placed under the airtight platform of the transition component. When the crane is in position to support the weight, the transition piece will be cut [39] or maybe lifted together with the foundation altogether with appropriate consideration of added weight and safety.

Fig. 13 Transition piece, from [40]

2.1.4 Decommissioning Subsea Cables

Both export cables and inter-array, seen in Fig. 14, are included in subsea cables. Typically buried more than a meter beneath the seabed, they pose no safety hazards to maritime users and have no environmental or pollution implications, but this is usually dependent on the cable technology used [33], [37].

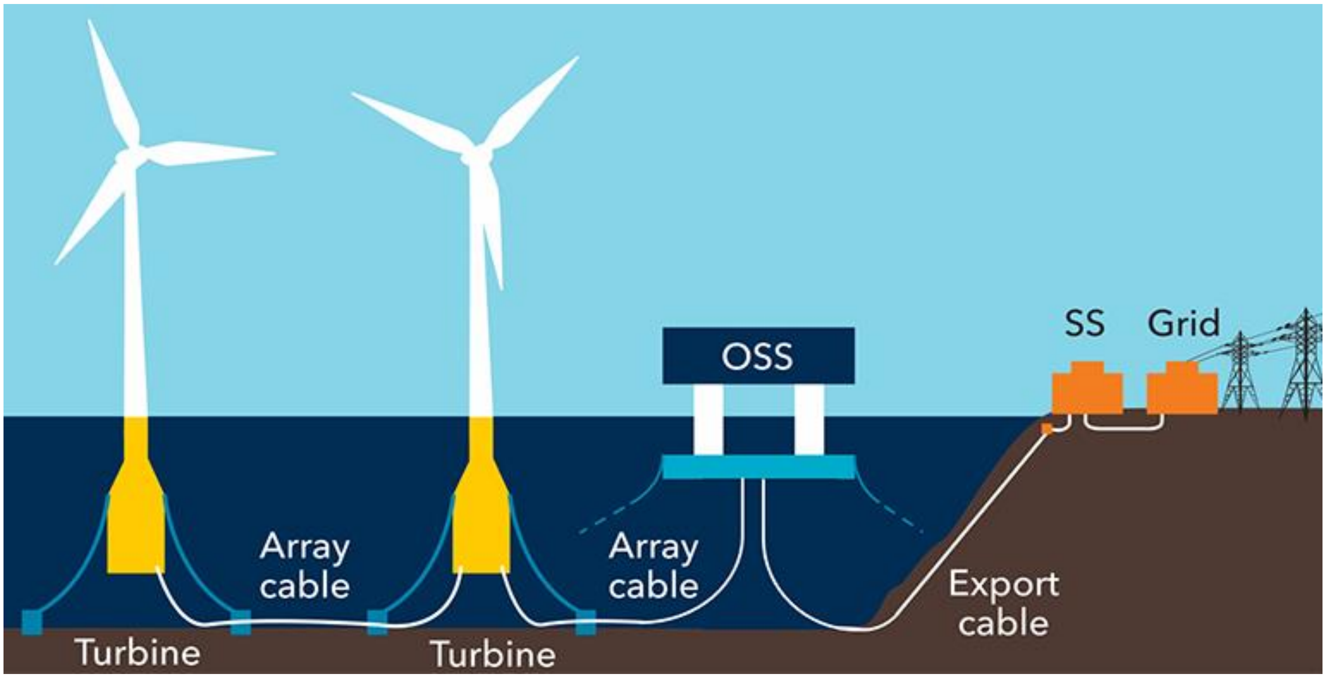

Fig. 14 array and export cables for an offshore wind farm, from [41]

Depending on whether the risk of the cable becoming exposed is minor, the offshore cables will either be removed or left in place. If left in place, the ends will be weighted down and buried (e.g. by a ROV) to avoid interfering with vessels and other structures. At cable or pipeline crossings, the cables are likely to stay in place to prevent putting the third-party cable or pipeline's integrity at risk [32]. It is feasible to assume that the recovery is only required in certain regions (cable crossings), in which case the process begins with the identification of the cables, which may involve use of remotely operated vehicles (ROVs). To raise the cables from the seabed, the needed sections are cut, weighted and the leftover ends returned to the seabed, or by elevating cable ends onto a recovery vessel where they are spooled into a drum, flow excavation and grapnels can be utilized. The cables will be cut as close to the foundation as practicable, with the ends buried to a depth of roughly 1 meter to minimize damage to the marine ecosystem and seabed [8], [32].

2.1.5 Decommissioning Scour Protection

Scour, which is one of the biggest challenges when building offshore wind turbine foundations, is the flow of sediment that can destroy the seafloor around a permanent structure. Scour affects the monopile foundation's bearing capacity, the offshore wind turbine system's dynamic behavior, and may potentially induce structural instability [1]. Scour protection techniques often used include dumping different grades of stones and putting concrete beds around the base (Fig. 15). A layer of tiny rocks may be deposited before or after pile driving for monopile foundations; afterwards, once cabling is connected, huge cover stones may be placed around the foundation [42].

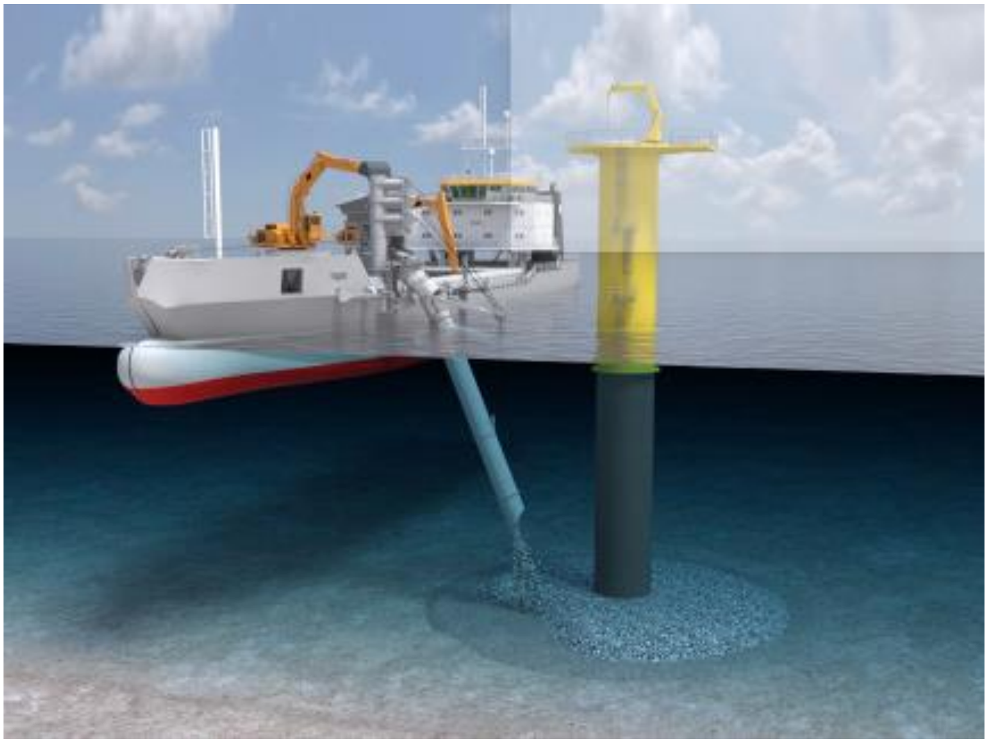

Fig. 15 Scour protection after the monopile (seen in gray) and transition piece are installed, from [43]

During decommissioning of the offshore wind farm foundation, it may be desirable to leave the scour protection in place since the environmental implications of removing it are likely to be larger than leaving it in place because the substratum will most likely be quickly colonized by marine species. However, if considered desirable to be retrieved, it will be dredged and sent for reuse or to a recycling facility. Fig x shows scour protection after installation of a monopile foundation [32], [37].

2.2 Decommissioned Wind Farms

Decommissioning of offshore wind turbine is still in its early stages throughout the world, with only a limited amount of data available in wind energy databases. While the importance of the necessary end-of-life solutions for offshore wind turbines can be seen as a future issue, it is already observed globally that some projects have reached the end of their lives and have been decommissioned. Table 3 provides a summary of decommissioned offshore wind farms in Europe. We take a closer look of some of these decommissioned offshore windfarms.

Table 3 Removed Offshore Wind Farms, from [8], [31]

Wind Farm	Country	Number x Size	Foundation	Built	End of Service	Removed
Nogersund/Blekinge/Svante	Sweden	1x220 kW	Tripod	1991	2004	2007
Yttre Stengrund	Sweden	5x2 MW	Drilled MPs	2001	2015	2015
Utgrunden I	Sweden	7x1.5 MW	MP	2000	2018	2018
Robin Rigg (2 of 60)	UK	2x3 MW	MP	2010		2015
Blyth	UK	2x2MW	MP	2000	2013	2019
WindFloat	Portugal	1x2 MW	Floating	2011	2016	2016
Hooksiel	Germany	1x5 MW	Tripile	2008	2011	2016
Lely	Netherlands	4x500 kW	MP	1994	2014	2016
Vindeby	Denmark	11x450 kW	GBS	1991	2016	2017

2.2.1 Example 1: Lely (Netherlands)

The Lely offshore wind farm, located 600 meters off the port of Medemblik in the Dutch freshwater lake IJsselmeer, was built in 1992 and had been in operation for 22 years. It was made up of four two-bladed wind turbines (Fig. 16) with a combined capacity of 2MW, each supported by a 26m long monopile foundation with diameters varying from 3.20 to 3.70 meters [44], [45]

Fig. 16 Lely offshore wind farm, Netherlands, from [45]

Fig. 17 Decommissioning of Lely offshore wind farm foundations, from [44]

The decommissioning of the Lely wind farm began in 2016 with the disassembly of the turbines. Using crane barges and tugs, the procedure was completed in three stages, with the rotors and nacelles removed first, followed by the removal of the two tower sections [45]. The monopiles, on the other hand, were retracted using a vibratory hammer as shown in Fig. 17. The approximately 80-ton piles were fully removed from the seabed in a relatively short period of time, employing the immense centrifugal force supplied by the PVE vibratory hammer, and were hauled away on pontoons [44].

2.2.2 Example 2: Vindeby (Denmark)

Vindeby (seen in Fig. 19) was the world's first offshore wind farm, built in 1991 and located two kilometers off the coast of the island of Lolland. The wind park consists of 11 Siemens wind turbines, each towering at just 54m. Vindeby's 0.45MW capacity turbines had a total export capacity of 5MW, laying the groundwork for today's huge wind farms. The turbines were erected on gravity foundations, which were concrete foundations laid in an artificial dock and floated out to sea [46], [47]. On January 10, 2017, the Danish Energy Agency approved the decommissioning of the Vindeby offshore wind farm after 25 years of operation [48].

Fig. 19 Vindeby offshore wind farm, from (Vindeby Offshore Wind Farm | PMI, 2019)

Fig. 18 Decommissioning of Vindeby wind turbine, from (Weston, n.d.)

The blades, nacelle and tower are removed and lowered separately by a mobile crane aboard the jack-up vessel during the decommissioning procedure. The concrete foundations were demolished on site, mainly by hydraulic demolition shears, and then collected for disposal [49]. Fig. 18 shows dismantling activity during decommissioning of the wind farm.

2.2.3 Example 3: Blyth (United Kingdom)

Developed in the late 1990's and commissioned in December 2000 as a pilot project, the Blyth Offshore Wind Farm, a modest coastal wind farm located approximately 1 km off the coast of Blyth in Northumberland, England, was the UK's first offshore wind farm. The farm was built with two Vestas V66-2 MW turbines that were supported by 3.5 m diameter monopile foundations of 25 m to 27 m lengths [50], [51].

The 230-tonne crane from the jack up platform Excalibur was deployed to decommission the two turbines and their monopile foundations. The decommissioning process, as seen in Fig. 20, involved dismantling the various major components of the structure piece by piece, beginning with the blades. The monopile, which was installed in a pre-drilled grouted socket, is cut 0.5 metres below the seafloor with a water-jetting tool. The monopile was then lifted free using the jack-up's inbuilt reaction beams before being transferred to the Excalibur's deck. To return the installation site to its original state, the remaining socket was covered with 250 tons of crushed stone to the level of the seabed [52].

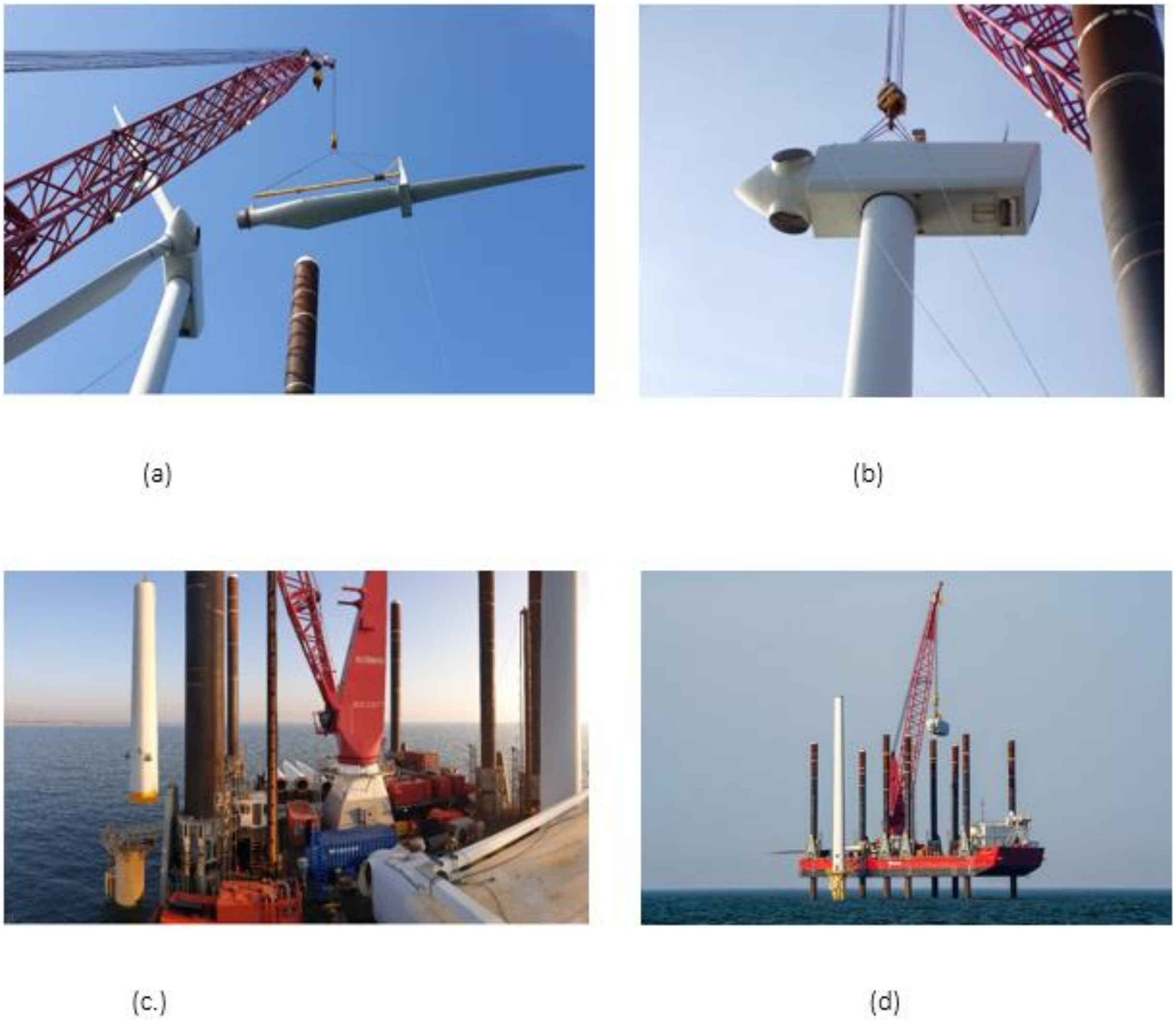

Fig. 20 Dismantling of Blyth wind farm components during decommissioning; (a) Blades (b) Nacelle (c.) Tower (d) Excalibur Jack-up platform, from [50]

2.3 Current Offshore Decommissioning Vessels

Although there are various vessels available for charter, there is no one accurate answer as to which appropriate vessel to utilize for decommissioning [8]. Deck space availability to accommodate number of turbines and foundations to be removed, crane capacity for lift operations, market availability, and site water depth and seabed type are all variables that influence the selection of a vessel [53]. The vessels used for the installation of the wind farm are able to dismantle the wind farms as the removal of the wind turbine system consisting of the rotor, nacelle, and tower can be approached as a reverse installation process. Wind Turbine Installation Vessel, heavy lift vessel (HLV) and cable-laying vessel or vessels with similar capacities carry out the decommissioning [54], where turbine installation vessels refer to any vessels capable of installing turbines or their foundations.

2.3.1 Jack-up Vessels

Jack-ups give a stable platform with no movement in reaction to the seas. As a result, they are suited for a variety of marine operations, and primarily suitable for operations in relatively shallow waters. Non-propelled barges and self-propelled jack up vessels with DP systems are the two main types of jack up vessels. The most common jack ups, however are the non-propelled barges, usually outfitted with four to eight large jacks and legs, made of either of tubulars or fabricated steel. Towed into position by tugboats (see Fig. 21), they employ other specialized vessels to carry out successful lifting operations. When the jack up vessel's legs enter the seabed, all six of the vessel's motions, such as the yaw, sway, heave, surge, pitch, and roll, are reduced to an absolute minimum, making the vessel behave like a fixed structure in its position [7].

For an offshore operation of a jack up vessel, the standard routine begins with the vessel traveling to the location while raising its legs. The legs are dropped to the bottom and allowed to penetrate under their own weight when the sea condition is quiet (waves and swells must generally be less than 1 m). Jetting and vibration might help with penetration in some soils. The legs are driven into the soil by using the jacks on one leg at a time, with the vessel serving as a reaction. The vessel is jacked up clear of the water, with all legs fully entrenched [42].

In the offshore wind industry today, jack up vessels are utilized for the installation (Fig. 22), maintenance [53], and decommissioning [52] of wind farms.

Fig. 21 Jack up barge towed to operation site, from [55]

Fig. 22 offshore jack-up crane vessel Vidar installation of an OWT, from [56]

2.3.2 Heavy Lift Vessels (HLV)

Heavy-lift vessels have high-capacity cranes, no elevating mechanism, and may or may not be self-propelled. The HLV might be mono-hull, catamaran, or semisubmersible, regardless of the kind of installed crane on the vessel, and they can be dynamically or traditionally anchored. Derrick barges, shearleg cranes, and other floating cranes are examples of heavy-lift boats. They are rarely utilized for turbine installation, however they may be employed for foundation construction, transporting fully constructed turbines, or constructing substations [57]. The most significant aspects of an HLV are its stability and seakeeping abilities. Fig. 23, Fig. 24, and Fig. 25 show HLVs in operation.

Fig. 23 Transition pieces transported on an HLV, from [58]

Fig. 24 HLV transporting monopoles, from [58]

Fig. 25 HLV Aegir installing a jacket foundation, from [56]

2.3.3 Cable Laying Vessels

Cable laying vessels are primarily in charge of installing, maintaining, and decommissioning subsea power cables between turbines and shore. The size of the ship is determined by the depth at which the cables are to be laid. Larger boats are utilized to install cables at higher depths, laying one or multiple cables at a time [59]. Large barges or self-propelled vessels, such as pictured in Fig. 26, devoted only to cable laying activities are known as export cable laying vessels. These vessels usually have a turntable capable of spooling over 1000 tons of cable and may also feature an ROV or a cable laying plow [57].

Fig. 26 Cable lay vessel, Connector, from [60]

2.4 Tools and Equipment: OWT Foundation (monopile) Installation and Decommissioning

Monopiles can be installed in a number of different ways. If just one vessel is used, the vessel can carry and install all foundations first, then all transition pieces, or it can transport and install both foundations and transition pieces at the same time and in the same order. A feeder vessel can also convey foundation and transition pieces to be installed. If more than one installation vessel is utilized, they can work independently, with one vessel driving piles and the other installing transition pieces, or they can work collaboratively, with one vessel driving piles and the other installing the transition pieces [61]. The decommissioning of the transition piece and foundation of the offshore wind turbine may be viewed as a reverse installation operation. Both procedures require the use of identical equipment for activities such as lifting and transporting pieces, as well as specialized equipment for operations such as cutting in the case of decommissioning and hammering in the case of installation [54].

2.4.1 Lift and Transport

Monopiles can be hauled to the site by the installation vessel, barged to the site, carried by a feeder vessel, or capped and wet towed. The size and weight of the monopile, the installation vessel's changeable deck load, the crane capability of the installation vessel, the proximity to shore, environmental conditions, and transit speed all influence the decision on lifting and transportation. Large installation vessels with large lift cranes, such as the Sea Jack (seen in Fig. 27), may be able to transport and lift many monopiles from port. Vessels with smaller capacity cranes or deck loads may be unable to lift a monopile clear of the sea and must rely on a wet tow. Specialized vessels called wind turbine installation vessels (WTIV) are vessel specifically designed for the installation and by extension decommissioning of offshore wind turbines. Most are self-elevating, similar to jackup rigs.

Fig. 27 Sea Jack lifting and transporting OWT foundations, from [62]

They are self-propelled to allow for fast mobility inside the wind farm. They also feature a slim ship-shaped hull for speedy turnaround, with the vessel transporting many foundations or wind turbines each time [63]. Pacific Orca, seen in Fig. 28, owned by Swire Pacific Offshore and Blue Amber from Neptun Ship Design are examples.

During loading, when the cargo is placed on the cargo vessel's deck, it must be secured for transit. Before transporting the pieces, the whole sea fixing must be completed. Sea fastening is performed in the same weather circumstances as lifting operations and has the same constraints, guaranteeing, among other things, safe crew working conditions on deck.

Fig. 28 Pacific Orca (WTIV), from [64]

The wind turbine must be lifted to heights of up to 175 meters when building wind turbine parks. For modern wind turbines that will require cranes capacities that can handle the heavy lifts. There are variety of heavy lift cranes used in the offshore wind industry like the Leg Encircling Cranes and Pedestal Mounted Cranes (Fig. 29). The Leg Encircling Crane (LEC), designed expressly for use on jack-up vessels is built to fit around the jack-up leg, and the boom may be placed around the other leg if necessary, conserving important deck space. The LEC features a modest tail swing, which allows for the most efficient use of available deck area [65].

(a) (b)

Fig. 29 (a) Leg Encircling Crane (LEC), (b) Pedestal Mounted Cranes, Source Huisman Equipment

Unloading supply vessels, offshore installation operations, pipe transfer, deck handling, and subsea installation are all activities that pedestal mounted cranes can handle. The minimal tail swing (which maximizes open deck area) and the fact that all drivers are housed within the enclosed crane house distinguish pedestal mounted cranes.

2.4.2 Cutting

Decommissioning offshore wind facilities necessitates extensive cutting work. There are various cutting tool and equipment solutions available, which are comparable to those used in the oil and gas sector. Saws, grinding and oxyfuel, guillotine, scissor, and explosives are examples of common tools. Regardless of cutting equipment and methodology, it is critical to evaluate all safety considerations for the selected procedure, including the safety of people, the environment, and property.

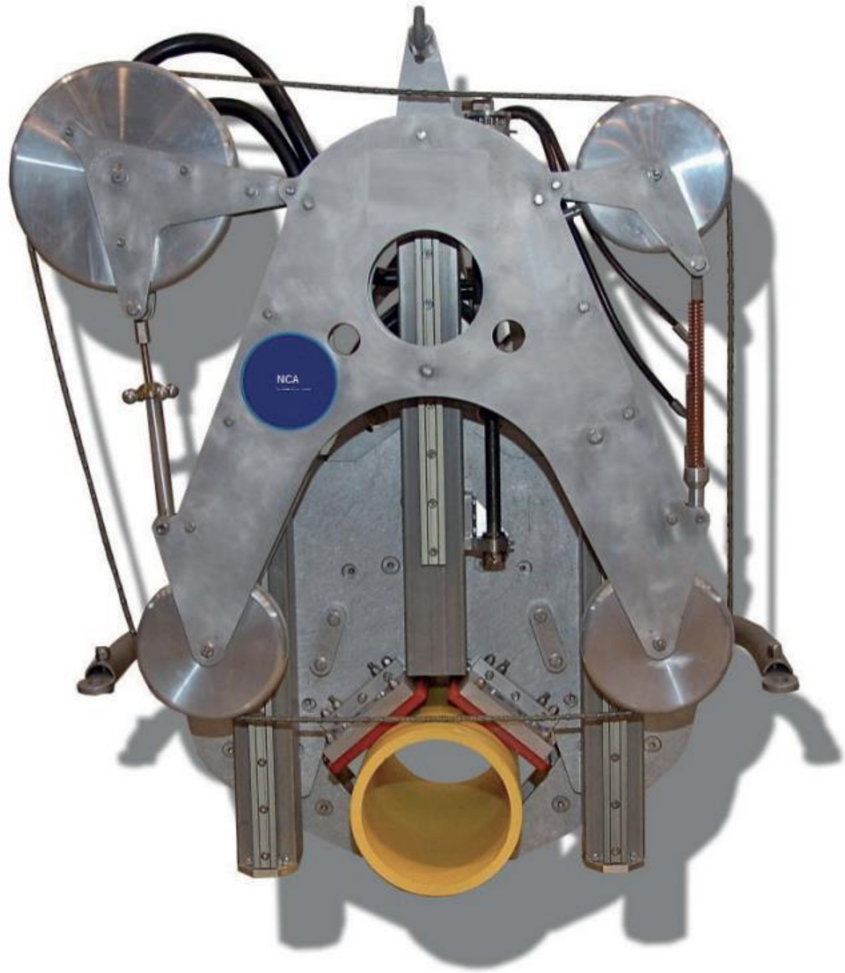

Fig. 30 Diamond wire subsea cutter, Source Oceaneering

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Diamond-wire saw cutter (Fig. 30.): Used to cut a range of materials and projects both subsea and topside. Offshore decommissioning and subsea or topside maintenance are common applications. The cut occurs as a result of the wire's friction against the structure. It has the advantages of having no vibrations, being less polluting, being able to wrap around practically any size or form, and being a cost-effective option. As a disadvantage, it necessitates easy access to the cutting area [8].

Abrasive water jet cutter (Fig. 31.): This cutting tool cuts through steel without creating a heat affected zone. It uses a high-pressure jet of water and an abrasive material. It can cut any material and is readily mechanized, but particles fly off and the environment suffers as a result. It also has greater expenses.

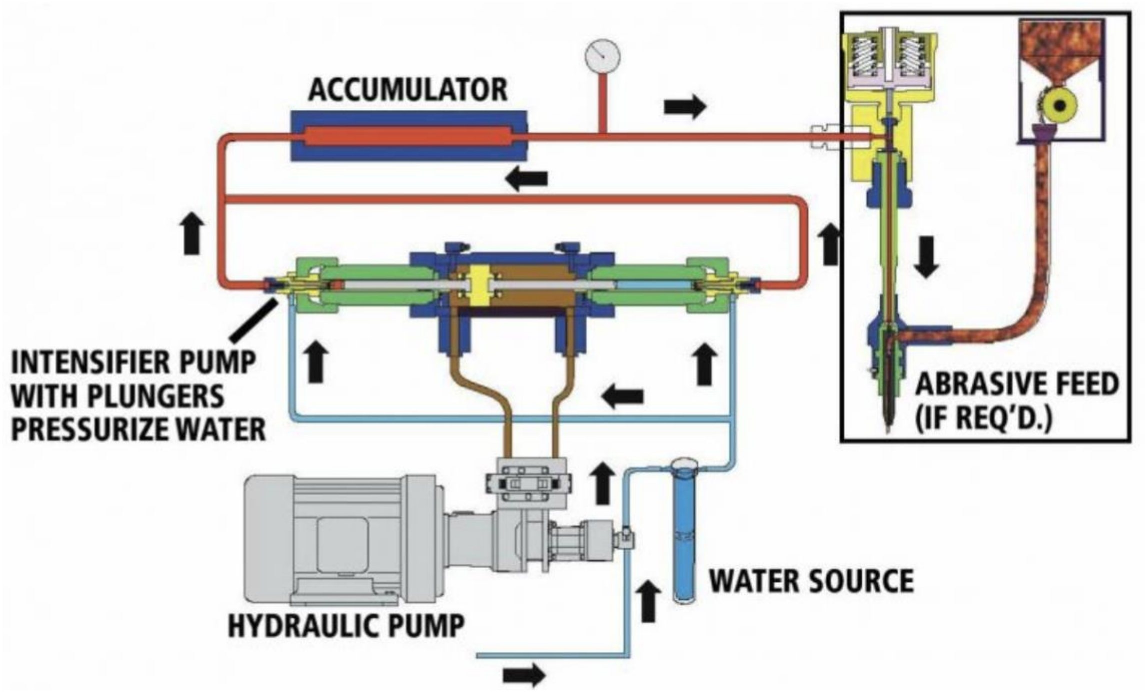


Fig. 31 Schematic of basic AWJ components and set up, from [66]

Fig. 32 Top side application of AWJ, from [67]

The abrasive cutting technique supports the oil and gas industry's decommissioning cost reduction by providing improved performance, cost reductions, and operational efficiency. The system provides improved performance with minimum downtime and a smaller operating footprint owing to its increased accuracy and success rate [68]. An example of its application is in Fig. 32, where the technique is used to cut a steel pile on the top side.

The following is a summary of the core mechanism of AWJ cutting [69] :

- A tiny aperture is used to expel a high-pressure water jet.
- A partial vacuum is created when a water jet travels through a mixing chamber.
- The partial vacuum draws abrasive particles into the mixing chamber.
- Abrasive particles are sucked into the waterjet.
- The abrasive water jet is then focused using a nozzle.
- Cutting occurs when the abrasive water jet contacts with the substance. Depending on the precise qualities of the material being profiled, cutting of the material happens as a result of erosion, shearing, failure under rapidly changing localized stress fields, or micromachining processes.
- The movement is accomplished by a gantry or robot system manipulating the focused jet.
- Process factors such as abrasive mass flow, waterjet pressure, water flow rate, workpiece hardness and stand-off distance affect the cutting rate.

Oxy-Fuel: This is a cutting technology that uses a stream of oxygen to burn the iron out of the steel. One or more gas burners heat the steel to ignition temperature (about 1150°C) in order to achieve combustion. A separate flow of oxygen is directed through the brander's core as illustrated in Fig. 33. This causes oxidation, which causes the steel to burn and release a lot of heat, keeping the cut process going both through the metal and in the cutting direction. The kinetic energy of the stream of oxygen forces the iron oxide, or slag, generated during the operation out of the kerf, leaving a clean-cut edge. The purity of the oxygen, which must be at least 99.5 percent, determines the quality and cutting speed of the resultant cut to a greater or lesser extent [70].

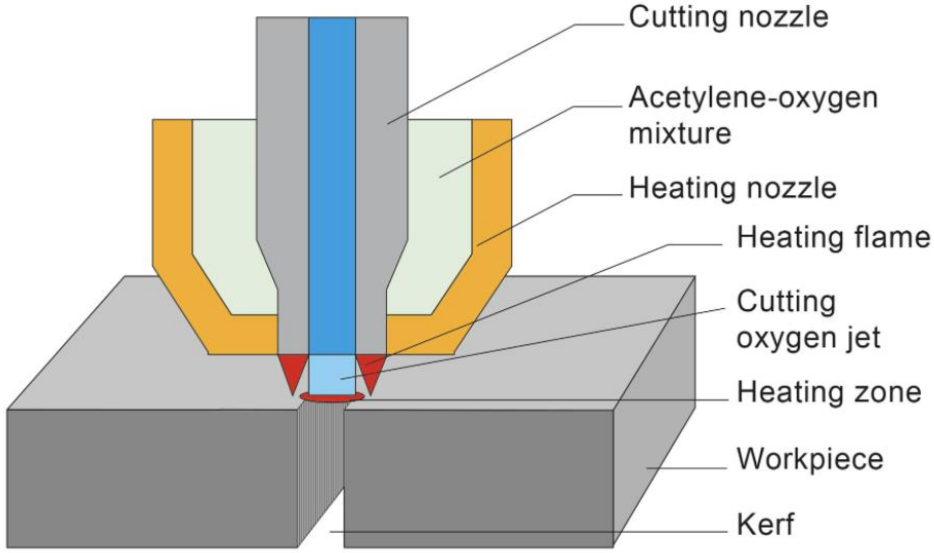


Fig. 33 Oxy-Fuel cutting, from [71]

Plasma Cutting: The plasma arc technology has long been thought of as a viable alternative to the oxy-fuel process. The procedure is depicted in Fig. 34. The arc created between the electrode and the workpiece is restricted by a fine bore copper nozzle in the basic concept. The temperature and velocity of the plasma emerging from the nozzle are thus increased. The plasma has a temperature of over 20 000°C and a velocity that approaches that of sound. When the plasma is used for cutting, the gas flow is increased such that the deeply penetrating plasma jet cuts through the material and the molten material is removed in the efflux plasma.

The plasma process varies from the oxy-fuel process in that the arc is used to melt the metal, whereas the oxygen oxidizes the metal and the heat from the exothermic reaction melts the metal in the oxy-fuel process. Unlike the oxy-fuel technique, the plasma process may be used to cut metals such as aluminum, cast iron, stainless steel, and non-ferrous alloys that generate refractory oxides [72].

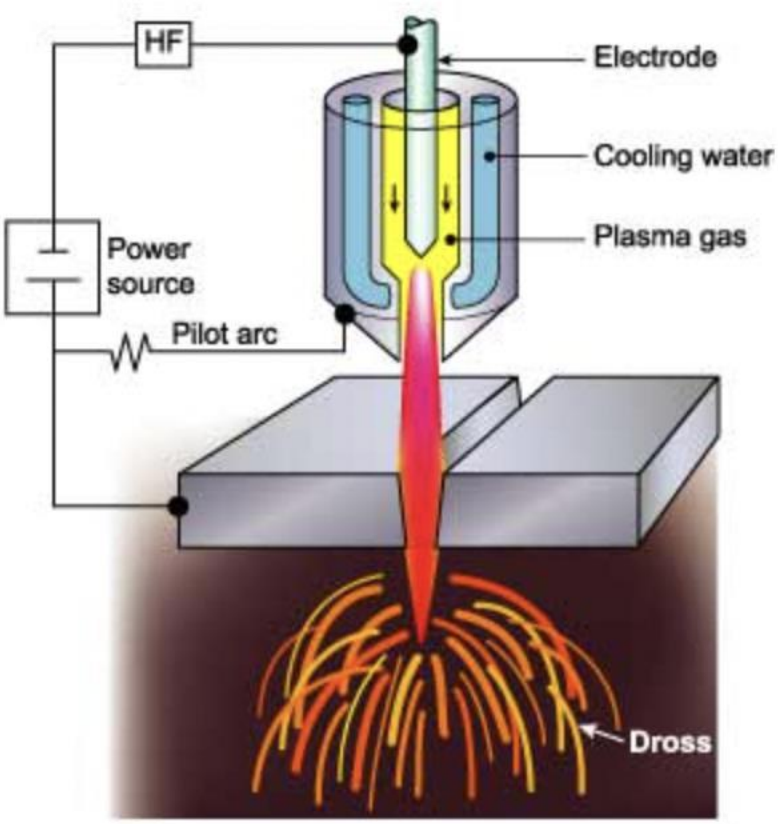


Fig. 34 Plasma arc cutting process, from [72]

Pros and Cons of cutting tools and techniques:

The two most popular cutting methods with the longest track records for pile separation are abrasive water jet cutting and diamond wire cutting, which are the two most favored procedures for operators and contractors in the decommissioning business. Abrasive cutting is three times quicker than diamond wire cutting on average. The abrasive cutting spread, on the other hand, is more expensive to deploy and requires more professional and experienced staff, as well as a higher number of personnel on board (POB) [73].

However, if there is limited deck area, the diamond wire cutting approach may be preferable since it can be done with ordinary saws and allows for longer cut times. Pile size, deployment, and installation are additional important factors to consider while making a decision for tool selection. Table 4 lists the benefits and drawbacks of various cutting tools and techniques.

Table 4 Advantages and disadvantages of cutting tools, from [74]

	Advantages	Disadvantages
Oxy-fuel	Low capital cost	Mostly restricted to kiln and alloy steels
	No electrical requirements	Stainless steels and aluminum are less suitable.
	Consumable costs low	Wide heat affected zone (HAZ)
	Manually or mechanically operated	Parameters, torch nozzle, and plate surface condition all effect quality.
	Transportable	
	Can be used to cut thick sections	
Plasma	Low consumable costs	When cutting in the air, arc glare occurs.
	Narrow heat affected zone	Relatively large cut width
	High quality cut edge	Fume when cutting in air
	Wide range of materials including stainless steel and aluminium	Noise when cutting thick sections
	When cutting underwater, the fumes are minimal.	costs of consumables such as electrode and nozzle
	Ideal for this sheet material	Typically limited to 50mm (air-plasma) plate
Diamond wire	High flexibility of applications	
	Mobile units with short set-up periods and a small size and weight	Workpiece has to be firmly affixed to avoid pinching the wire
	no restrictions on cutting depth or work piece form	High tool wear
	High accuracy of the cut	High risk through snipping diamond wire
	Low personnel costs	Relatively coarse cutting surface
	Easy machine handling	
Abrasive water jet	Hazardous (explosive) environments	Abrasive cost (cannot be recycled)
	Wide range of metals and non-metals	Safe handling of water jet
	Minimal distortion	Wide cut width
	No heat generated	Noise
		High capital cost
		Containment of water

2.5 Environment

2.5.1 North Sea Region (NSR) Area

Europe's North Sea Region (NSR) refers to European nations and territories with access to the North Sea. The coastal areas around the North Sea region will include the entire territory of Denmark and Norway, the eastern parts of the United Kingdom, the north-western regions of Germany, the south-western area of Sweden, three provinces of Belgium's Flemish region, and the western and northern parts of the Netherlands [75] as illustrated in Fig. 35 . The North Sea, an area covering approximately 850,000 square km (Fig. 36), is a semi-enclosed sea on the continental shelf of northwestern Europe. It is bordered by the coastlines of the United Kingdom, Scotland, Norway, Denmark, Sweden, the Netherlands, France, Germany, and Belgium. The sea is shallow in the south and shallower in the north, with depths of up to 725 meters in the Skagerrak [76]

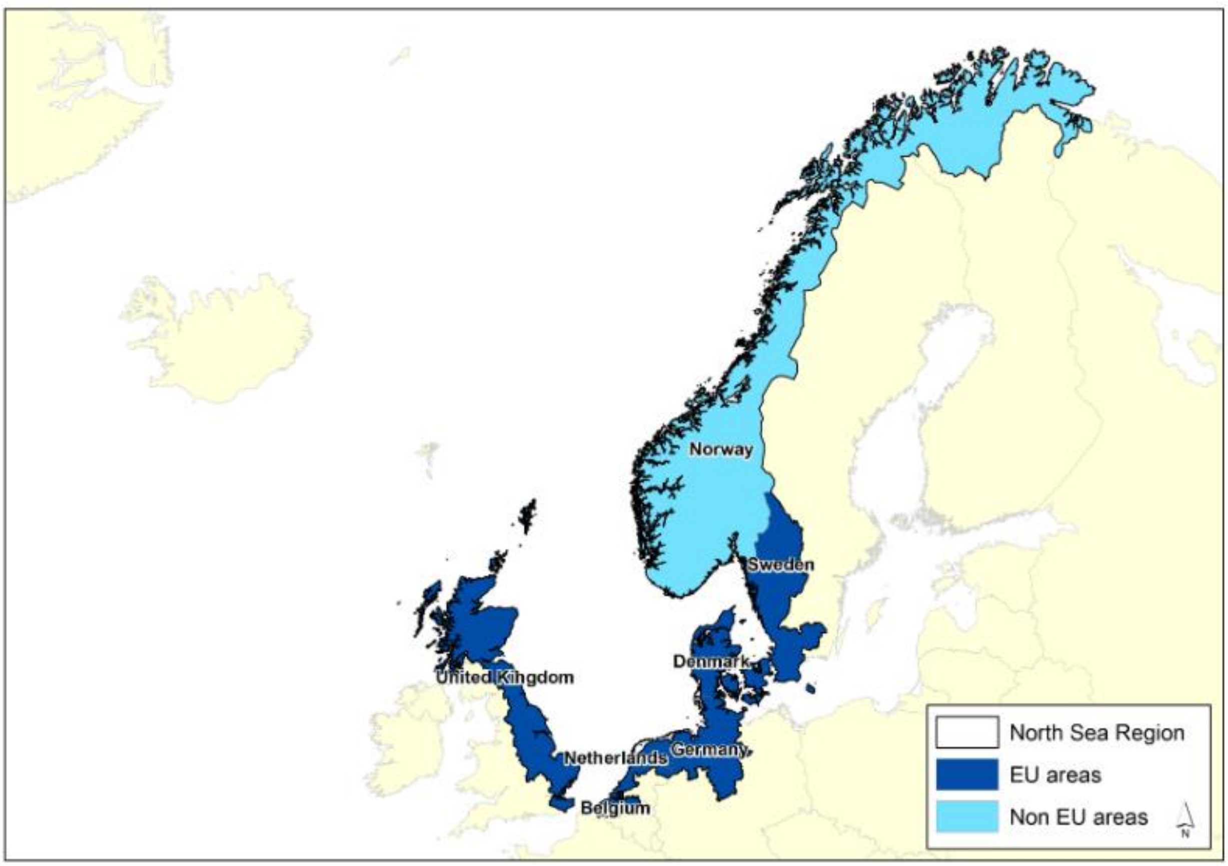


Fig. 35 Countries making up the NSR territory, from [75]

The North Sea now features the world's highest concentration of offshore wind arrays (wind farms), most of which were built in recent years in response to the Renewables Directive

(009/28/EC). Shallow waterways, regular and strong wind speeds, and closeness to electrical demand centers are all indicators of their location [77].

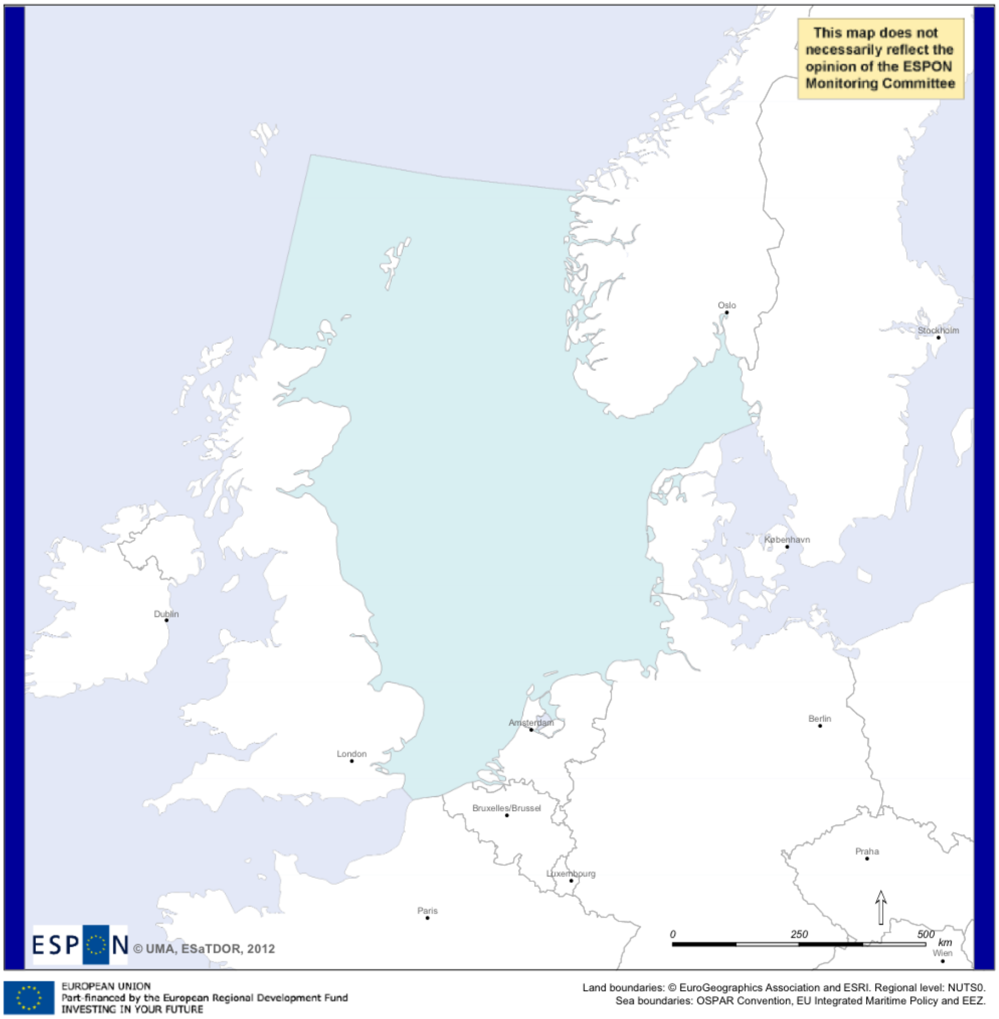


Fig. 36 North sea boundaries, from [77]

2.5.2 Sea and Seabed Characteristics

The North Sea is shallow in comparison to other European regional seas, with an average depth of 90 meters and a maximum depth of about 700 meters (Fig. 37). The 50-meter isobath represents the shift from shallow, well-mixed turbid waters typical of the southern North Sea and beaches to deeper, seasonally stratified waters to the north [77], [78]. The seabed is mostly sand, mud, sandy mud, and gravel, with a wide range of marine sceneries such as fjords, estuaries, sandbanks, bays, and intertidal mudflats.

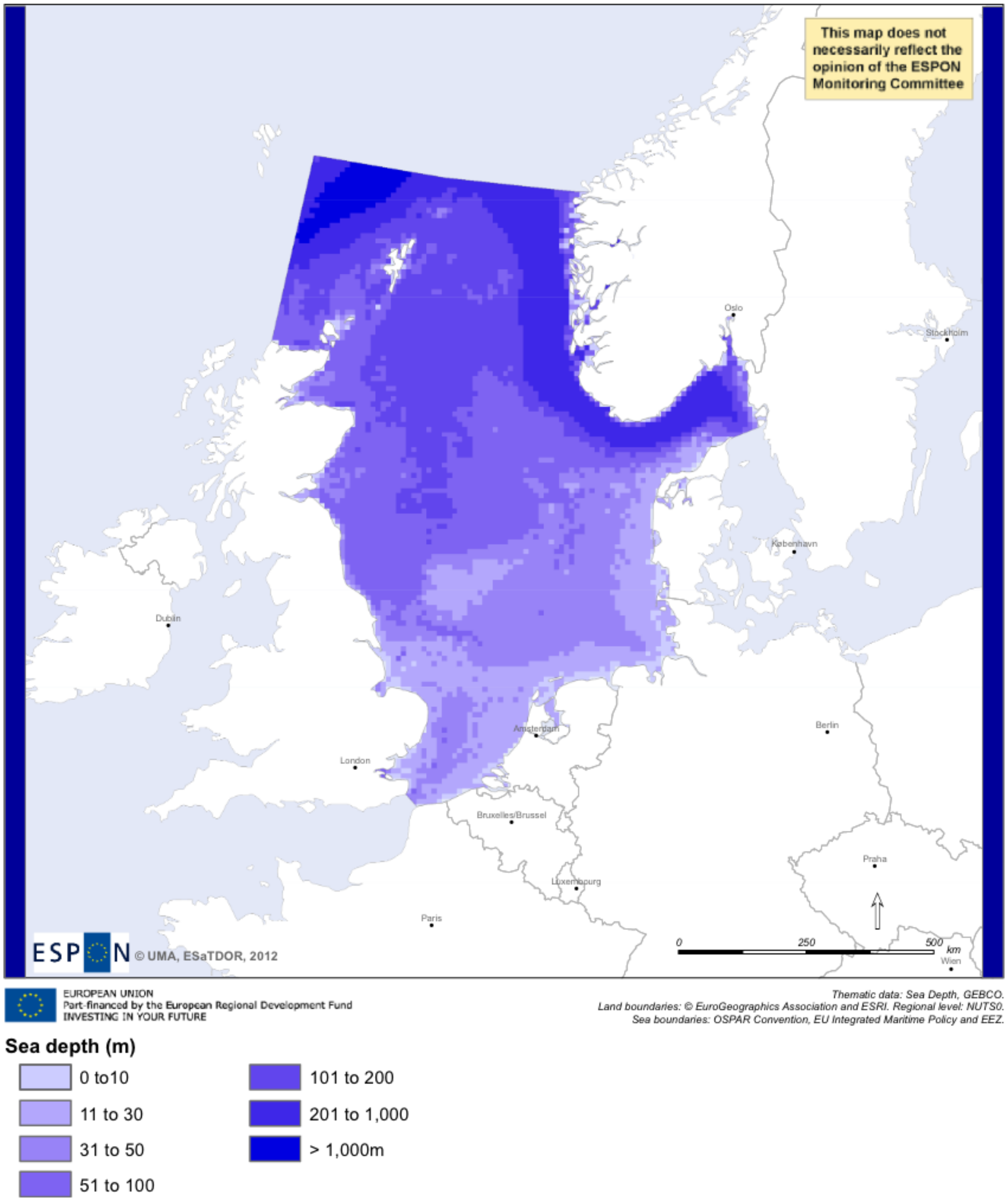


Fig. 37 Sea Depth (NSR), from [77]

The climate of the North Sea is heavily impacted by the entrance of oceanic water from the Atlantic Ocean, as well as the large-scale westerly air circulation, which regularly features low pressure systems. Extreme weather has a direct influence on hydrography, which is characterized by strong tides and water exchange with adjacent ocean areas [78].

2.6 Current Offshore Wind Decommissioning Options and Concepts

The decommissioning activities will be mostly determined by the kind of foundation. Due to the enormous lifting required by the foundations' considerable weight, specialized boats are necessary. The offshore wind foundations are often the largest mass in a wind turbine installation, and there are two techniques for decommissioning these structures once the turbine has been removed, which are complete removal or removal to a distance below the seabed and leaving the rest of the pile in situ. In both circumstances, all structural fabrications such as J-tubes and access ladders will be removed. After complete removal, some landfilling will be required to fill the inevitable hole. While partial removal does not necessitate this cost, the expenses of cutting the foundations are often rather substantial. Cutting and leaving the remainder in place is typically the preferred choice since it eliminates hazards, is more cost-effective, and causes less disruption to the site [8]. As previously mentioned, depending on the type of foundation, the removal procedures will be rather different. In this study, however, we will only explore the monopile foundation.

2.6.1 Partial Removal

Only a few offshore foundations related to offshore wind energy have been decommissioned in Europe thus far [31]. The decommissioned (mono)piles in most cases were cut just below the mud line. To create the cut at the desired height, mechanical casing cutters, diamond wire, abrasive water jets, or explosives can be employed; the choice is based on technical feasibility, environmental circumstances, regulatory alternatives, and corporate preferences. Internal and external monopile cutting are two methods for cutting beneath the mud line.

External pile cutting, as Fig. 38 illustrates, which entails dredging or digging the soil around the pile to the desired depth is one such option. Once the desired depth is achieved, the cut can be made by divers or a remotely operated cutting instrument. The restricted operation depth and maritime environmental implications of this technology might be disadvantages. The precision of the dredging tool or excavator reduces below a certain working depth [4]. If a diver operation is required, the water depth is an important consideration in the decommissioning process. The exterior cutting process is heavily influenced by the sea environment (tide, current, and waves). External cutting is thus most commonly utilized in shallow water. Remotely operated vehicles (ROVs) or hard-shelled diving suits are commonly employed for deep water cutting activities.

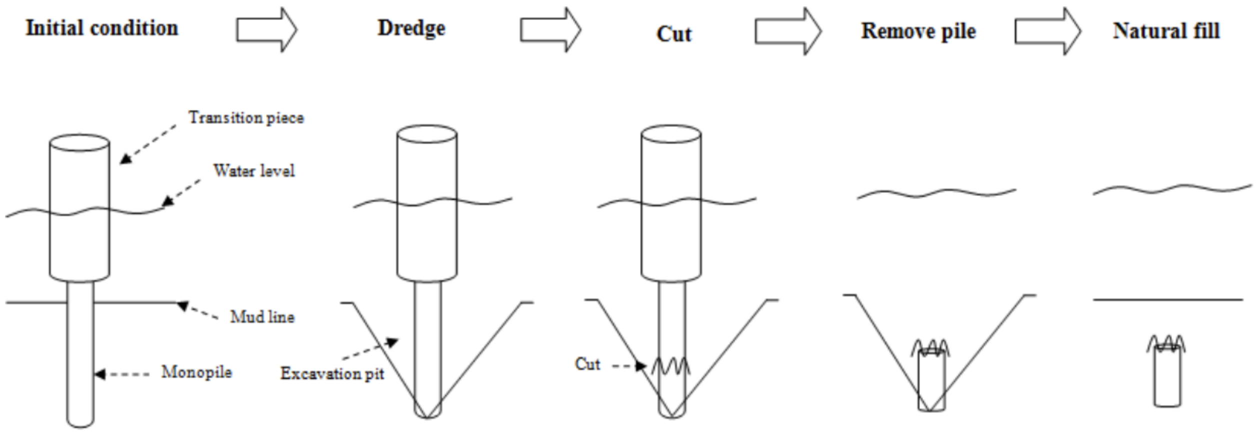


Fig. 38 External cutting during foundation removal, from [61]

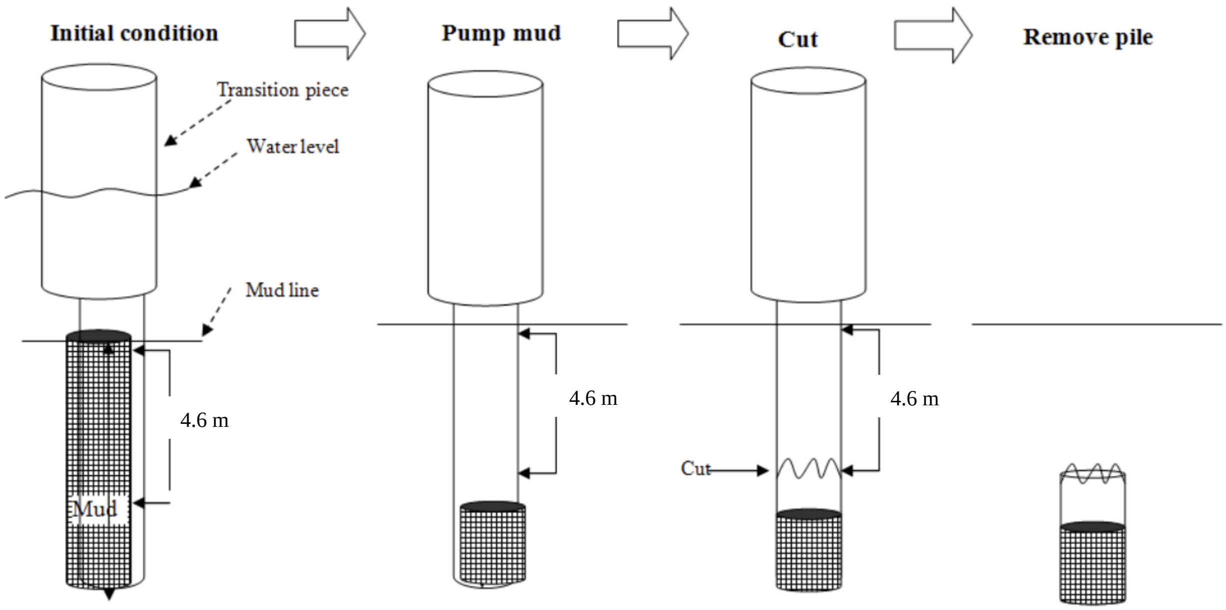


Fig. 39 Internal cutting during foundation removal, from [61]

The internal pile cutting method is depicted in Fig. 39. Mud is pumped and jetted from the inside of the monopile to the predetermined below mudline depth for an internal cut. After removing the interior dirt or plug, the cutting tool may be lowered to the desired depth, secured, and the cutting operation can begin. Internal cutting, as opposed to external cutting, is protected from environmental consequences by the (mono)pile. Because scour protection would increase the expense and complexity of an external cut, inside cuts are considered to be more plausible [61].

2.6.2 Complete Removal

As previously stated, partial removal of offshore wind monopile foundations, particularly the residual pile stump in the soil, has various drawbacks and risks. The entire pile should be extracted from the seabed to reduce the negative environmental effect and hazards. Some offshore wind foundations, such as the Lely offshore wind farm in the Netherlands, have been decommissioned by removing the entire pile using oil and gas industry techniques. Several projects are developing innovative wind farm decommissioning approaches that aim to attain similar goals. Some of these techniques and concepts are examined.

Vibration

Onshore, vibratory pile drive is an approved method for pile installation and extraction, and it looks to be one of the most promising techniques for offshore monopile decommissioning [79]. The lowering of shear resistance along the pile shaft-soil contact is the core principle of vibratory pile drive. The vibro hammer and pile system must be in a constant up and down action in order to eliminate

Fig. 40 Vibrator on an offshore monopile, from (Wassink, 2018)

shear resistance and hence pile shaft resistance. The vibro hammer is permanently linked to the pile head for installation and retrieval of piles. The vibro hammer's vertical movement or oscillation is caused by counter rotating eccentric masses, as seen in Fig. 40 [80]. Continuous agitation of the earth around the pile causes the soil to lose its particle structure, resulting in liquefaction. During this decommissioning process, the shaft resistance tends to zero, and the crane just has to raise the weight of the pile and the hammer [81].

Hydraulic Extraction Technique

Another approach for overcoming total breakout resistance is to employ hydraulic force to lift the pile off of the seafloor, as illustrated in Fig. 41. The Hydraulic Pile Extraction Scale Tests (HyPE-ST) project is one such example. With this approach the pile is sealed after removing the top structure of the wind turbine, and the void is filled with water and pressurized, driving the pile to move up once the inside pressure on the pile cap exceeds the pile resistance.

The research successfully proved the hydraulic extraction method for various soil configurations, defined the necessary pile extraction parameters, and created a model to estimate the breakout pressure. On the tested scale, the breakout pressure was shown to be strongly dependent on soil type and soil layout. Although the project is not yet completed as the demonstration of the extraction technique offshore is scheduled for later. By 2025, the monopile hydraulic extraction process is projected to be ready for commercial use [82].

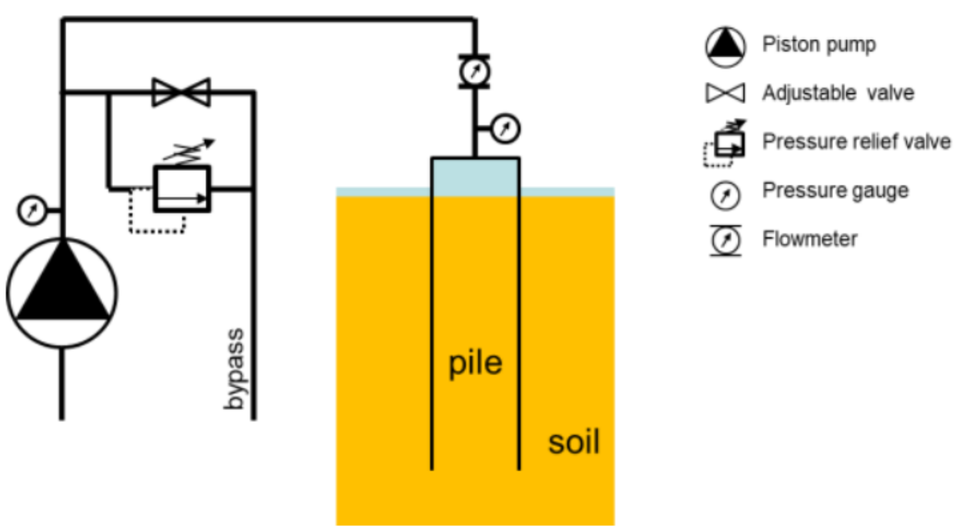


Fig. 41 Schematic overview of HyPE-ST set up, from [83]

3.0 DATA AND METHODS

3.1 Introduction

This chapter provides an extensive explanation of the theoretical and philosophical foundations of the research. It further explains the data collection approach, methodology and analysis applied to answer the research questions.

3.2 Data Collection

As the research is based on the concept vessel design, most of the data was collected from the thesis work, "Decom Tools Vessel Design - Presenting an Eco-Sustainable Approach to Decommissioning Offshore Wind Park by designing a New Ship, New Tools and efficient and reliable procedures". Data such as the maximum buoyancy force, maximum vessel draft change, equipment types, and physical system interactions were sourced from the work. Data was collected from files and papers from the Decomtools project. We also collected data from Original Equipment Manufacturers (OEMs), and a number of Industrial suppliers.

Finally, data from books and research papers were accessed from online libraries, and other online sources such as electronic journals, videos, and references to selected projects in the European Union (EU) decommissioning portfolio.

3.3 Methodology and Analysis

The research methodology begun with online research for literature review on the offshore wind farm decommissioning industry. The familiarization with common practice and methods used in the industry was an important component of the preparation work for this study. It also included the in-depth study of the primary source material, which is the Decomtool vessel conceptual design, and particularly the monopile extraction system. An on-going detailed design on the gripper mechanism being developed in HVL also served as a bases for analyzing the individual components.

As discussed in Chapter one, this thesis aims to evaluate the technical feasibility of the monopile extraction system of the concept vessel design proposed under the Decomtools project. The evaluation of the technical feasibility focused on the gripper support beam, the cutting tool and method, and the gantry crane equipment.

In assessing the technical feasibility of the support beams for the gripping mechanism, we evaluate the beam support for failure based on the expected loads or forces acting on the members during the extraction process. We use the maximum design force delivered by the vessel as referenced in the concept vessel design thesis. We assumed the buoyancy force that is transmitted to the gripper is evenly distributed to all beam support members. Utilizing the engineering design software tool Autodesk Finite Element Analysis (FEA), we simulate the behavior of gripper beam support members under the expected forces to obtain stress values. Finite element analysis (FEA) is a computational approach for predicting how a product will react to physical forces, fluid movement, vibration, heat, and other physical phenomena. Most of these phenomena may be analyzed using partial differential equations, but in more complicated cases involving numerous highly variable equations, Finite Element Analysis becomes a very valuable technique. The FEA determines if a part will break, wear out, or perform as intended [84].

The stress values obtained from FEA are compared to designed calculated values for allowable stresses and bending moments using construction steel i-beams. The FEA also shows deflections as a result of the simulated load interactions.

A basic engineering design calculation is used to estimate the power rating for a hydraulic unit, and subsequently its footprint on the vessel deck. This approach is mainly founded on the movement mechanism of the gripper arm. The movement is controlled by a hydraulic cylinder powered by the hydraulic unit on deck. The force exerted on the gripper arms is a product of the force of the fluid in the cylinder, and the cylinder piston arm length (moment). Theoretically, a small fluid force coupled with a long piston arm will generate enough momentum to control the gripper arms. The cylinder design was not considered in the scope for this work, however, by selecting available cylinders with specific characteristics, we obtain the required power rating in watts for the hydraulic unit. We then select available hydraulic units of equivalent ratings and determine their footprint from the supplier data sheet.

The Horns Rev1 wind farm is used as a base case for evaluating the cutting tools and methods, with regards to expected cutting time, and footprint of the entire equipment required. It involved using documented experiment data of average cutting time with reference to cut material (mild steel in this case) and material thickness. Using this data, and the data obtained from the Horns Rev1 monopile foundation we estimate the total cutting time for that project. The cutting time was then used as the basis to calculate the gas consumption for the operation, and subsequently the footprint of the entire equipment, which is largely due to the gas cylinders for the oxy-fuel cut method.

We evaluate the gantry cranes on the suitability to the operation based on documented industrial experiences. We examine the availability of gantry cranes with equivalent specification within the offshore industry, and estimate the footprint.

4.0 DECOM TOOLS VESSEL DESIGN (MONOPILE EXTRACTION SYSTEM)

As part of the Interreg North Sea Project, a vessel is designed to resolve the bottlenecks in the decommissioning of offshore wind parks, and to reduce emissions and environmental impact of such operations. The concept vessel design (seen in Fig. 42 and Fig. 43) in the thesis "DecomTools Vessel Design – Presenting an Eco-Sustainable Approach to decommission Offshore Wind Park by designing a New Ship, New Tools and efficient and reliable procedures", entails the design of a concept multi-function, multi-purpose, efficient, green vessel, with new concept tools, that is reliable and safe for offshore wind industry operations.

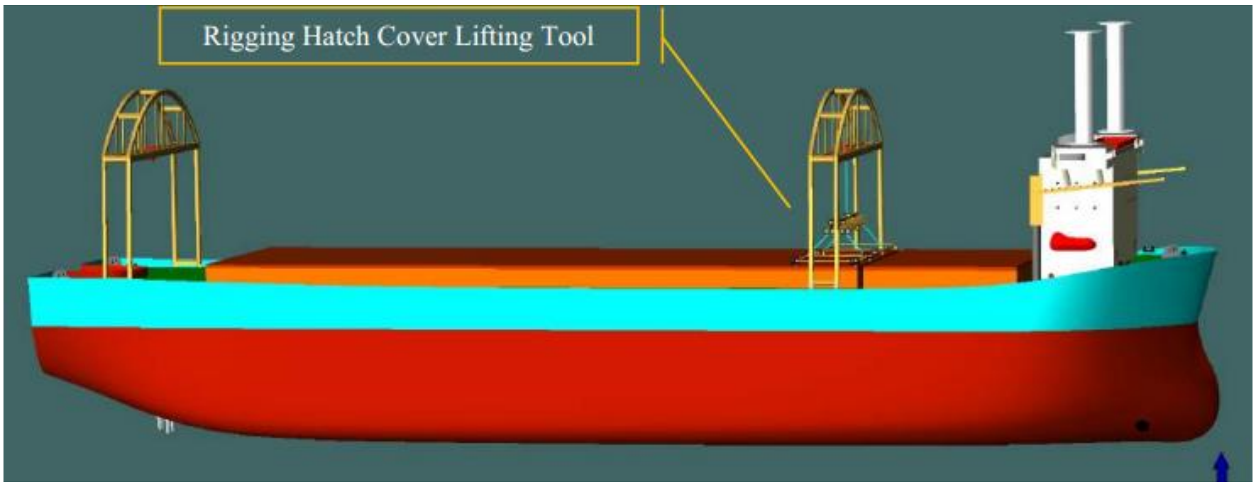


Fig. 42 Side view of concept Decomtools vessel, from [7]

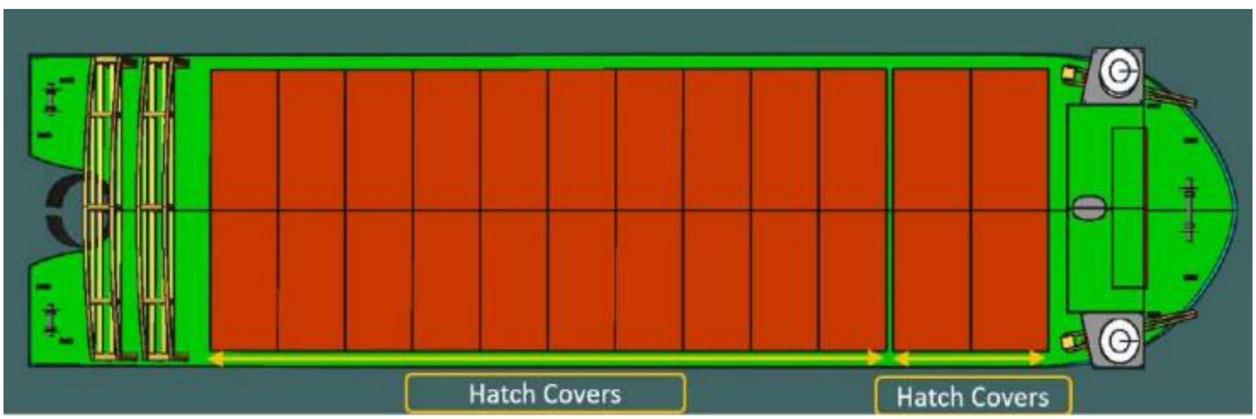


Fig. 43 Top view of concept Decomtools vessel, from [7]

According to the authors, the decomtools vessel is a green and hybrid state-of-the-art vessel that can be utilized for both installation and decommissioning of offshore wind parks and has characteristics as listed in Table 5. The design is based on the largest wind turbine ever installed, the GE designed and manufactured 12MW X-Heliade wind turbines [7, p. 224], [85]. Askari and Halimah state that their vessel concept design meets the requirements for decommissioning smaller offshore wind turbines in the same way that it satisfies the requirements for decommissioning larger offshore wind turbines.

The vessel performs complete decommissioning of a wind farm, which includes dismantling of wind turbines, removal of foundation and cables, and transportation of decommissioned parts to shore. It is outfitted with the equipment necessary to carry out these operations effectively, drastically reducing operating times for these processes with the goal of lowering costs and emissions. It also provides an innovative approach to various procedures.

Table 5 DecomTools Vessel Specifications [7]

SPECIFICATION OF MULTI-PURPOSE AND MULTI-FUNCTION GREEN DECOM TOOLS VESSEL		
Vessel Name	Decom Tools Vessel	
Dimensions (m)		
Length overall	195	
Breadth overall	48	
Moulded depth	26.5	
Summer Draught	19.762	
Summer Freeboard	6.738	
Tonnage (tons)		
Lightweight	20741.78	
Summer Deadweight	132322.2	
Summer Displacement	156064	
Main Machinery and Equipment		
Main Cranes	2 x Gantry Crane	750 tons (Each)
Provision Cranes	2 x pedestal Crane	50 tons (Each)
Pile Extraction System	Hydraulic Grippers	Extract with Vessel buoyancy
Pile Cutting (tool) System	Oxy-Fuel	
Cable Recovery System	Winches and rollers	Holding with Hydraulic clamp
Cable Cutting System	Hydraulic shear Cutter	

This work focuses on the decommissioning aspect of the vessel, and evaluates the technical feasibility of the vessel's extraction system for the monopile foundation of the wind turbines. It assesses the viability of the extraction system's primary components in terms of loads, space, and market availability for design requirements.

We utilize the Horns Rev 1 wind farm as a case study in our assessment.

4.1 Horns Rev 1

Horns Rev 1 is the first phase of Horns Rev, a three-phase offshore wind farm in Danish waters in the North Sea. It had a total capacity of 160 MW and was the world's first large-scale offshore wind farm, the first in the North Sea, and the first to employ the monopile foundation type [86]. The farm is equipped with 80 Vestas V80 wind turbines, each generating 2.0 MW.

Horns Rev 1 is about 18 kilometers from shore, and the sea depth ranges from 6.5 to 13.5. A monopile steel pipe and a transition piece make up the foundation. As illustrated in Fig. 44, the monopile steel pipe is 4 m in diameter and is driven approximately 28 m into the seafloor. The monopile foundation features scour protection in the form of stones of various sizes with a diameter of around 25 m [87].

The dimensions of the Horns Rev 1 wind turbine foundation is summarized below in Table 6

Table 6 Horns Rev 1 wind turbine monopile foundation dimensions [86]

Monopile (Horns Rev 1)	
Penetration [m]	approx. 28
Water depth [m]	13.5
Outer diameter [m]	4
Length [m]	42
Weight [t]	approx. 230
Wall thickness [m]	0.05

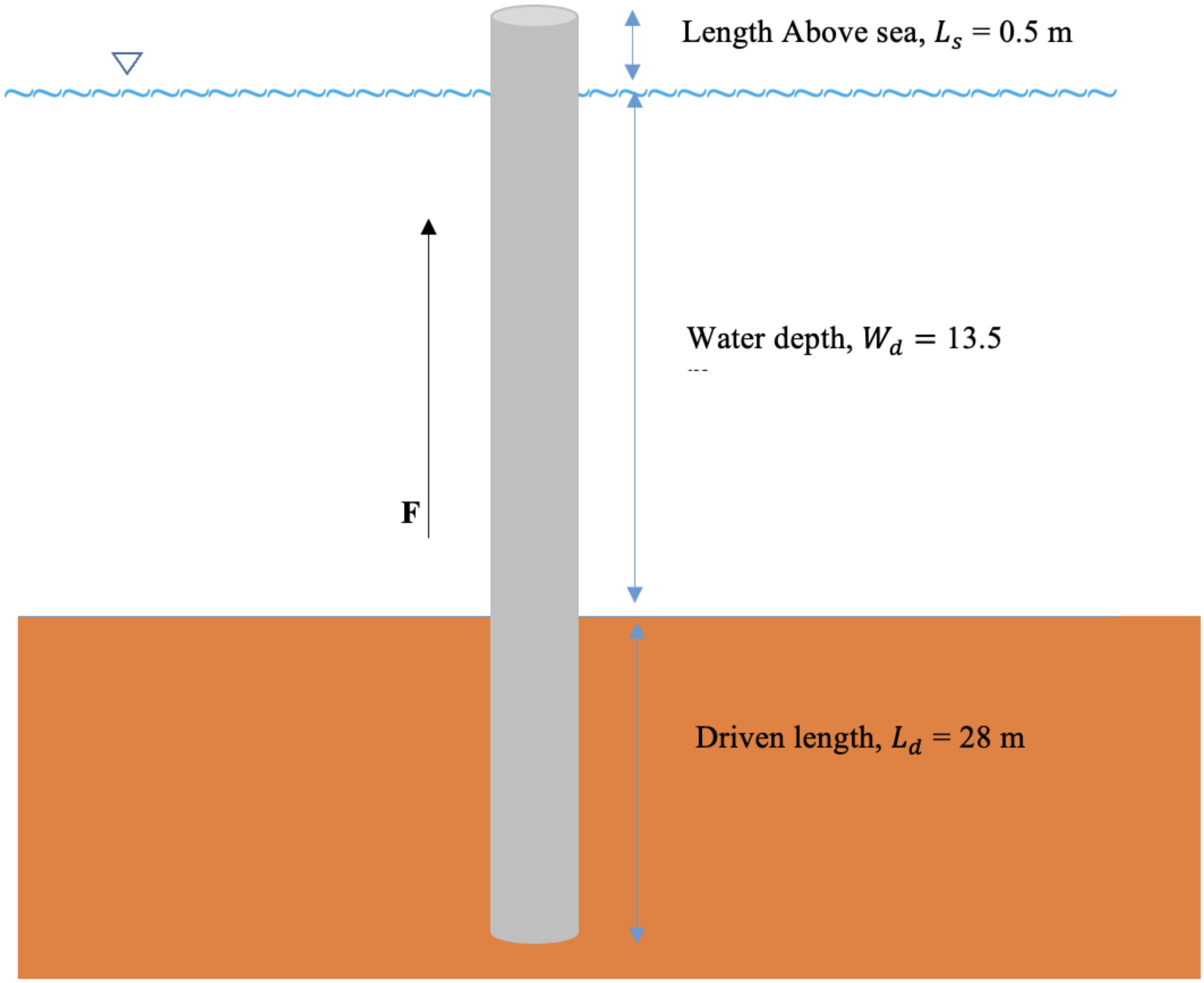


Fig. 44 sketch of Horns Rev1 monopile profile in seabed

4.2 Extraction System

In the decomtools vessel design, Askari et al [7] aim to demonstrate using a conceptual design that full removal of a monopile foundation is possible without the need of high-energy-demanding equipment such as a vibratory hammer. It has been demonstrated that pile extraction is achievable by utilizing the capabilities of the floating vessel.

The objective is to utilize the buoyancy force of a floating vessel to remove the monopile from the seafloor during decommissioning. A change in buoyancy will provide the uplifting force necessary to overcome downward forces acting on the monopile for a successful removal. This is achieved by varying the ballast of the floating vessel, changing its draught accordingly. When the uplifting force created exceeds the downward forces acting on the monopile, a successful extraction is theoretically feasible.

The Decomtool vessel is equipped with a mechanical extraction system to do this. It is specifically designed to retrieve monopile foundations. The extraction system's primary function will be to remove the full length of the pile from the seabed, as well as to facilitate the cutting of the retrieved monopile into smaller pieces and the arrangement of the cut pieces on the vessel's deck. Fig. 45 shows the design of the pile extraction system of the decomtools vessel.

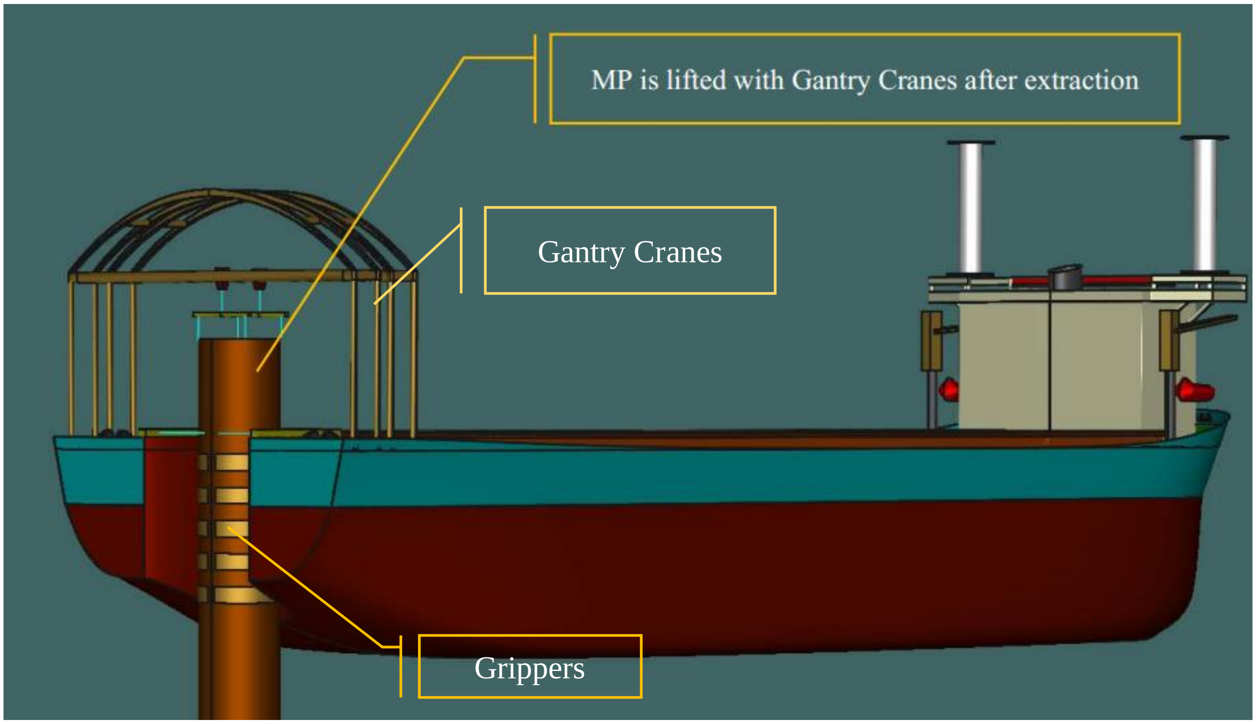


Fig. 45 Monopile extraction system of Decomtools vessel showing gripper, from [7]

The Decomtools pile extraction system is made up of three major components: a gripper, a pair of gantry cranes, and cutting tools, which will be analyzed in depth in subsequent sections. The vessel's aft is built to accommodate these components, and the size of apertures and position of the system on the vessel are illustrated in Fig. 46 and Fig. 47.

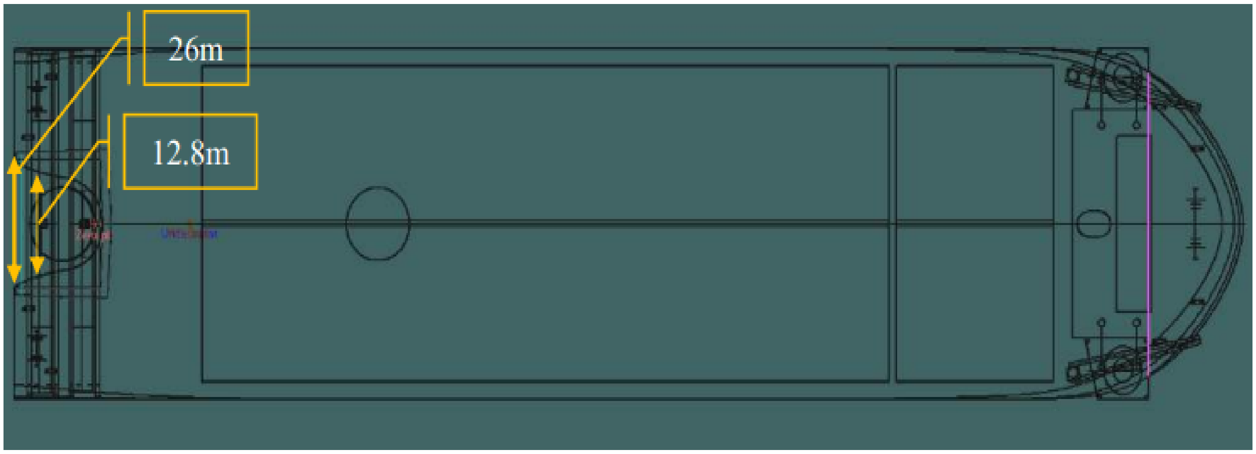


Fig. 46 Dimensions of apertures of Decomtools vessel monopile extraction system, from [7]

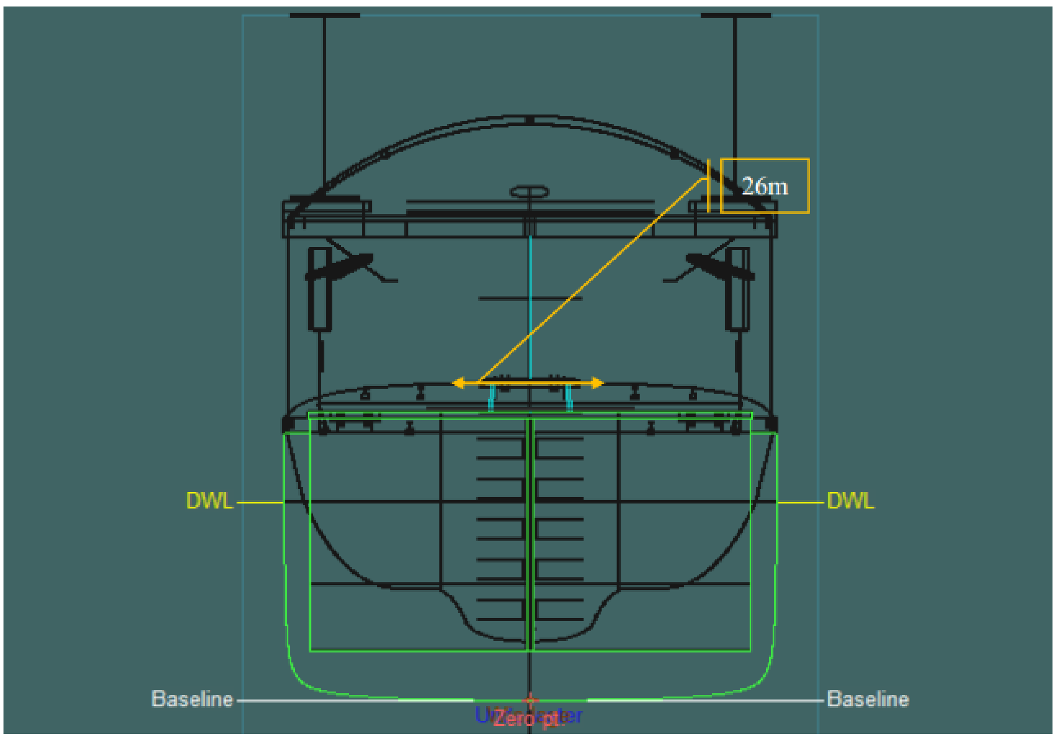


Fig. 47 Position of Monopile Extraction System on vessel, from [7]

4.3 Forces on Monopile

To remove a monopile from the seabed, the pile loading capacity must be exceeded. This load capacity is achieved by skin friction - developed between the monopile and the soil - along the pile's walls or end bearing pressure on the pile's end [88]. It consists of shaft and toe resistance, with the former being further divided into outside and inside resistance for hollow piles. However, by mobilizing shaft resistance alone, piles can offer resistance to uplift (tension) loads as in the case of decommissioning [4], [88]. Fig. 48 illustrates, the direction of load and pile slenderness influence on resistance in the soil (seabed).

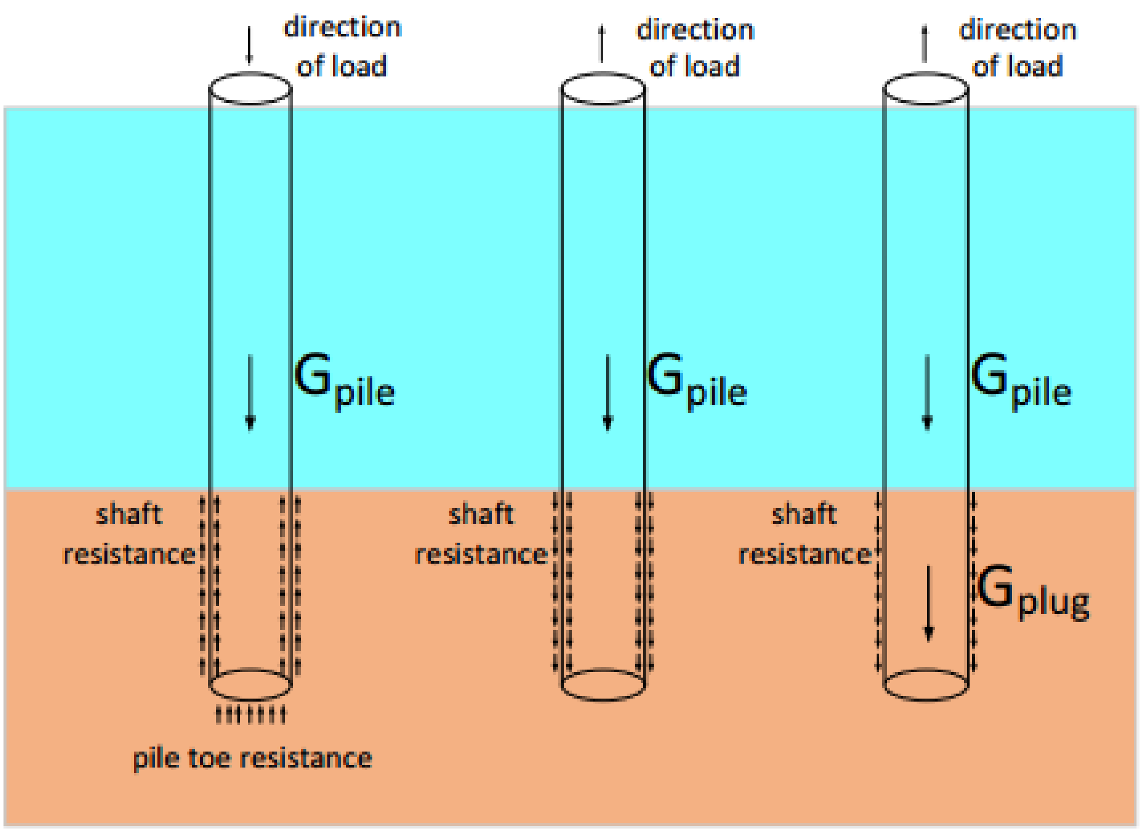


Fig. 48 Simplified pile resistance: Driving force (left), Uplifting force (center), Uplifting force slender pile (right), from [4]

To analyse the forces acting on the Decomtool vessel gripper, which is the main component for extracting the pile, a determination of the resistant force to be overcome is required. As indicated by Hinzmann et al. [4], this force, which is the maximum breakout resistance, F, comprises of the monopile weight and total shaft resistance as a consequence of skin friction between the earth strata and the pile. Mathematically, this is represented by:

$$F = \sum F_{s,r} + W_{mp} \quad (1)$$

$$F_{s,r} = F_{int.wall} + F_{ext.wall} \quad (2)$$

Where:

$F_{s,r}$ = Total shaft resistance

W_{mp} = Weight of Monopile

$F_{int.wall}$ = Internal shaft resistance

$F_{ext.wall}$ = External shaft resistance

4.4 Vessel Bouyancy and Forces

As previously stated, the bouyancy of the floating body is leveraged to extract the monopile from the seafloor. This will necessitate adjusting the vessel's ballast in order to maintain appropriate vessel stability. To accomplish this, the Askari et al [7] recommended that the center double bottom ballast tanks stay full while the remaining ballast tanks be totally emptied or filled, causing the vessel to rise or sink, and that the procedures be performed at an even keel draft. Table 7 shows maximum and minimum ballast characteristics of Decomtools conceptual vessel.

Table 7 Decomtools Vessel at maximum and minimum ballast for monopile extraction, from [7]

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

The difference in drafts for maximum and minimum recommended ballasts determine the maximum height of pile extraction for each attempt. The tonnage of ballast water required to be pumped out, that is, the difference between the maximum and minimum recommended ballasts, also indicates the vessel's lifting capability on the piling.

The calculated results from Askari et al [7] is listed in Table 8 as follows;

Table 8 Decomtool vessel parameters, from [7]

Maximum ballast on board (94.35% capacity)	47,579.678 mt
Minimum ballast on board (30.88% capacity)	14,431.006 mt
ballast pumped out, ∇W	33,148.672 mt
Lifting capacity, F_{lift}	33,148.672 mt
Draft at minimum ballast	6.137 m
Draft at maximum ballast	10.17 m
Maximum extractable length per attempt, L_{max}	4.033 m

∇W = F_{lift} = 47579.678 – 14431.006 = 33,148.672 mt

F_{lift} = 33,148.672 mt x 9.81 ms^{-2} = 325,182 kN

4.5 Gripper System

The present utilization of grippers in the offshore wind industry is to maintain the vertical position of piles during installation, when the piles are hammered into the seabed. The gripper may come in a variety of configurations, including a gripper frame mounted on the vessel's deck [89] or installed directly on a section of the vessel [90]. So far, the decommissioning operations and procedures of offshore wind farms do not necessitate the use of a gripper, and the grippers available on the market are not intended to undertake any decommissioning tasks.

The decomtool vessel, on the other hand, has a gripper and is an essential element of the extraction system for decommissioning of the monopile foundation. The grippers are intended to function similarly to an external lifting tool (ELT) in order to securely grasp the monopile throughout the extraction operation. The extraction grippers apply force to the monopile to overcome the pile's dead weight during lifting as well as overcome the skin friction between the soil strata and pile contact surfaces.

4.5.1 Configuration of gripper on Decomtool vessel

The concept gripper design (Fig. 49) on the decomtool vessel consists of two grippers, each supported on two sides by a pair of steel beams, illustrated in Fig. 50 and Fig. 51. The grippers are set up parallel to each other in a vertical orientation, allowing both gripper arms to hold the monopile at the same time. The grippers may be adjusted to handle monopiles of varying diameters; however, we consider a case study involving the Horns Rev1 wind farm featuring monopiles of 4 m diameter. The grippers may operate independently and are controlled by a hydraulic system that will not be discussed in detail as part of this work.

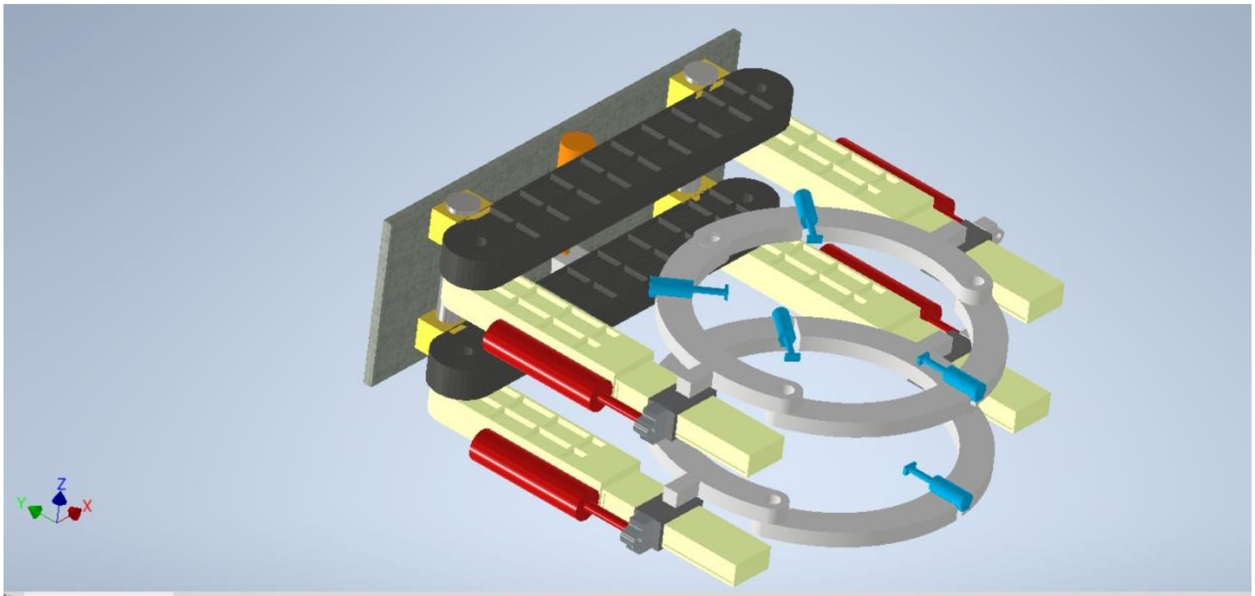


Fig. 49 Concept design of gripper system

The steel beam supports for the grippers are rigid members that form a cantilever with one end fastened to the vessel and one end free to support the gripper arms. These beams convey the buoyancy force of the vessel to the grippers during monopile extraction. A feasibility assessment will involve the determination of the steel beams' capacity to withstand the resultant stresses for a successful operation and a safe working procedure.

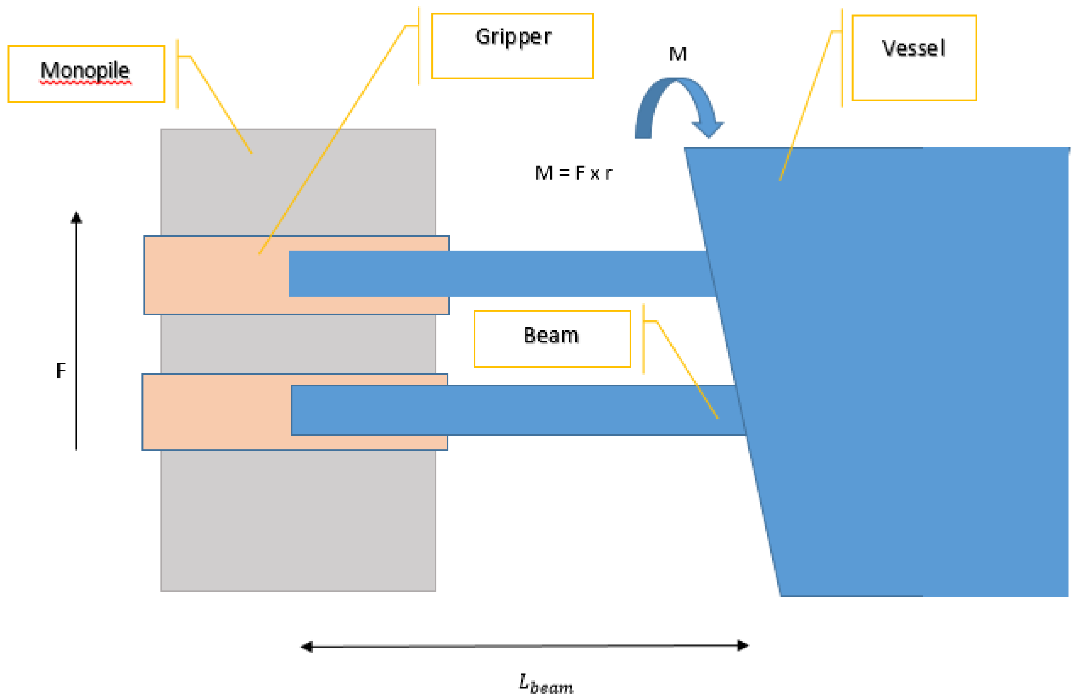


Fig. 50 Side view: Decomtools vessel gripper arrangement at the aft

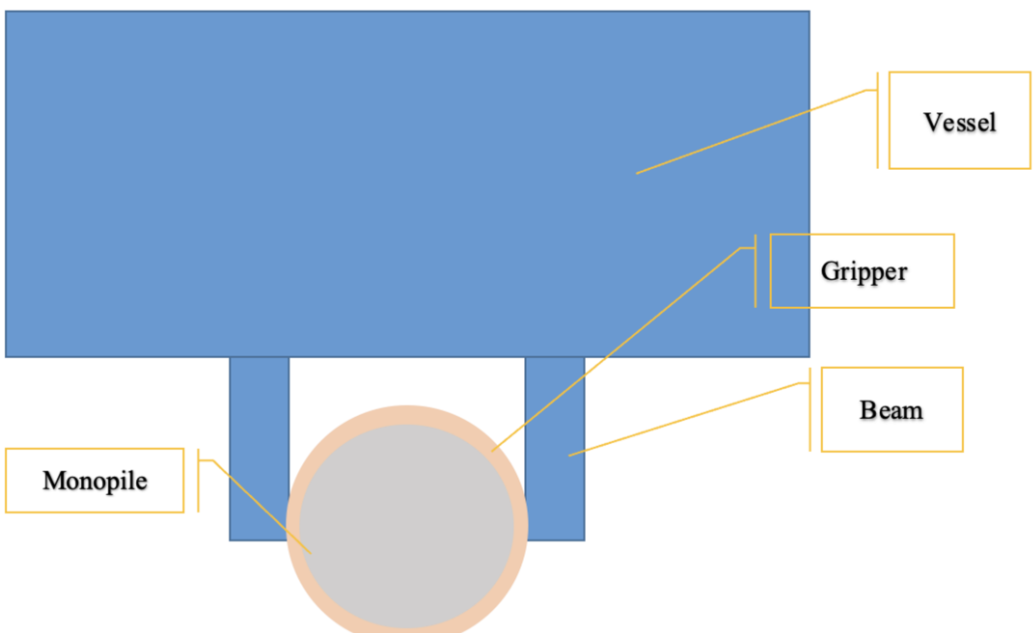


Fig. 51 Top view: Decomtools vessel gripper arrangement at the aft

4.5.2 Force on gripper support beams

The decomtool vessel gripper arrangement, as previously stated, comprises of two grippers, each supported on two sides by a pair of steel beams. The grippers, which are positioned vertically in parallel, hold and lift the monopile load to be removed. As a result, and illustrated in Fig. 52, the lifting Force is assumed to be spread uniformly among the four beams.

To meet the vessel's design requirements, we analyze the maximum force experienced by the beams, which will be the vessel's lifting capacity, F_{lift}, since the vessel lift capacity must be greater than the combine forces of monopile weight and monopile-soil friction.

The lifting capacity of vessel, F_{lift} = 325,182 kN

This will imply that the force,F_{beam} , acting on each beam

F_{beam} = $\frac{325{,}182 \text{ kN}}{4}$ = 81, 295.5 kN

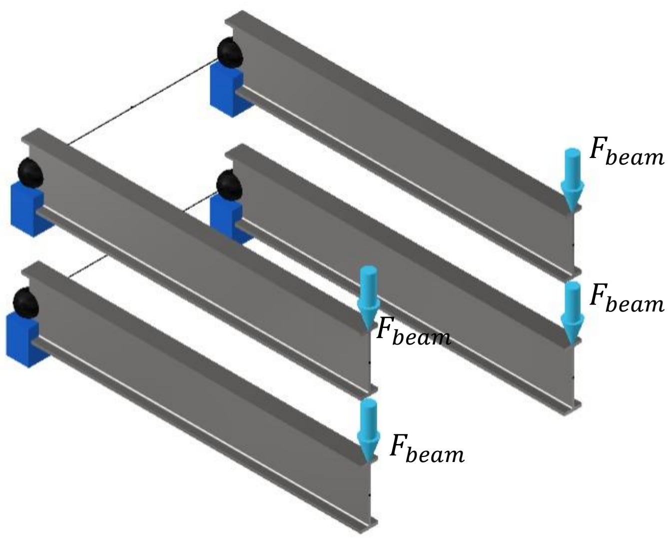


Fig. 52 distributed load on beams

4.5.3 Gripper support beams

Material

Structural steel is a major construction material in the offshore industry, possessing attributes such as strength, stiffness, toughness, and ductility that are very desirable in the industry. A material's strength is its capacity to resist stresses. It is expressed in terms of yield strength, F_y, and ultimate or tensile strength, F_u. In the case of steel, the typical F_y and F_u ranges used in construction are 248 to 345 MPa and 400 to 483 MPa, respectively, while greater strength steels are becoming increasingly prevalent [91]. Many grades of structural steel are utilized in the fabrication of engineering components and structures across Europe; however, grades S355, S420, and S460 are the most commonly used in the offshore industry [92], [93]. The minimum yield strength, F_y, for S355 structural steel for example is 355 Mpa, which indicates the origin of the steel's name. This value of yield strength diminishes as plate thickness increases [94].

Failure Consideration of beam

For a beam member, the two main failure types are the shear failure and flexural failure. A beam is said to undergo shear failure when the shear stress induced by an external force exceeds the maximum permissible shear stress. Flexural failure, however, occurs as a result of bending stress subjected by an external load. Flexural members such as beams are prone to this failure when subjected to large flexural loads, causing them to bend or buckle.

Shear Failure of steel beams

The allowable shear stress of a steel beam, F_a, is given by

$$F_a = \frac{\mathrm{F_y}}{\Omega_\mathrm{v}} \tag{3}$$

Where,

F_a = Allowable shear stress of a beam

F_y = Yield strength

Ω_v = Safety factor

Induced shear stress, F_s, due to load must be less than the allowable shear stress, F_a.

Moment Resistance (Flexural failure) of steel beams

For a moment resistance analysis of the beams, the bending ratio is given by [95]:

$$\frac{M_x}{M_{c,Rd}} \leq 1.0 \tag{4}$$

But

$$M_{c,Rd} = \frac{M_{pl}}{y_{mo}} = \frac{W_{pl}\, x\, F_y}{y_{mo}} \tag{5}$$

M_x = Induced bending moment

$M_{c,Rd}$ = Maximum moment capacity

M_{pl} = Plastic bending moment

W_{pl} = Plastic section modulus (about the major axis)

F_y = Yield strength

y_{mo} = Partial factor (Resistance of section)

4.5.4 Beam Profile (I-Beam), and Shear Stress and Moment Resistance Analysis

We consider an I-beam (Fig. 53) for the beam support in the support analysis. Due to their high functionality, I-beams are typically the preferred form for structural steel construction. The I-beams' form makes them ideal for unidirectional bending parallel to the web. The horizontal flanges resist bending, whereas the web resists shear stress [95].

In analyzing the support members of the gripper for failure, we use available standard manufactured i-beams on the market. This data is obtained from material data sheet from Rainham steel attached in the appendix A.

We select the maximum standard universal beam size from the data sheets with the following characteristics in Table 9.

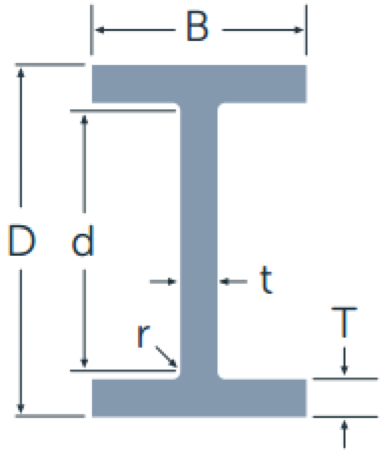


Fig. 53 cross section of i-beam

Table 9 Universal Beam (UB) standard size parameters, from [96]

Serial size	Mass per metre	Depth of section	Width of section	Thickness	
		D	B	web (t)	flange (T)
mm x mm x mm	kg/m	mm	mm	mm	mm
1016 x 305 x 487	486.7	1036.3	308.5	30	54.1

Length of beam, L_{beam} = 6 m

Shear Stress

From equation (3), we estimate an allowable shear stress, F_a, of the i-beam

$$F_a = \frac{F_y}{\Omega_v}$$

F_y = 355 MPa (Yield strength of s355 steel beam with a nominal thickness ≤40mm) [97]

Ω_v = 1.15 (Safety factor steel beam in shear) [98]

$$F_a = \frac{355}{1.15} = 308.7 \text{ MPa}$$

From a frame analysis simulation (Report in appendix B) for one steel universal beam gripper support and;

F_{beam} = 81, 295.5 kN

We obtain results presented in Fig. 54 showing moment and shear stress in steel beam, and a summary result in Table 10.

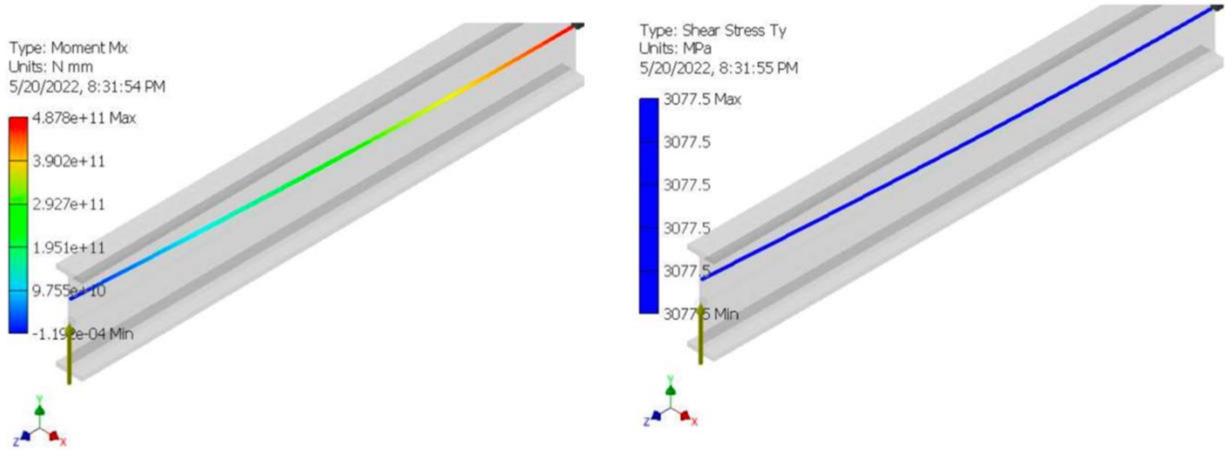


Fig. 54 showing moment and shear stress in steel beam

Table 10 Static Result Summary

Name		Minimum	Maximum
Displacement		0.000 mm	2604.784 mm
Forces	Fx	-0.000 N	-0.000 N
	Fy	81295475.000 N	81295475.000 N
	Fz	0.000 N	0.000 N
Moments	Mx	-4.878E+11 N mm	0.000 N mm
	My	-0.000 N mm	0.000 N mm
	Mz	0.000 N mm	0.000 N mm
Normal Stresses	Smax	0.000 MPa	24739.150 MPa
	Smin	-24739.150 MPa	-0.000 MPa
	Smax(Mx)	0.000 MPa	24739.150 MPa
	Smin(Mx)	-24739.150 MPa	-0.000 MPa
	Smax(My)	-0.000 MPa	0.000 MPa
	Smin(My)	-0.000 MPa	0.000 MPa
	Saxial	0.000 MPa	0.000 MPa
Shear Stresses	Tx	0.000 MPa	0.000 MPa
	Ty	-3077.527 MPa	-3077.527 MPa
Torsional Stresses	T	0.000 MPa	0.000 MPa

Shear stress on each beam, F_s = 3077.527 MPa

This implies that for each beam, the shear stress experienced, F_s, is greater than the allowable shear stress, F_a.

Moment Resistance Analysis

From Equation (5) we estimate the maximum moment capacity of the selected beam

$$M_{c,Rd} = \frac{M_{pl}}{y_{mo}} = \frac{W_{pl}\ x\ F_y}{y_{mo}}$$

W_{pl} = Plastic section modulus = 23208 cm^3 (from appendix A)

F_y = 355 MPa (Yield strength of s355 steel beam with a nominal thickness ≤40mm) [97]

y_{mo} = 1.0 [95]

$$M_{c,Rd} = \frac{M_{pl}}{y_{mo}} = \frac{W_{pl}\ x\ F_y}{y_{mo}} = \frac{(23208\ x\ 355)x\ 10^{-3}}{1} = 8238 \text{ kNm}$$

From Table 10

M_x = $4.8\ x\ 10^{11} Nmm$

= $4.8\ x\ 10^5\ kNm$

Substituting $M_{c,Rd}$ and M_x values into Equation (4)

$$\frac{M_x}{M_{c,Rd}} = \frac{4.8\ x\ 10^5\ kNm}{8238 \text{ kNm}} = 58.3$$

Since, $\frac{M_x}{M_{c,Rd}} > 1.0$, implying that the maximum moment capacity of the steel cross section is far lower than the induced moment from the load.

Based on the above calculation, the proposed design for four support beams and beam section is inadequate in resisting the bending moment due to the applied load.

We can however estimate the number of beams that can be employed theoretically to sustain the load by finding an induced moment that satisfies Equation (4) as follows:

$$\frac{M_x}{M_{c,Rd}} \leq 1.0$$

$M_x \leq$ 1.0 x $M_{c,Rd}$

But,

$M_{c,Rd}$ = 8238 kNm, and

$M_x = F_{beam} \text{ x } L_{beam} = F_{beam} \text{ x } 6 \text{ m}$

therefore

$F_{beam} \text{ x } 6 \text{ m} \leq 1.0 \text{ x } 8238 \text{ kNm}$

$F_{beam} \leq 1373 \text{ kN}$

Finding the total number of beams is then obtained as

$$\frac{uplifting\ force}{force\ on\ each\ beam} = \frac{F_{lift}}{F_{beam}} = \frac{325{,}182 \text{ kN}}{1373 \text{ kN}} = 236.84$$

The required number of beams to withstand the maximum uplift force given the proposed design is 236. This is practically not feasible as the decomtool vessel hull aft has vertical dimension of approximately 23 m [7]. A possible solution that reduces the breakout resistance, F, and by extension the force on each support beam, F_{beam} , is discussed in chapter 5. This will potentially make the four support beam design for the decomtool vessel feasible.

4.5.5 Estimating Gripper Hydraulic Unit Footprint

The hydraulic unit as part of the gripper system controls the gripper arms. Four hydraulic cylinders, one on each support beam as depicted in Fig. 49, transmit unidirectional hydraulic force to the grippers by a unidirectional stroke. The hydraulic cylinders in this configuration delivers moment of the force to the gripper arm whose magnitude is a product of the cylinder rod length and transmitted force in the cylinder. We can then estimate the power rating of the required hydraulic unit for the operation.

We begin by selecting a standard cylinder used for a jack up vessel with characteristics as seen in Fig. 55

JACK UP CYLINDER

Jack up cylinder	Example
Piston diameter	600 mm
Piston rod diameter	280 mm
Stroke length	3,150 mm
Function	Lowering / lifiting the legs

Fig. 55 Selected cylinder, from [99]

Estimating power requirement for hydraulic unit

Considering 4 cylinders:

Max. Pressure of Cylinder, $\rho_{c,max}$ = 250 bar = 25,000 kPa

Diameter of Cylinder, $\varnothing_{cyl}$ = 0.6 m

Pushing Area of Cylinder, $A_{cyl} = \frac{\pi \varnothing_{cyl}{}^2}{4} = \frac{\pi \times 0.6^2}{4}$ = 0.281 m^2

Velocity of Cylinder, V_{cyl} = 0.1 ms^{-1}

Volumetric flow rate in Cylinder, Q_{cyl} = A_{cyl} x V_{cyl}

Q_{cyl} = 0.281 m^2 x 0.1 ms^{-1}

= 0.0281 m^3s^{-1}

For 4 cylinders, the total Volumetric flow rate, Q_t = 4 x 0.0281 m^3s^{-1}

= 0.1124 m^3s^{-1}

Estimated hydraulic power in watts, P = $\rho_{c,max}$ x Q_t

= 25,000 kPa x 0.1124 m^3s^{-1}

= 2.81 kW

We assume 60% efficiency of the unit

⇒ Electric Power required, $P_{eff} = \frac{P}{0.6} = \frac{2.81 \text{ kW}}{0.6}$ = 4.7 kW

A 5.5 kW hydraulic power unit is selected for an estimate of its footprint. As seen in appendix C, the selected hydraulic unit has a length of 0.78 meters and a width of 0.57 meters.

The hydraulic unit footprint is calculated as follows;

Foot print (Floor Area) = 0.78 m x 0.57 m

= 0.45 m^2

4.6 Cutting Tool/Techniques

Decommissioning offshore installations involves extensive cutting work. Large offshore constructions may need to be divided into smaller portions with more tolerable lift weight. There are several options available; however, in the present decommissioning procedures for OWT foundations outlined before, the choice of a specific cutting method or system is often determined by accessibility to the foundation monopiles. A review of the technology, equipment, and techniques for cutting various materials and section geometries must be included in any study of the choices available for decommissioning of offshore structures. Regardless of the approach used, careful planning and execution are critical to the success of the operations.

In the Decomtools vessel approach, illustrated in Fig. 56, the cutting operation for the monopile occurs at the top side and will involve conventional cutting methods regularly employed for dismantling onshore facilities. The pile cutting system is designed as part of the extraction mechanism, and installed 0.5 to 1 meter above the vessel's weather deck [7, p. 313].

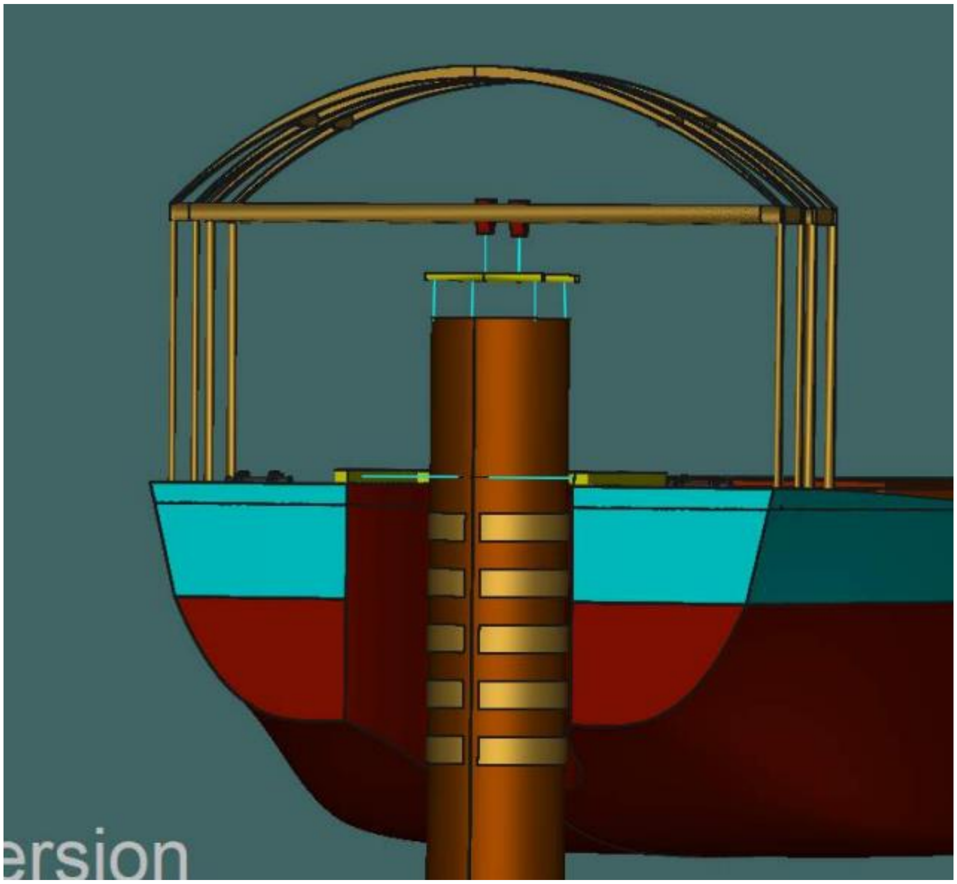


Fig. 56 cutting operation of extraction system, from [7]

Traditionally, European Standard EN10025 S355 (or EN 10225 S355) has been the primary structural steel used in the design of wind turbine structures [93], [94]. The Horns Rev1 wind farm foundation piles are roughly 0.05 m thick. The ability of a cutting tool to perform the cut will be considered while choosing one. A viable cutting method for the vessel will be one that best fulfills the overall project goal of reducing decommissioning time and, by extension, emissions, as well as other technical aspects such as space constraints, safety, and process efficiency. For our analysis, we consider a variety of conventional cutting equipment and techniques utilized in the energy industry.

4.6.1 Length of Cut

Length of cut, L_{cut}, in the transverse direction for a cylindrical monopile relative to its length will be the circumference of the cross-sectional area. Given by:

$$L_{cut} = 2\pi r = \pi D \quad (4)$$

Where

L_{cut} = Length of cut

r = Outer radius of monopile

D = Outer diameter of monopile

For a 4 m monopile, as in the case for the foundation of the Horns Rev1 wind farm turbines

$L_{cut} = \pi \times 4$

$= \mathbf{12.6\ m}$

4.6.2 Oxy-fuel Cutting

Oxy-fuel cutting (Fig. 57) oxidizes the cut material (steel) in an exothermic process using pure oxygen and fuel gas, which can be acetylene, propane, methane, or ethane. To achieve combustion, the steel is heated to ignition temperature (around 1150°C) by one or more gas burners before a separate flow of oxygen is sent through the core as Fig. 58 illustrates, resulting in oxidation that causes the steel to burn and releases large amounts of heat that maintains the cutting process both through the metal and in the cutting direction [70].

(a)

(b)

Fig. 57 Oxy-acetylene cutting of steel pipes

The exothermic reaction of this fine stream of high pressure oxygen converts pre-heated unprotected steel into oxidised liquid steel. Since this slag has a lower melting point than steel, the oxygen stream may blast the liquid slag out of the cavity while leaving the non-oxidised solid steel undisturbed. This continuous exothermic reaction cuts the steel as the torch moves. Because this is accomplished by oxidation, it is only effective on metals that oxidize readily at this temperature. Mild steel and low allow steels are examples of such metals. Oxy-fuel cutting can cut thicknesses ranging from 6.35 mm to 304.8 mm. The purity of the oxygen, which must be at least 99.5 percent, has a major impact on the cutting speed and quality of the final cut [100].

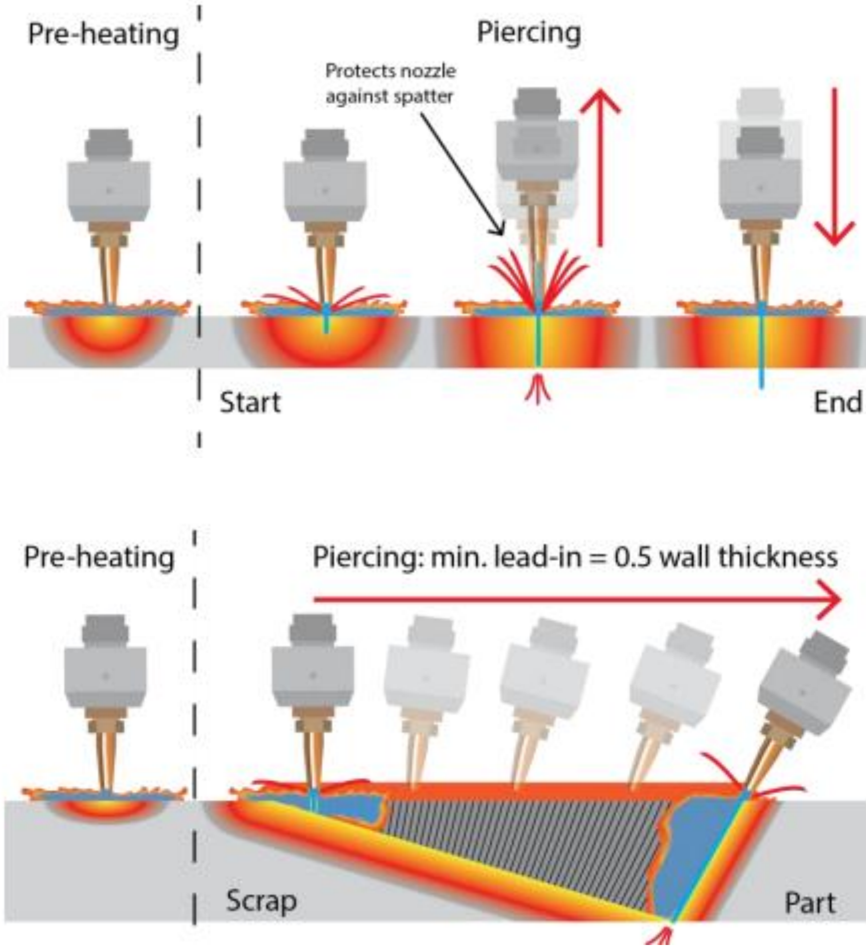


Fig. 58 Oxy-fuel cutting processes, from [101]

4.6.3 Cutting Time

The cutting time, t_{cut}, is the time required to complete a cut of the monopile section and represented mathematically by;

$$t_{cut} = \frac{L_{cut}}{S_{cut}} \tag{5}$$

Where,

t_{cut} = cutting time

S_{cut} = hand cut speed

L_{cut} = Length of cut = 12600 mm

From Table 11, and considering Horns Rev1 monopile of thickness 50 mm, an estimation of the cut time for one cutting operation on a monopile is as follows:

S_{cut} = 300 mm/minute

$\Rightarrow t_{cut} = \frac{12600}{300}$ = 42 minutes

Table 11 Oxyacetylene cutting information, from [102]

Mild Steel Thickness		size of nozzle	Operating Pressure		Gas consumption						cutting speed
			Oxygen	Acetylene	cutting oxygen		heating oxygen		Acetylene		
mm	in	Asnm	bar	bar	l/h	ft3/h	l/h	ft3/h	l/h	ft3/h	mm/m
6	1/4	1/32	1.8	0.14	800	28	480	15	400	14	510
13	1/2	3/64	2.1	0.21	1900	67	570	20	510	18	480
25	1	1/16	2.8	0.14	4000	140	540	19	470	17	400
50	2	1/16	3.2/3.5	0.14	4500	160	620	22	560	19	300
75	3	1/16	3.5/4.2	0.14	4800	170	680	24	620	22	205
100	4	5/64	3.2/4.8	0.14	6800	240	850	30	790	27	150
150	6	3/32	3.2/5.5	0.21	9400	330	960	34	850	30	125
200	8	1/8	4.2	0.28	14800	510	1380	48	1250	44	100
250	10	1/8	5.3	0.28	21500	760	1560	55	1420	50	75
300	12	1/8	6.3	0.28	25000	880	1560	55	1420	50	50

4.6.4 Oxy-Fuel Cutting Equipment

Two cylinders filled with cutting gases are fitted with two regulators, pressure gauges, two lengths of hose, and a cutting torch or machines equipped with cutting nozzle in an oxygen-fuel apparatus. Regulators are attached to the cylinders and are used to lower and maintain consistent gas pressure at the torch. The hoses transport the low-pressure gases to the torch. High and low pressure gauges are included in the regulators to show the contents of the cylinder as well as the operating pressure on each hose. At the torch the gasses are combined, and combustion occurs at the cutting tip.

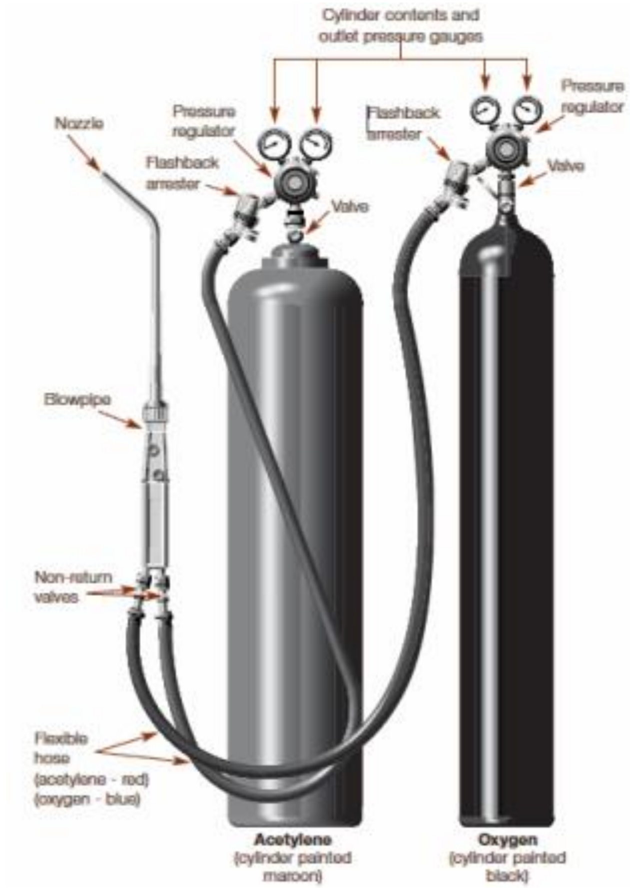


Fig. 59 Basic Oxy-Acetalyne Apparatus, from [100]

The oxy-acetylene apparatus (Fig. 59) basically comprises the following

1. Oxygen and Acetylene gas cylinders
2. Oxygen and Acetylene pressure regulators
3. Oxygen and Acetylene gas hoses
4. Torches or cutting machines
5. Trolleys for cylinder transportation

Oxygen Tanks Or Cylinders

Suppliers can provide oxygen in liquid or gaseous form. Handling and storing liquid and gaseous oxygen necessitates the use of specially developed equipment. Liquid oxygen tanks and oxygen cylinders are the most common types and are usually drawn from high strength steel plates.

Liquid oxygen is kept in very low temperature service (cryogenic) tanks. They are built in the style of a thermos bottle (Fig. 60), with an exterior and inner vessel configuration. A liquid oxygen vessel, also known as a mini-bulk container, has an interior pressure that is rarely more than 1655 kPa. The evaporation of some of the liquid oxygen keeps the remaining liquid at a temperature of around –183°C [103].

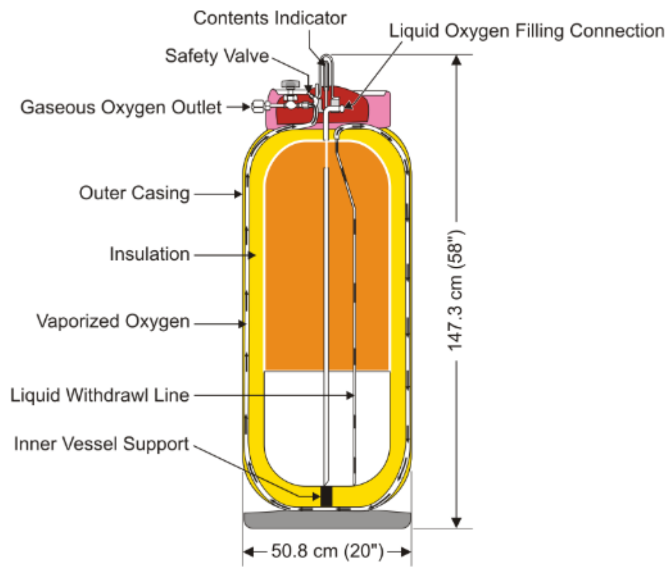


Fig. 60 typical oxygen cylinder for an oxy-fuel equipment, from [103].

Sizes: Compressed oxygen cylinders come in a variety of sizes, with capacities ranging from less than 20 cubic feet (0.56m^3) to over 300 cubic feet (8.5 m^3). The most common cylinder is approximately 5 feet (1.5 meters) tall (including the cap) and 9 inches (229 millimeters) in diameter [104].

Acetylene Cylinders

Acetylene cylinders are welded, as opposed to the seamless hot drew containers used for oxygen confinement. Because acetylene cylinders operate at substantially lower operating pressures, their design and construction do not have to meet the same criteria as oxygen cylinders. Balsa wood, shredded asbestos, charcoal, portland cement, or infusorial earth are commonly used to fill older acetylene cylinders. This aggregate combination is 75 to 80 percent porous, highly heavy, and crushes on impact, leaving a gap in the cylinder (Fig. 61) [103].

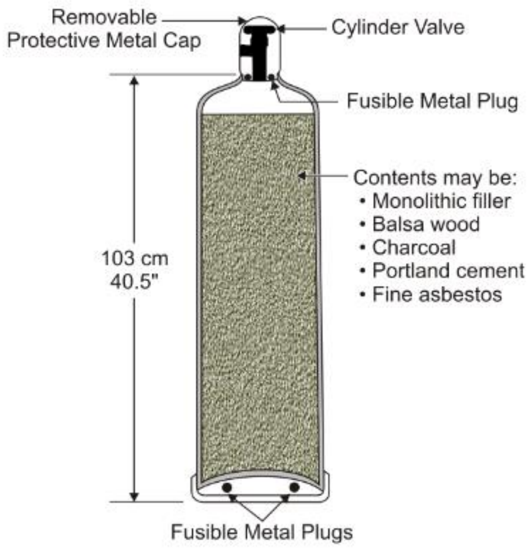


Fig. 61 typical acetylene cylinder for an oxy-fuel equipment, from [103].

Sizes: Acetylene cylinders on the market range in capacity from 10 cubic feet to 420 cubic feet. The largest capacity, 420 cf, come with usually standard nominal outer diameter of 304.8 mm, nominal length of 1155.7 mm, and weighs approximately 102.1 kg when empty [105].

Regulators

A full cylinder of oxygen has a pressure of approximately 15200 kPa at 200°C; a full cylinder of acetylene has a pressure of about 1725 kPa at 200°C. Welding and cutting torches require oxygen at pressures ranging from around 69 to 35 kPa and acetylene at pressures of 103 kPa or less [104]. Adjustable pressure-reducing regulators are used to lower cylinder pressures to desired operating pressures. They are designed to maintain constant operating pressure while cylinder pressure declines.

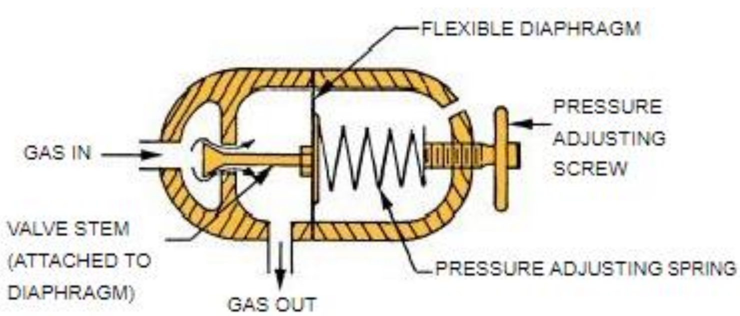


Fig. 62 typical regulator for gas cylinder, from [104]

The basic elements of a typical regulator are shown in Fig. 62. The high-pressure gas goes via a flexible diaphragm-controlled valve.

Hose And Hose Fittings

Hose is normally not utilized at pressures more than 200 psi, even though the minimum bursting pressure for new hose is substantially higher. The cover of an oxygen hose is green, smooth or corrugated, whereas the cover of an acetylene hose is red, smooth or corrugated. A complete oxygen or acetylene hose connection consists of three parts: a nipple with a sitting surface that matches the internal seat on the torch or regulator connector, a swivel nut, and a clamp or hose ferrule that secures the hose tight onto the nipple end [104].

Size: Hose utilized for most welding and cutting applications has an internal diameter ranging from 4.8 to 9.6 mm. When the length of hose required between the regulator and the torch is less than 7.62 m, 4.76 mm. hose is sufficient for all welding, as well as most cutting and heating. However, when hose lines longer than 7.62 m. is required, or some fairly heavy cutting or heating is anticipated, 6.35 mm hose is preferable since it has less pressure loss at high flows [104].

The Cutting Torch

The cutting torch, seen in Fig. 63, measures and mixes oxygen and fuel gas to feed the flames needed for oxygen cutting, as well as controlling the oxygen stream needed for the cutting jet. Almost all hand-cutting torches use a single oxygen line to deliver all of the oxygen to the torch. The stream of oxygen is split just inside the torch body, with one half traveling through the valve that controls the cutting oxygen jet's "on-off" control and the other half travelling through the throttle valve that regulates oxygen supply to the mixer. Cutting torches for use in cutting machines are often equipped with two oxygen intake connections, each with its own regulator.

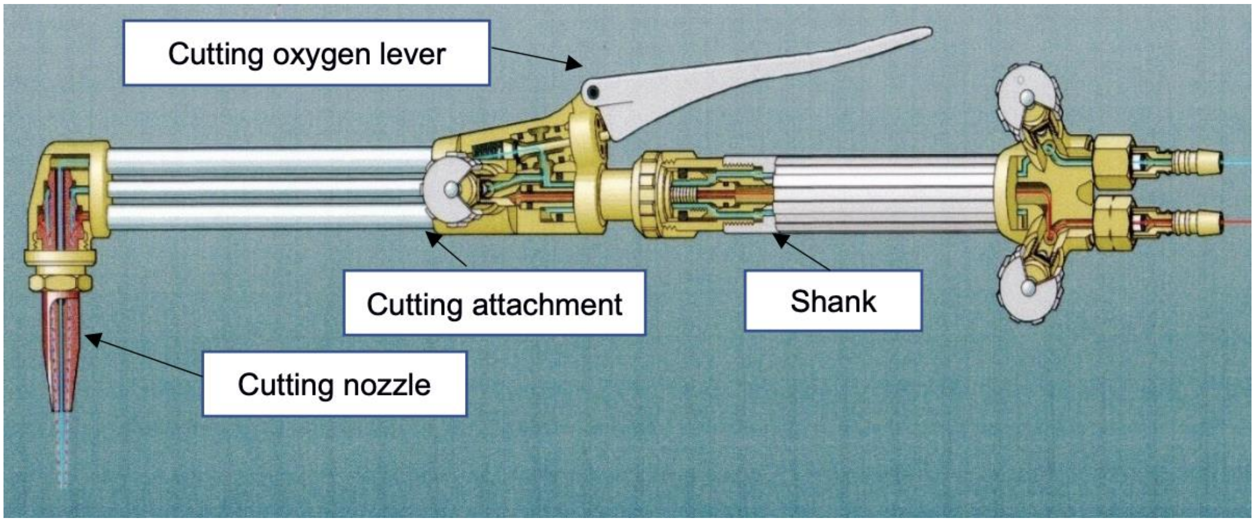


Fig. 63 Simplified sketch of a typical cutting torch, from [106]

There are two types of mixers available for cutting torches: injector and medium-pressure. By far the most prevalent is the medium-pressure kind. A single mixer is utilized in most cutting torches to span the whole range of nozzle diameters [104]. Fig. 64 shows some styles of cutting torch equipment.

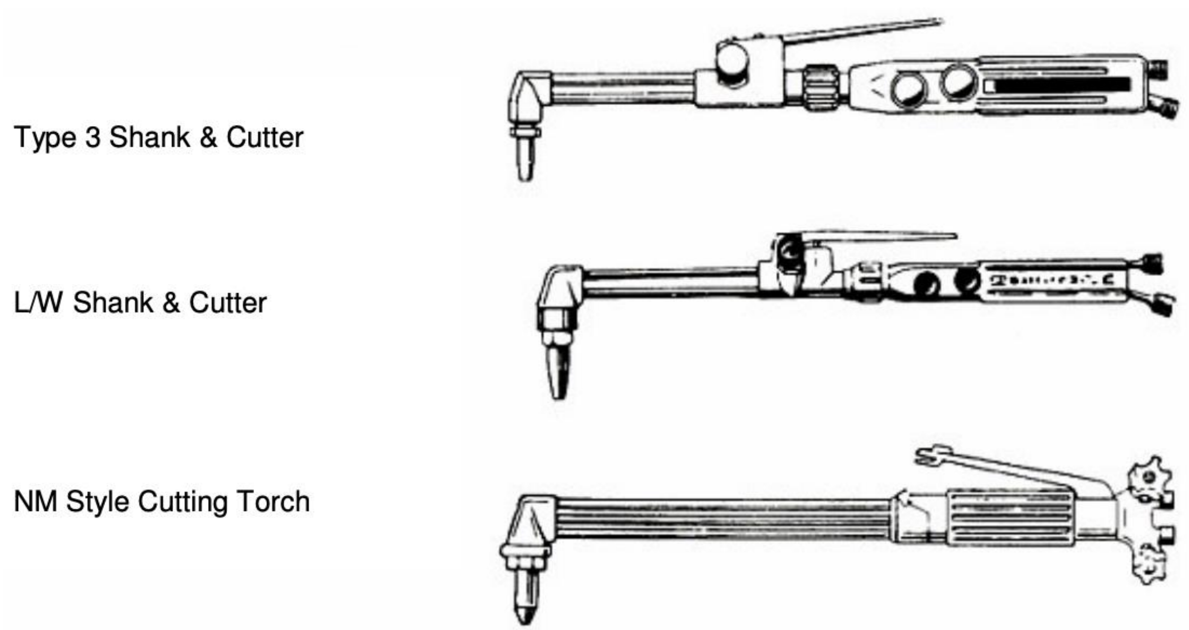


Fig. 64 Styles Of Cutting Torch Equipment ("blowpipes"), from [102]

4.6.5 Deck Space Requirement for Oxy-Acetylene Equipment

The sizes of cylinders for the oxy-acetylene equipment determines the deck space requirement for the equipment. The sizes of these cylinders will be selected after an estimate of the gas consumptions for one complete monopile removal.

To reduce the offshore operation duration, Askari et al [7] proposed cutting should take place every 12 meters, that is, after three attempts of extraction since the maximum extraction length per cycle is 4.033 m. This will imply, for the Horns Rev1 monopile foundations of length 42 (Table 11), there will be 3 complete cuts for one monopile extraction.

Therefore we can estimate cutting time for one complete monopile as,

cutting time for 1 complete monopile, $t_{cut,monopile}$ = 3 x 42 mins = 126 mins

Also from Table 11, the consumption rates for cutting 50 mm thick steel

Oxygen = 4500 l/h (160 ft^3/h)

Acetylene = 560 l/h (19 ft^3/h)

Finding the gas consumption for one monopile extraction for Horns Rev1

Oxygen consumption, C_{oxy} = 2.1 h x 4500 l/h = 9,450 litres (336 ft^3)

Acetylene consumption, $C_{acetylene}$ = 2.1 h x 560 l/h = 1,176 litres (39.9 ft^3)

SELECTION OF STANDARD CYLINDERS

Standard cylinders are selected based on the estimated consumption for one monopile extraction.

Table 12 Selected Oxygen and Acetylene Cylinder Sizes, from Appendix D

Gas	Model	Diameter (mm)	Height (mm)	Qty	Footprint ($\frac{\pi D^2}{4}$), (m^2)
Acetylene	40 CF (B-Standard)	152.4	589	1	0.0182
Oxygen	45L 310 BAR	239	1290	1	0.0449

Although the number of monopiles extraction that the vessel can perform in one trip is not explicitly stated by the authors of the DecomTools concept vessel design, we reference from page 244 of the vessel design thesis that for a 3.6 MW turbine windfarm the vessel can dismantle and transport 33 full set of complete turbines at a time. We therefore assume for the 4MW Horns Rev1 windfarm, the vessel can extract and transport 3 monopiles. We can now estimate the total number of cylinders for each cutting gas required for this activity and their deck space requirements as indicated in Table 13. However, these cylinders are stored and transported on racks.

Total number of cylinders required in the cutting operation for 33 monopiles considering Horns Rev1 as base case:

Oxygen = 33 cylinders
Acetylene = 33 cylinders

Table 13 total footprint of cylinders

Gas	Model	Diameter, D (mm)	Qty	Total Footprint, (m^2)
Acetylene	40 CF (B-Standard)	152.4	33	0.6006
Oxygen	45L 310 BAR	239	33	1.4817

The Offshore Bottle Rack (shown in Fig. 65) is a specialized storage and transit container for industrial gas cylinders. The modules are generally equipped with interior lashing connections and cargo straps to guarantee that contents are securely kept and certified to DNV 2.7-1 requirements. Although the oxygen and acetylene cylinders have a specific footprint, they are kept in these racks. This will imply the footprint of the total number of racks required will be the deck space requirement for the Oxy-Acetylene cylinders.

Fig. 65 Offshore gas rack, from [107]

From Appendix E we select the 3x12 Acetylene/Oxygen rack with the following dimensions;

Internal: 1195 x 1043 x 1882 (mm)

External: 1295 x 1143 x 2082 (mm)

This implies the rack internal total floor area = 1.192 x 1.043 = 1.24 m^2

Estimating the number of oxygen and acetylene cylinders that can be accommodated in the rack will give the following;

number of oxygen cylinders in one rack = $\frac{1.24}{0.0449}$ = 27.6 ≈ 27 cylinders

number of acetylene cylinders in one rack = $\frac{1.24}{0.0182}$ = 68.1 ≈ 68 cylinders

Although each rack is meant to hold 36 cylinders, requiring two racks for a total of 66 gas cylinders, the operation requires a total of three racks when the rack floor space is compared to the footprint of each gas cylinder type.Two racks for the oxygen cylinders and one rack for the acetylene cylinder as listed in Table 14.

Table 14 Rack and Cylinder Arrangement

Rack no.	Gas	no. of cylinders in rack
1	Acetylene	33
1	Oxygen	27
1	Oxygen	6

The combined footprint of 3 racks is calculated using the external dimensions of the rack;
Footprint = 1.295 x 1.143 x 3 = 4.44 m^2

4.7 Gantry Cranes

The cranes employed in the Decom Tools Vessel Design are gantry cranes, an integral part of the extraction system, whose main functions are lifting and loading components of the offshore wind turbine during decommissioning including its foundation. As shown in Fig. 66, the design comprises two gantry cranes, each with a Safety Working Load (SWL) of 750 tons that are operable in tandem. This implies a total SWL capacity of 1500 tons. The concept incorporates an additional compact electrical motor capable of lifting loads weighing up to 50 tons.

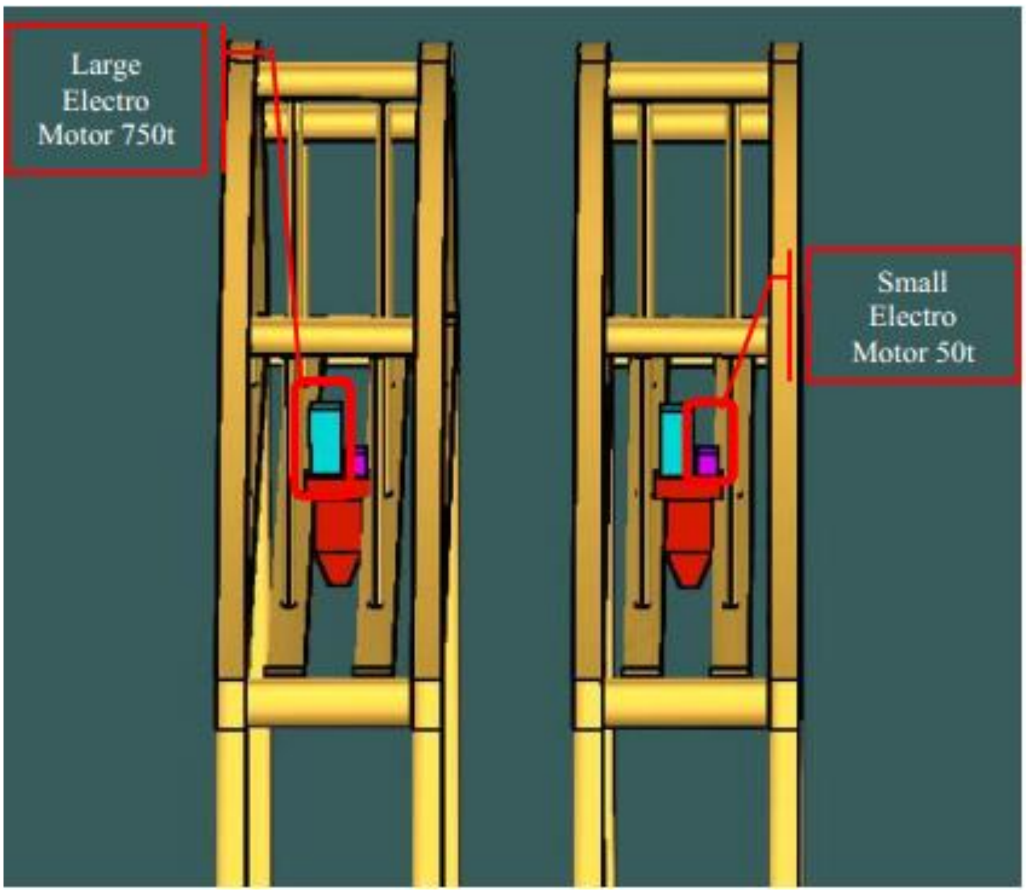
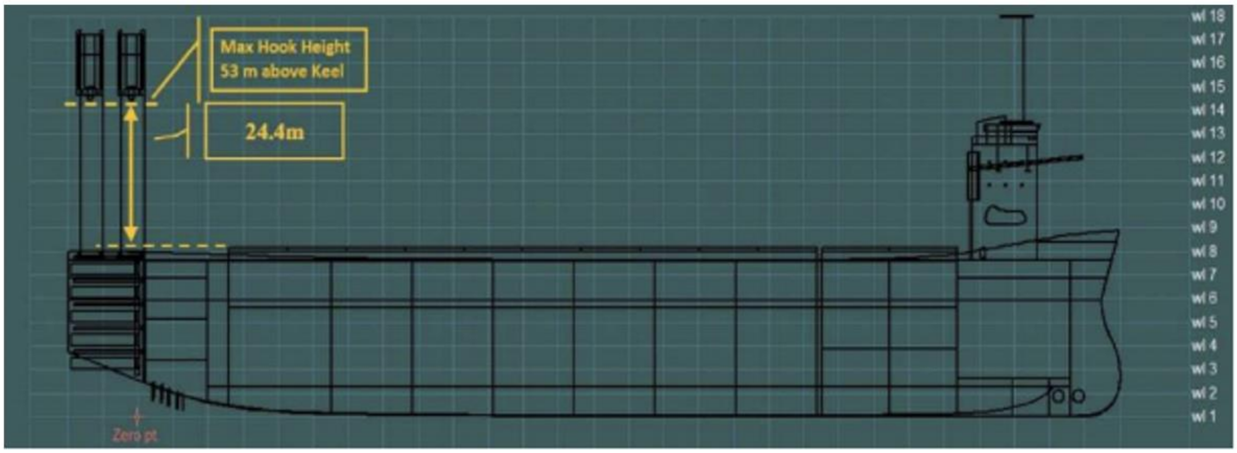


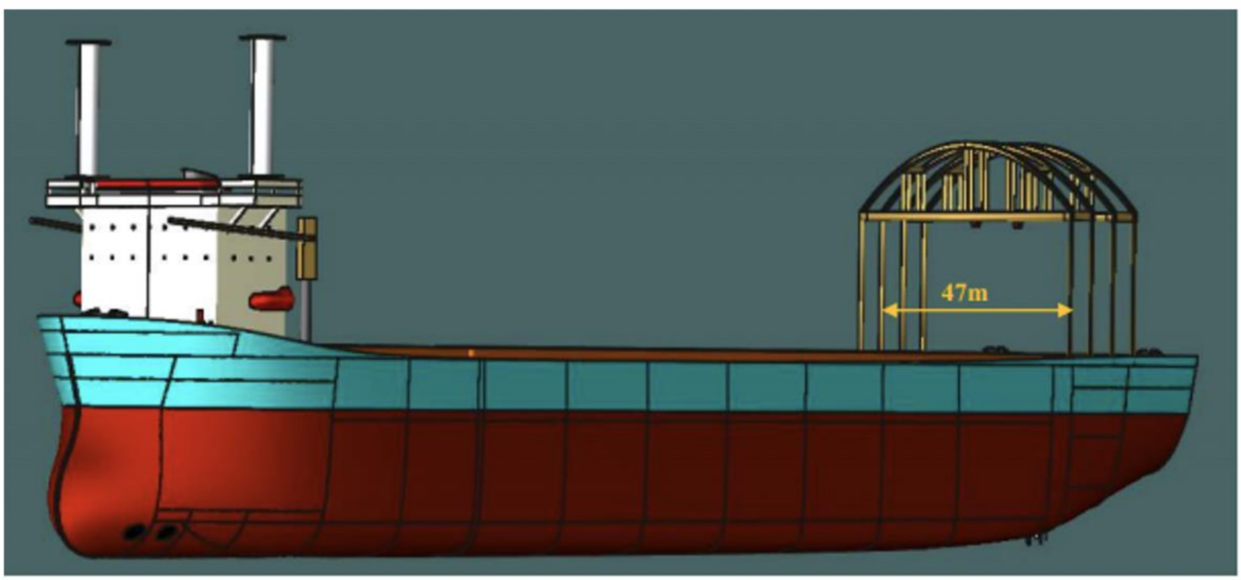
Fig. 66 Electro motors of gantry cranes, from [7]

4.7.1 Work Area

The DecomTool vessel's gantry cranes each have the following work area dimensions seen in Fig. 67:



(a)



(b)

Fig. 67 Dimensions of gantry crane for Decomtool vessel (a) Max. hook height (b) Rail to Rail length, from [7]

Maximum hook height from vessel deck = 24.4 m

Width (from rail to rail) = 47 m

Considering a monopile cut length (height) of 12 m, and diameter of the Horns Rev1 monopile diameter of 4 m, the working area is sufficient for the extraction operations for the monopile.

4.7.2 Tonnage and Available Comparable Crane Capacity

As mentioned earlier, the Safety Working Load (SWL) data for the DecomTool vessel: 2 x 750 tons. During the first extraction of the pile, the crane bears the full weight of the monopile. This means that the crane's maximum SWL must sustain at least the initial weight of the uncut monopile. Given the Horns Rev1 OWF monopile's gross tonnage of roughly 230 tons, the decomtools vessel crane fits the operation's requirements. However, the gantry cranes will not be ideal for bigger contemporary monopiles, such as the GE designed and produced 12MW X-Heliade wind turbines, which weigh roughly 2000 ton [85].

We explore deck gantry cranes of comparable capacity and operation on the market.

Konecranes Gantry Crane For Lash

Fig. 68 Konecranes gantry crane for Lash [108]

The Konecranes gantry crane for Lash – type barge carrier seen in Fig. 68, goes along the rails on the ship deck and is used to load and unload LASH-type barge carriers. The crane has an automated loading gear that hoists up or deploys the barges behind the ship. The barges are transferred into and out of the ship's cargo area using the same crane. Barges with a length of 18.745 meters, a width of 9.5 meters, and a maximum weight of 500 tons are handled by the crane [108]. Its technical data is presented in Table 15.

Table 15 Konecranes gantry crane for lash data, from [108]

Hoisting capacity	500 tons
Height of lift above the rail	12 m
Depth of lower below the rail	15 m
Rail span	21.3 m
Estimated footprint	
Transverse (width)	4 m
Longitudinal (length)	10 m

Konecranes Gantry Crane for Cargo Carrier

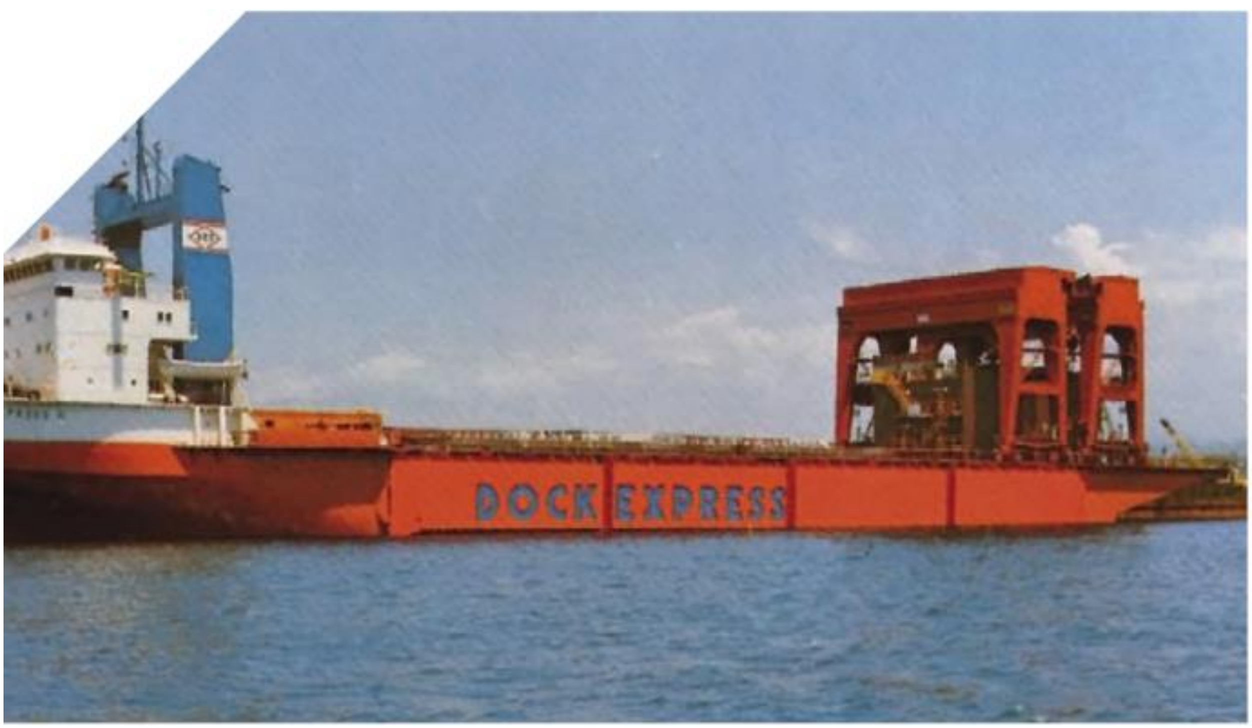


Fig. 69 Konecranes gantry crane for cargo carrier SWL 2x500 t, from [108]

The 500 ton Konecranes gantry crane mounted on a cargo carrier as shown in Fig. 69, is designed to load and unload heavy cargo. Two gantry cranes are mounted aboard cargo carriers and travel along the ship's deck rails. The cranes can work separately or in tandem. The two cranes' maximum weight during dual hoist is 1,000 tons. The crane has a 33-ton auxiliary hoist that can carry goods from the outboard and assist with cargo handling onboard [108]. Its technical data is summarized below in Table 16:

Table 16 Konecranes Gantry Crane for Cargo Carrier data, from [108]

Hoisting capacity	1000 tons
Height of lift above the rail	14 + 9 m
Estimated footprint	
Transverse (width)	2 m
Longitudinal (length)	2 x 6 m

Palfinger Deck Gantry Crane

Fig. 70 Palfinger marine deck gantry crane max SWL 600 t each, from [109]

Fig. 70 shows the Palfinger Marine deck gantry crane TKG 200 with a total SWL of 1200 tons. It travels within a given area of operation by a rail-wheel arrangement on deck, and delivered electric or hydraulic driven [110][109]. Table 17 presents the marine deck cranes technical data.

Table 17 Palfinger Deck Gantry Crane data, from [110]

Hoisting capacity	2 x 600 tons
Height of lift above the rail	14 m
Span	50 m
Estimated footprint	
Transverse (width)	2 m
Longitudinal (length)	2 x 6 m

Gantry Crane Footprint Estimate

An estimate of the footprint of the decomtool vessel gantry cranes is made from data of available equipment of comparable capacity and operation. The technical data can then be summarized as the following:

Table 18 Decomtool vessel gantry crane data

Hoisting capacity	2 x 750 tons
Height of lift above the rail	24.4 m
Estimated footprint	
Transverse (width)	2 m
Longitudinal (length)	2 x 6 m

5.0 DISCUSSION

The thesis set out to evaluate the technical feasibility of the monopile extraction system of the decomtool vessel for offshore wind farm decommissioning. It focused on the three major components of the vessel's extraction system, which includes the gripper system, the cutting tool, and the crane equipment.

Gripper system

The work focused its analyses on the gripper support beams and hydraulic control system. The analyses was based on the concept decomtool vessel design and an on-going design of the gripper system. Designing the gripper system is a major challenge for the realization of the decomtool vessel. Due to the large forces generated by the vessel buoyancy and requirement for extracting the monopile. As discussed in the following paragraph, initial design proposal which featured four universal beam members of the largest available production sizes supporting two gripper arms was determined to be inadequate to sustain the forces.

The gripper support beams design was analysed for failure, that is, shear and flexural when subjected to the largest design extraction force of 325,182 kN from the vessel. The support beam design consisted of four beams supporting two separate grippers that carry out the extraction in tandem. The extraction force is assumed to be distributed evenly across all beams. The force-beam interaction process was simulated using a finite element analysis software. Whiles the yield stress of the s355 mild steel material selected had a yield strength of 355 MPa, and an allowable shear stress of 308.7 MPa after applying a safety factor of 1.15, the induced shear stress on each beam was 1163.687 MPa. This indicated that the gripper support beams will fail under the maximum design extraction force. The highest induced moment of $4.8\ x\ 10^5\ kNm$, which occurs at the fixed point of the beam, was more than the maximum moment capacity of the beam by a factor of 58.3, indicating flexural failure, according to the moment resistance analysis.

A possible solution for this challenge is to consider techniques that help reduce or overcome the breakout resistance, F, of the pile in the seabed as part of the extraction system. One such technique is a technique proposed by Hinzmann et al [79] which leverages the buoyancy force of another equipment to lift the monopile. Consisting of a tube of inflatable floating element with negative or low buoyancy, and equipped with a releasable ballast ring, it is pulled over the pile and lowered to the seabed. The floating element is inflated with air and presses against the pile surface. This controlled process steadily increases the buoyancy force of the element until it exceeds the breakout resistance or reduces in considerably to a point where the gripper system can extract the pile without having to overcome the soil resistance of the pile-soil strata interface. This potentially reduces significantly the force, and by implication the induced bending moment, M_x, acting on the support beams.

With respect to the hydraulic unit footprint on the vessel deck, an estimated power requirement of 4.7 kW was calculated for the unit on the basis of a selected available hydraulic cylinder data sheet. A 5.5 kW hydraulic unit is selected from the market, and its footprint for the vessel deck space consideration determined to be 0.45 square meter.

Cutting Equipment

The proposed cutting equipment for the vessel was the oxy-fuel cutting equipment based on technical consideration in comparison to other cutting equipment. This analysis was addressed in the decomtool vessel design proposal and was not considered in this work.

The thesis focused on the cutting time and footprint of the cutting equipment using the Horns Rev1 offshore wind farm monopile as the base case. The steel monopile had an external diameter of 4 meters, a 50-millimeter thickness and a total length of 42 meters. The calculated cut time for one complete cut was 42 minutes, making a total cutting time of 126 minutes for three cuts during the extraction of one monopile.

In reference to Askari et al [7, p. 244], the overall extraction and transport capacity of the vessel in one journey was assumed to be 33 full monopiles, and the total gas consumption need for one voyage was calculated. The total footprint for the acetylene gas cylinders was 0.6006 square meters, and 1.4817 square meters for oxygen gas. However, because gas cylinders are stored and transported on racks, the actual footprint will be that of the required number of racks for the gas cylinders.

A standard rack of dimensions 1195 m x 1043 m was selected from an original equipment manufacturer (OEM). A set of three racks with a combined footprint of 4.44 square meters was the resultant estimate.

Gantry Cranes

The use of gantry cranes for the monopile extraction system of the decomtools vessel design has several advantages, one of which is that the lifting capacity is fixed in all conditions because the boom angle does not change. There is also no need to build a large structure on the vessel deck to complement the operations for this type of crane because it is transportable and moves longitudinally. The crane may move from the aft of the vessel to the cabin, and the winches can move from the port to the starboard side.

The estimated footprint of both gantry cranes, considering cranes of similar capacity on the market, is 24 square meters.

Footprint

The estimated footprint representation for the hydraulic unit, oxy-fuel equipment, and gantry cranes on the decomtools vessel is illustrated in Fig. 71.

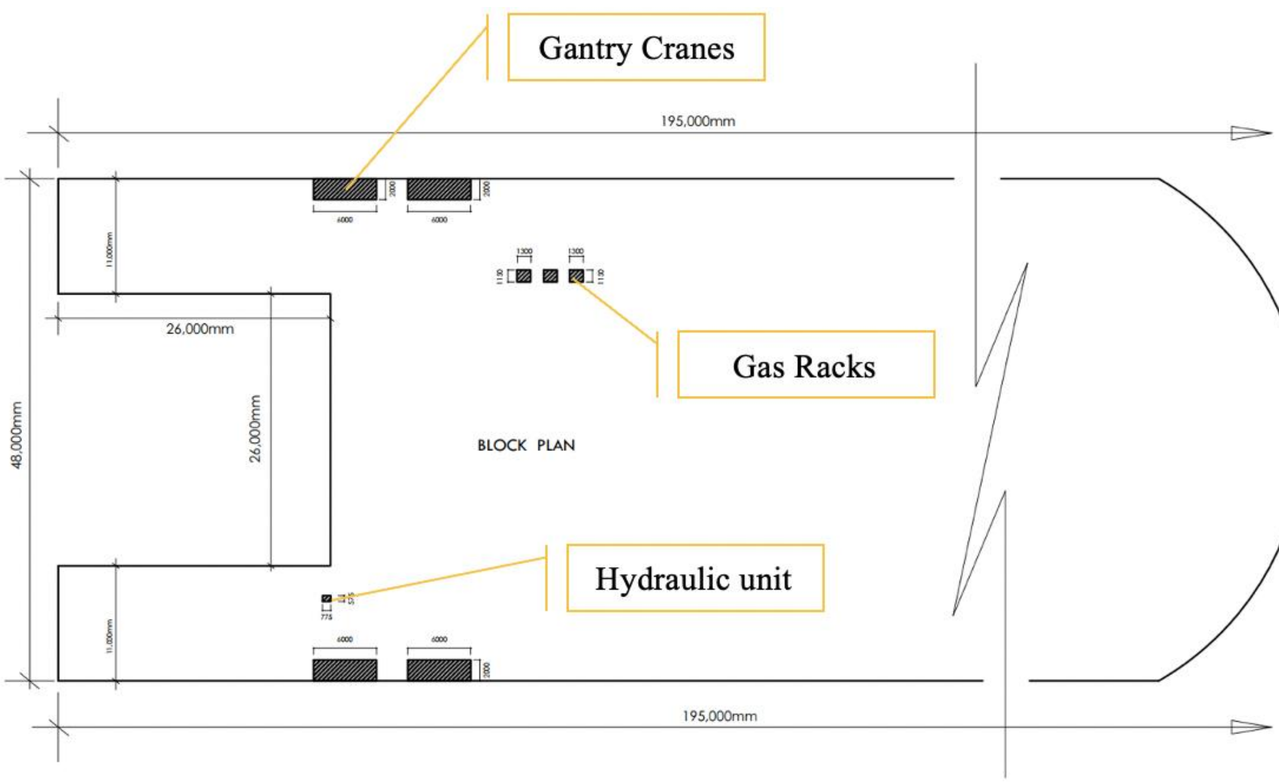


Fig. 71 Representation of equipment estimated footprint

6.0 CONCLUSION AND FUTURE WORKS

6.1 Conclusion

The need for innovative ways for decommissioning offshore wind structures has become necessary for the future of the industry. The concept of the decomtool vessel design, if successful, its implementation has the potential to reduce greenhouse emissions by reducing the number of vessels required for decommissioning as well as the operational time for the activity. It also provides a means of completely removing the monopile foundation from the seabed.

In this work, an initial assessment of the technical feasibility of the monopile extraction system of the decomtool vessel design is made. The gripper support beams, cutting method and equipment, and the gantry cranes were evaluated. The gripper support design is determined to be insufficient to sustain the extraction forces on the system. The oxy-acetylene cutting method is suitable for the cutting operation, enabling a total cut time of 126 minutes for the Horns Rev1 monopile base case. The cutting equipment takes up a minimal footprint considering other cutting options as well as available deck space of the vessel. Gantry cranes of similar capacity and operation are found available on the market. Indicating the availability of technology for the lifting system of the operation.

6.2 Future Works

The decomtool vessel design remains in the conceptual phase. Further research involving detailed design for various components of the vessel will enhance the development of the design. Technical feasibility focused on different aspects of the systems as well as detailed designs of these systems are areas recommended for further work and research.

In my view, other areas of focus will be the analysis of force interactions at the gripper-monopile connection, and the monopile-soil strata in the seabed. An improved understanding of the magnitude of forces to be overcome will improve on design and technical feasibility analysis of the decomtool vessel systems.

Finally, other solutions as highlighted in chapter 5, where other extraction techniques can be combined with the decomtool extraction system to help overcome the design challenges for the gripper system can be considered in further development of the vessel.

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APPENDIX

Appendix A: Rainham Steel UB Data Sheet

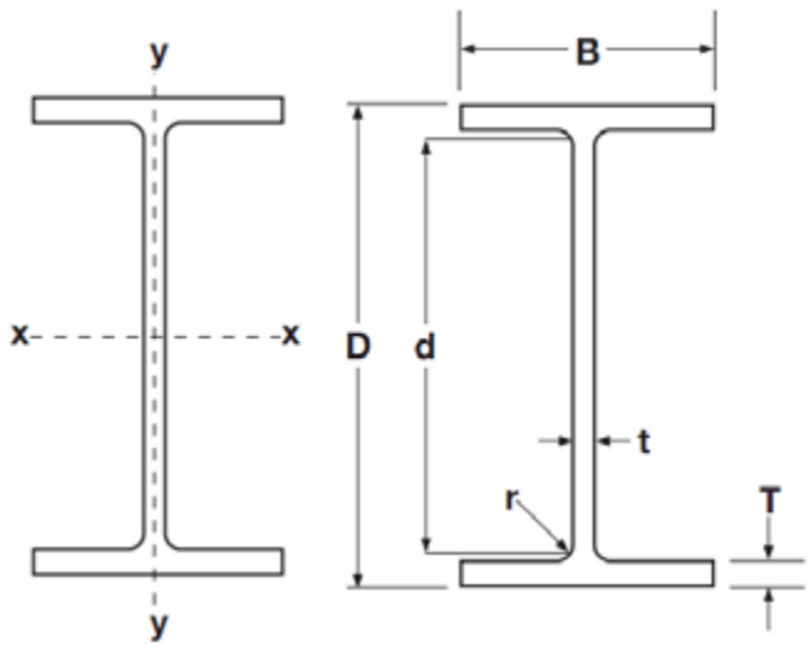
RAINHAM STEEL

Head Office
Rainham office sales +44 (0) 1708 558 211
Bury office sales +44 (0) 161 796 2889
Scunthorpe office sales +44 (0) 172 4273 282
sales@rainhamsteel.co.uk

UNIVERSAL BEAMS

Material to EN 10025-2:2004
Dimensions and properties to BS4-1:2005

AVAILABLE IN S355JR & S355JO

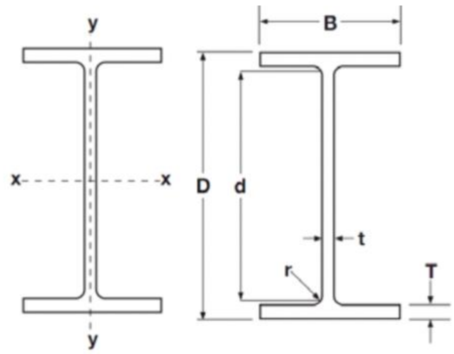


Serial Size mm x mm x mm	ation n	Radius of gyration Axis y-y cm	Elastic modulus Axis X-X cm3	Elastic modulus Axis y-y cm3	Plastic modulus Axis X-X cm3	Plastic modulus Axis y-y cm3
914x305x224		6.27	8269	739	9535	1163
914x305x253		6.42	9501	871	10942	1370
914x305x289						
914x419x343						

Material to EN 10025-2:2004

Dimensions and properties to BS4-1:2005

AVAILABLE IN S355JR & S355JO



Serial Size mm x mm x mm	Radius of gyration Axis y-y cm	Elastic modulus Axis X-X cm3	Elastic modulus Axis y-y cm3	Plastic modulus Axis X-X cm3	Plastic modulus Axis y-y cm3	Buckling parameter u	Torsional index x
914x305x289	6.51	10883	1014	12570	1601	0.867	31.9
914x419x343	9.46	13726	1871	15478	2889	0.883	30.1
914x419x388	9.59	15627	2161	17666	3340	0.885	26.7
1016x305x222	5.81	8409	636	9808	1019	0.85	45.7
1016x305x249	6.09	9819	784	11350	1244	0.861	39.8
1016x305x272	6.35	11190	934	12827	1469	0.873	35
1016x305x314	6.37	12883	1082	14850	1712	0.872	30.7
1016x305x349	6.44	14346	1223	16593	1940	0.872	27.9
1016x305x393	6.4	15897	1353	18538	2167	0.868	25.5
1016x305x437	6.49	17743	1535	20769	2467	0.868	23.1
1016x305x487	6.57	19722	1732	23208	2799	0.867	21.1

Appendix B: FEA Analysis Report

Frame Analysis Report

AUTODESK

Analyzed File:	Beam Analysis.iam
Version:	2022.1 (Build 261234000, 234)
Creation Date:	5/20/2022, 8:31 PM
Simulation Author:	Prince
Summary:	

Simulation:2

General objective and settings:

Simulation Type	Static Analysis
Last Modification Date	5/20/2022, 8:30 PM
Model State	Master
Design View	Default
Positional	Master

iProperties

Summary

Title	s355 Steel Beam Analysis
Author	Prince

Project

Part Number	Beam Analysis
Designer	Prince
Cost	$0.00
Date Created	4/20/2022

Status

Design Status	WorkInProgress

Physical

Mass	2919.694 kg
Area	192921.519 mm^2
Volume	371935.600 mm^3
Center of Gravity	x=-1.042 mm y=2230.002 mm z=2072.021 mm

Material(s)

Name	Steel, Carbon	
General	Mass Density	7.850 g/cm^3
	Yield Strength	350.000 MPa
	Ultimate Tensile Strength	420.000 MPa
Stress	Young's Modulus	200.000 GPa
	Poisson's Ratio	0.290 ul
Part Name(s)	BS 4 1016x305x487 - 6000	

Cross Section(s)

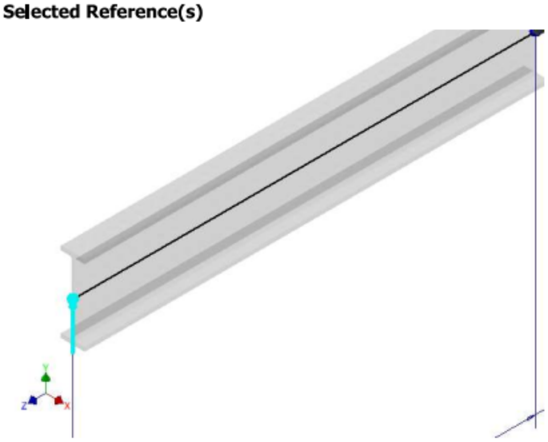
Geometry Properties	Section Area (A)	61989.267 mm^2
	Section Width	308.500 mm
	Section Height	1036.100 mm
	Section Centroid (x)	154.250 mm
	Section Centroid (y)	518.050 mm
Mechanical Properties	Moment of Inertia (I_x)	1.0214203910698E+10 mm^4
	Moment of Inertia (I_y)	267211145.987 mm^4
	Torsional Rigidity Modulus (J)	42979544.742 mm^4
	Section Modulus (W_x)	19716637.218 mm^3
	Section Modulus (W_y)	1732325.096 mm^3
	Torsional Section Modulus (W_z)	561707.540 mm^3
	Reduced Shear Area (A_x)	24265.755 mm^2
	Reduced Shear Area (A_y)	26415.844 mm^2
Part Name(s)	BS 4 1016x305x487 - 6000	

Operating conditions

Force:1

Load Type	Force
Magnitude	81295500.000 N
Beam Coordinate System	No
Angle of Plane	90.00 deg
Angle in Plane	90.00 deg
Fx	0.000 N
Fy	81295500.000 N
Fz	0.000 N

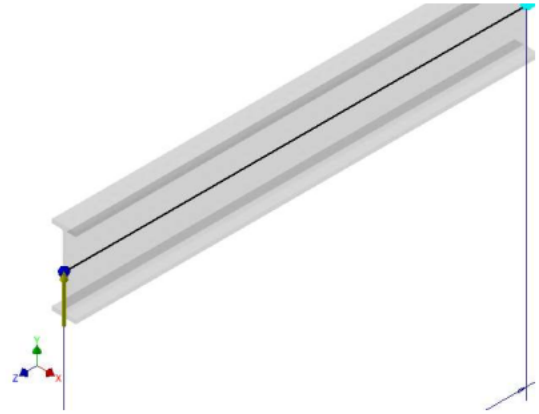
Selected Reference(s)



Fixed Constraint:1

Constraint Type	Fixed

Selected Reference(s)



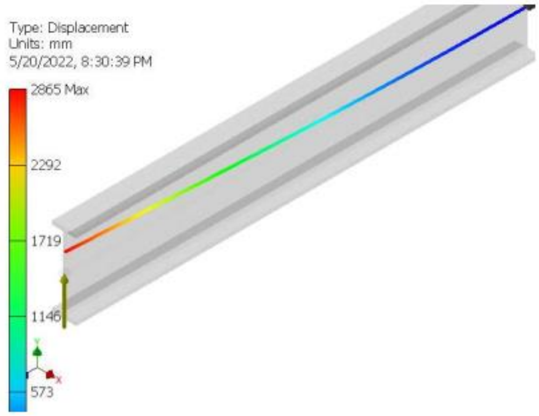
Results

Static Result Summary

Name		Minimum	Maximum
Displacement		0.000 mm	2865.263 mm
Forces	Fx	0.000 N	0.000 N
	Fy	-81295500.000 N	-81295500.000 N
	Fz	0.000 N	0.000 N
Moments	Mx	-0.000 N mm	4.87773000000000E+11 N mm
	My	-0.000 N mm	0.000 N mm
	Mz	0.000 N mm	0.000 N mm
Normal Stresses	Smax	0.000 MPa	24739.158 MPa
	Smin	-24739.158 MPa	-0.000 MPa
	Smax(Mx)	0.000 MPa	24739.158 MPa
	Smin(Mx)	-24739.158 MPa	-0.000 MPa
	Smax(My)	0.000 MPa	0.000 MPa
	Smin(My)	-0.000 MPa	-0.000 MPa
	Saxial	0.000 MPa	0.000 MPa
Shear Stresses	Tx	-0.000 MPa	-0.000 MPa
	Ty	3077.528 MPa	3077.528 MPa
Torsional Stresses	T	0.000 MPa	0.000 MPa

Figures

Displacement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Units: mm
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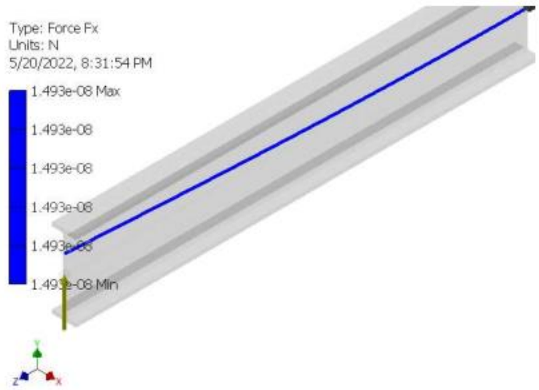
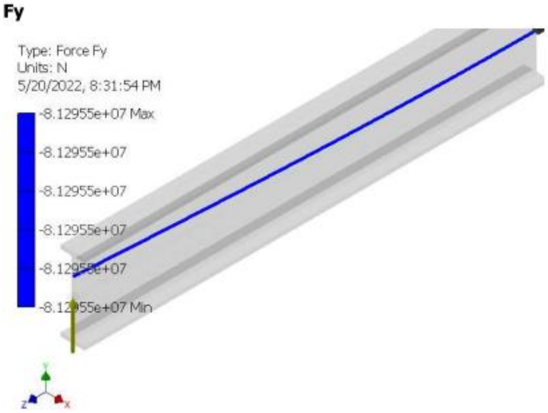
2865 Max
2292
1719
1146
573

Fx


Type: Force Fx
Units: N
5/20/2022, 8:31:54 PM
1.493e-08 Max
1.493e-08
1.493e-08
1.493e-08
1.493e-08
1.493e-08 Min

Fy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Units: N
5/20/2022, 8:31:54 PM
-8.12955e+07 Max
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-8.12955e+07
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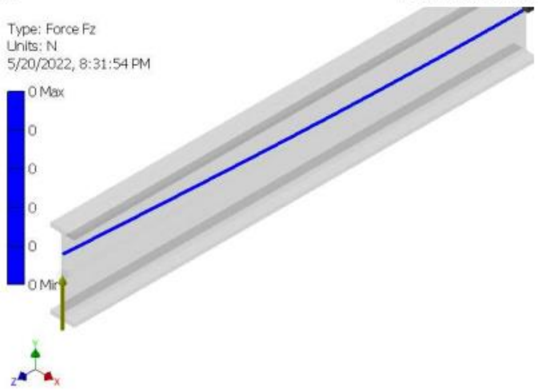
-8.12955e+07 Min

Fz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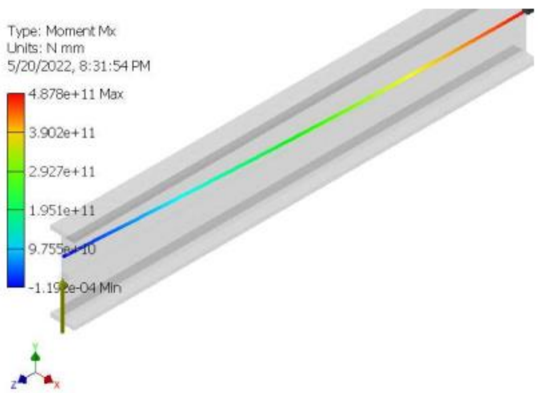
Units: N
5/20/2022, 8:31:54 PM
0 Max
0
0
0
0
0 Min

Mx


Type: Moment Mx
Units: N mm
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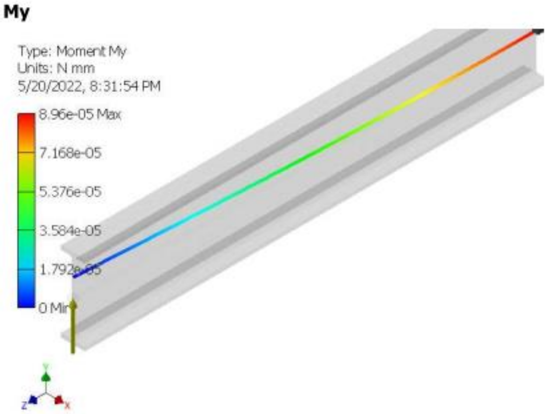
4.878e+11 Max
3.902e+11
2.927e+11
1.951e+11
-1.192e-04 Min

My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Units: N mm
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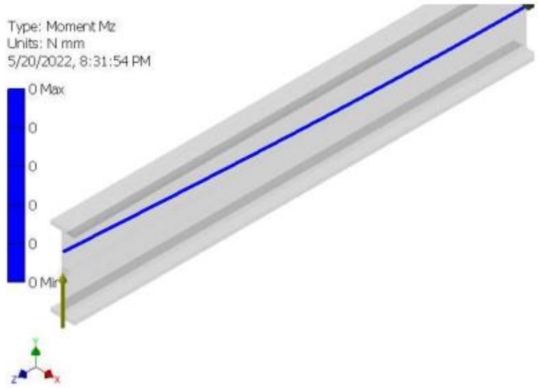
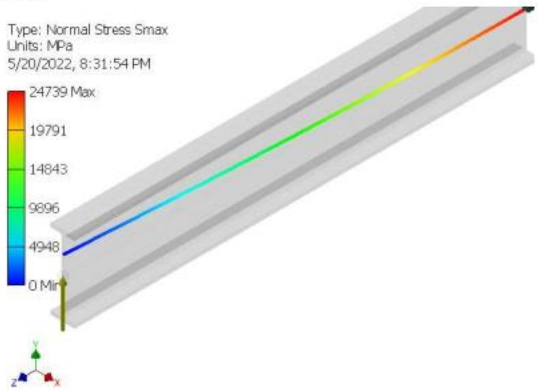
5.376e-05
3.584e-05
0 Min

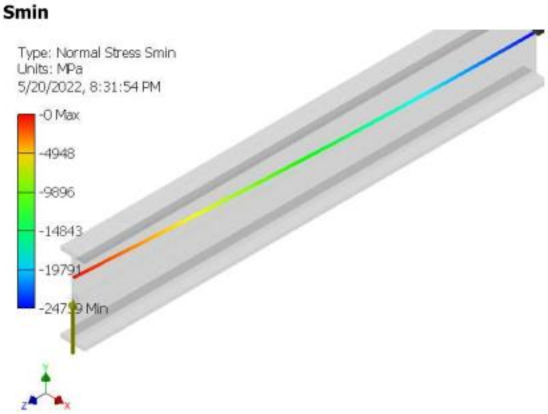
Mz



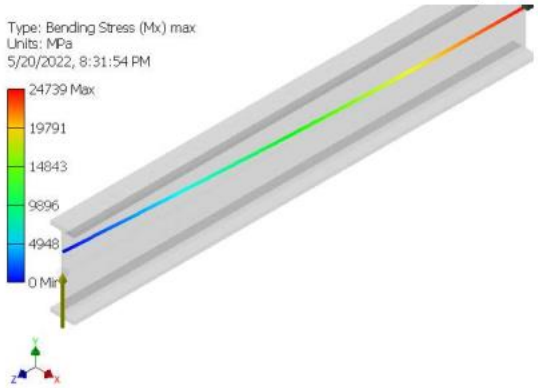
Smax



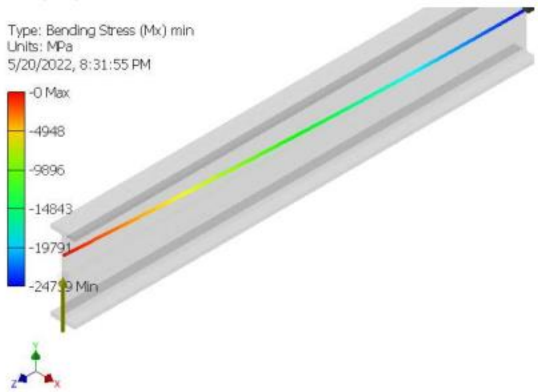
Smin



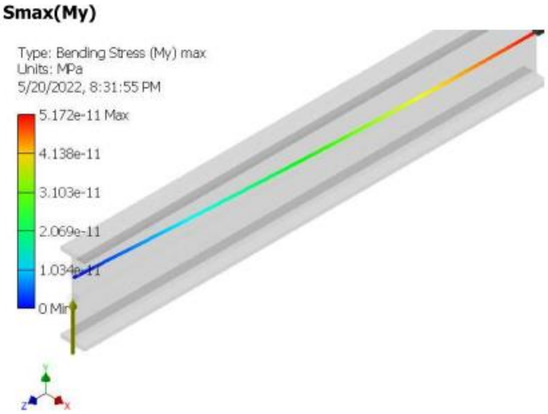
Smax(Mx)



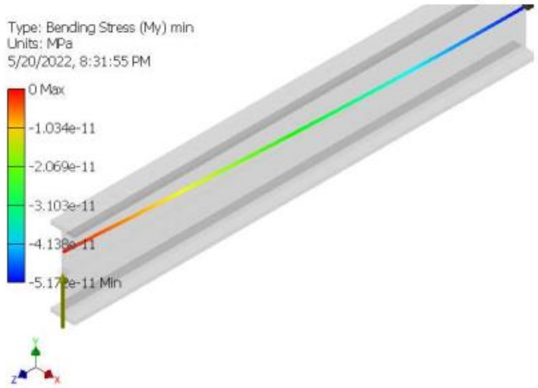
Smin(Mx)



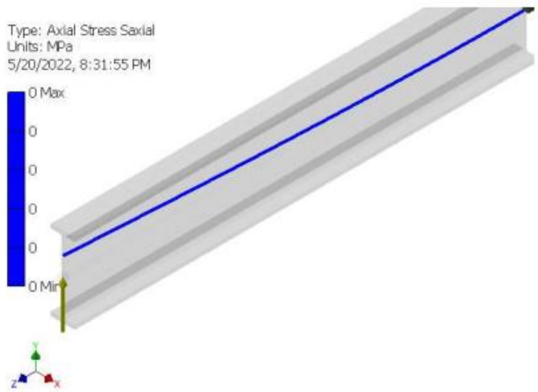
Smax(My)



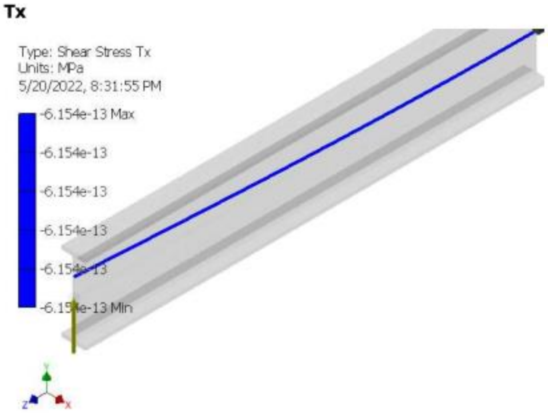
Smin(My)


Type: Bending Stress (My) min
Units: MPa
5/20/2022, 8:31:55 PM
0 Max
-1.034e-11
-2.069e-11
-3.103e-11
-4.138e-11
-5.172e-11 Min

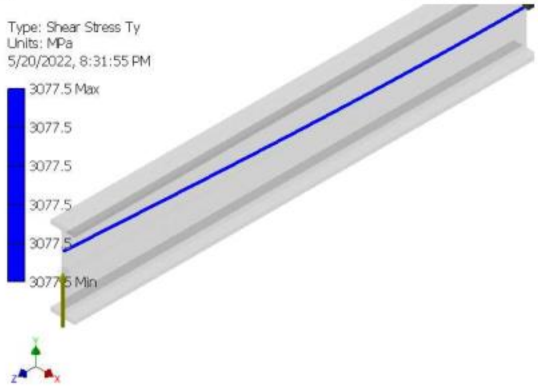
Saxial


Type: Axial Stress Saxial
Units: MPa
5/20/2022, 8:31:55 PM
0 Max
0
0
0
0
0 Min

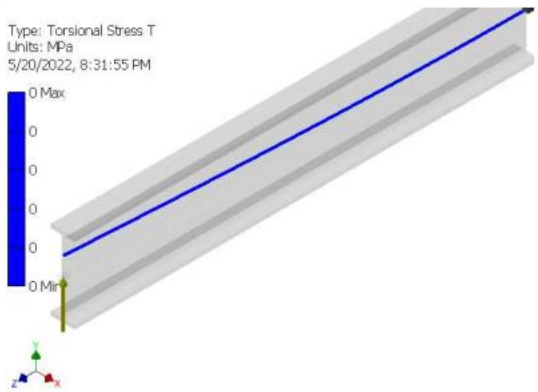
Tx


Type: Shear Stress Tx
Units: MPa
5/20/2022, 8:31:55 PM
-6.154e-13 Max
-6.154e-13
-6.154e-13
-6.154e-13
-6.154e-13
-6.154e-13 Min

Ty

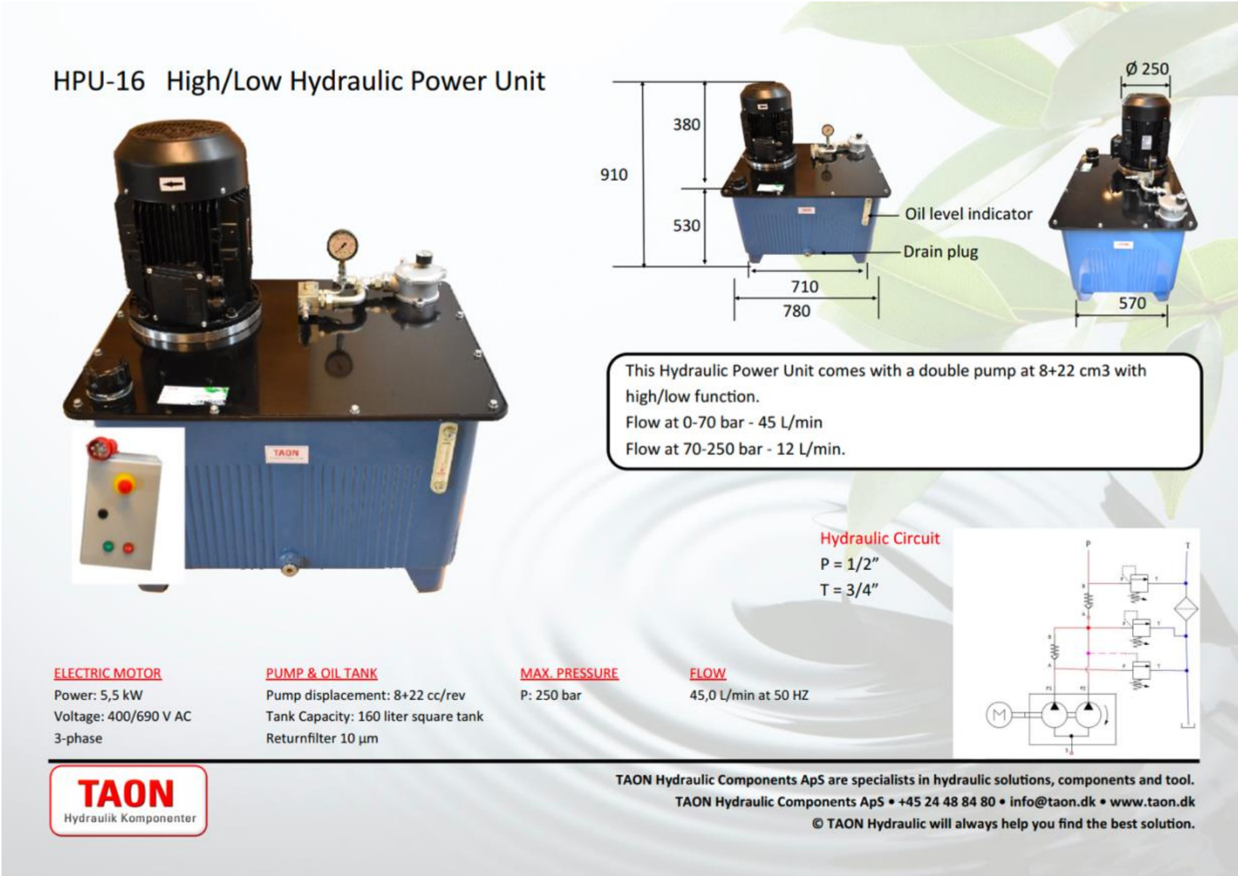


T



C:\Users\sposa\OneDrive\Documents\Inventor\Metric\Bending Nastran\Beam Analysis.iam

Appendix C: Data sheet of 5.5 kW Hydraulic Unit

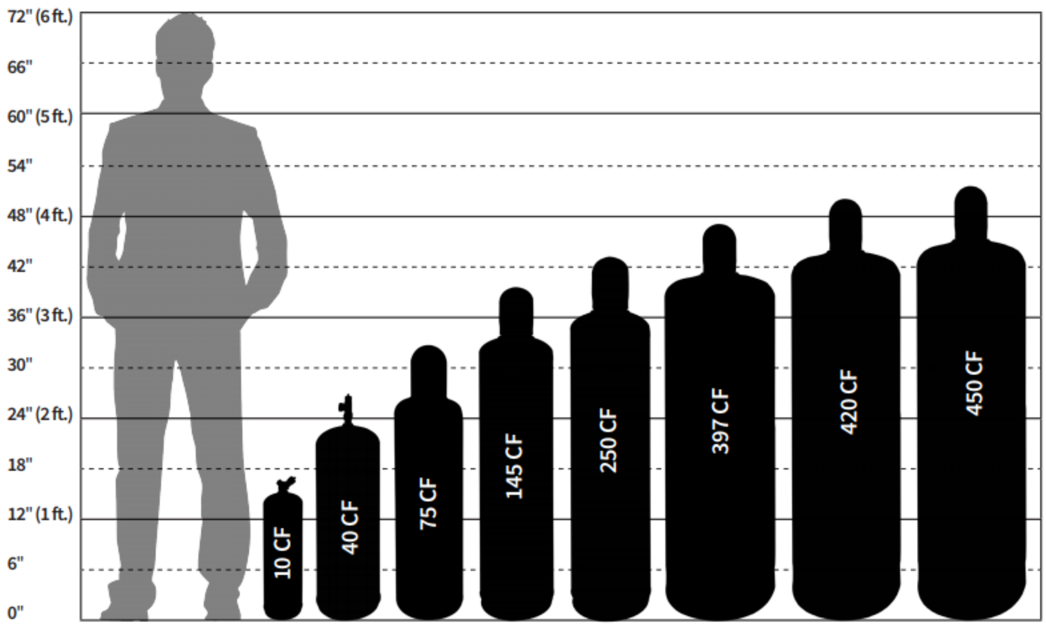


Appendix D: Oxygen – Acetylene Gas Cylinder Selection

ACETYLENE CYLINDERS

Cyl-Tec
One Resource. Zero Headaches.
100% Employee-Owned

SIZE REFERENCE CHART



ACETYLENE CYLINDERS

MODEL	Service Pressure		Diameter		Height (with Cap)		Tare Weight (without Cap**)	
	psig	bar	in.	mm	in.	mm	lb.	kg
10 CF (MC)	250	17.2	3.8	96.5	15.4	390	7.7	3.5
40 CF (B - Standard)	250	17.2	6.0	152.4	23.2	589	25.2	11.4
40 CF (B - Big Flange)*	250	17.2	6.0	152.4	25.8	655	27.9	12.7
75 CF	250	17.2	7.0	177.8	31.3	795	43.8	19.9
145 CF	250	17.2	8.0	203.2	39.5	1,003	72.0	32.7
250 CF	250	17.2	10.0	254.0	43.3	1,100	117.5	53.3
397 CF	250	17.2	12.3	312.4	46.6	1,184	170.0	77.1
420 CF	250	17.2	12.3	312.4	48.9	1,242	177.0	80.2
450 CF	250	17.2	12.3	312.4	50.9	1,293	185.0	84.0

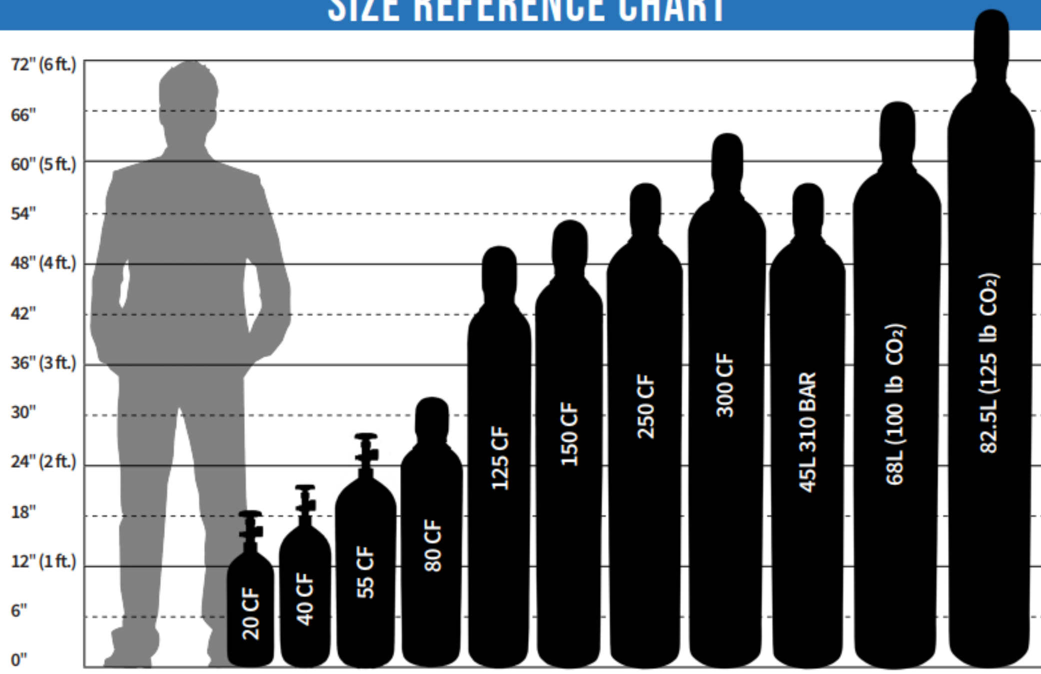
**All cylinders are DOT-8AL/TC-8WAM – except 40 CF (B - Big Flange) is DOT-8AL only. ** Cap weight = add 2 lb. (.9 kg).*

Cyl-Tec
971 W. Industrial Drive
Aurora, IL 60506
Phone: 630-844-8800
Toll Free: 888-429-5832
info@cyl-tec.com
www.cyl-tec.com

HIGH PRESSURE STEEL CYLINDERS

Cyl-Tec
One Resource. Zero Headaches.
100% Employee-Owned

SIZE REFERENCE CHART



HIGH PRESSURE STEEL CYLINDERS

MODEL	Specifications	Service Pressure	Diameter	Height
	UN ISO or DOT-3AA	*psig (bar)*	*in. (mm)*	*in. (mm)*
20 CF	UN ISO 9809-1 DOT-3AA2015	2,234 (154) 2,015 (139)	5.2 (133) 5.2 (133)	14.8 (375) 14.8 (375)
40 CF	UN ISO 9809-1 DOT-3AA2015	2,234 (154) 2,015 (139)	7.0 (178) 7.0 (178)	17.9 (455) 17.3 (439)
55 CF	UN ISO 9809-1 DOT-3AA2015	2,234 (154) 2,015 (139)	7.0 (178) 7.0 (178)	23.2 (590) 22.5 (572)
80 CF	UN ISO 9809-1 DOT-3AA2015	2,234 (154) 2,015 (139)	7.0 (178) 7.0 (178)	32.1 (815) 31.0 (787)
125 CF	UN ISO 9809-1 DOT-3AA2265	2,524 (174) 2,265 (156)	7.0 (178) 7.0 (178)	42.7 (1,085) 41.7 (1,060)
150 CF	UN ISO 9809-1 DOT-3AA2015	2,234 (154) 2,015 (139)	7.4 (188) 7.4 (188)	46.3 (1,175) 46.1 (1,170)

MODEL	Specifications	Service Pressure	Diameter	Height
	UN ISO or DOT-3AA	*psig (bar)*	*in. (mm)*	*in. (mm)*
250 CF	UN ISO 9809-1 DOT-3AA2265	2,524 (174) 2,265 (156)	9.0 (229) 9.1 (232)	51.6 (1,310) 50.4 (1,280)
300 CF	UN ISO 9809-1 DOT-3AA2400	2,669 (184) 2,400 (166)	9.3 (235) 9.1 (232)	55.5 (1,410) 56.5 (1,435)
45L 310 BAR	UN ISO 9809-2	4,496 (310)	9.4 (239)	50.8 (1,290)
68 L (100 LB CO_2)	DOT-3AA2175	2,175 (150)	10.5 (267)	58.7 (1,491)
82.5 L (125 LB CO_2)	DOT-3AA2175	2,175 (150)	10.5 (267)	70.5 (1,791)

Cyl-Tec
971 W. Industrial Drive
Aurora, IL 60506
Phone: 630-844-8800
Toll Free: 888-429-5832
info@cyl-tec.com
www.cyl-tec.com

Appendix E: Offshore Gas Cylinder Rack Specifications

Product Datasheet

CYLINDER - BOTTLE RACKS

OEG Offshore

FEATURES

- Offshore cylinder racks c/w certified lifting slings and shackles as standard
- Access door and bottle lashing points
- Forklift pockets
- Stackable
- Rental and Sale

OPTIONS

- GPS tracking available
- Hot dip galvanized or blasted and painted
- Custom design and modifications available for purchase

CONTAINER TYPE	EXTERNAL DIMENSIONS (MM)	INTERNAL DIMENSIONS (MM)	TARE WEIGHT (KGS)	PAYLOAD (KGS)	MAX GROSS WEIGHT (KGS)
6 Gas Bottle Rack	1023 x 1023 x 2141	861 x 861 x 1790	710	2000	2710
12 Gas Bottle Rack (Tall)	1378 x 1108 x 2443	1218 x 948 x 2111	670	2000	2670
16 Gas Bottle Rack	1410 x 1368 x 2182	1198 x 1164 x 1825	1140	4000	5140
16 Slot Cylinder Rack	1310 x 1190 x 2250	1042 x 1030 x 1868	930	2500	3430
25 Gas Bottle Rack	1462 x 1634 x 2480	1250 x 1430 x 2280	1050	2550	3600
Multi-Purpose Cylinder Rack	2552 x 1412 x 1637	2340 x 1200 x 1310	1090	3000	4090
1 x 2 Acetylene / Oxygen Rack	1067 x 1016 x 2108	967 x 916 x 1908	748	1247	1996
2 x 8 Acetylene / Oxygen Rack	1524 x 813 x 2082	1424 x 713 x 1882	930	2472	3402
3 x 12 Acetylene / Oxygen Rack	1295 x 1143 x 2082	1195 x 1043 x 1882	2400	3100	5500
4 Slot Nitrogen Bottle Rack	812 x 660 x 2082	712 x 560 x 1882	397	2778	3175
4 Slot Nitrogen Rack with Hinged Doors	1067 x 1016 x 2108	967 x 916 x 1908	680	1315	1996
4 x 2 Dewar Cylinder Rack	1956 x 1422 x 2286	1856 x 1322 x 2086	1587	2494	4082
6 Slot Acetylene Bottle Rack	1156 x 787 x 2083	1056 x 687 x 1883	609	1660	2268
8 Slot Nitrogen Cylinder Rack	1168 x 813 x 2083	1068 x 713 x 1983	544	2630	3175

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All dimensions and weights are accurate at the time of creation. Please check exact specifications of units when ordering.

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