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MASTER'S THESIS

Optimization of the Dismantling Process of Wind Turbine Blades from Offshore Wind Farms during Decommissioning

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16.12.2019

I confirm that the work is self-prepared and that references/source references to all sources used in the work are provided, cf. Regulation relating to academic studies and examinations at the Western Norway University of Applied Sciences (HVL), § 12-1.

Abstract

The objective of this paper is to consider alternative approaches for the dismantling process of offshore wind turbine blades during the decommissioning process. This paper was developed as part of the EU-funded DecomTools project with the overall goal to reduce the decommissioning costs within the North Sea Region by 20 percent and the environmental footprint by 25 percent. Since the world wide first offshore wind farm went into operation in 1991, followed by exponential growth of wind farms, the industry will be confronted with a huge increase of decommissioning work within the next decades.

To accomplish the goals set by DecomTools, two approaches have been considered within this paper. In a first step, a conceptual blade cutting tool has been designed. The idea of not loosen all high-tension bolts of the blade-to-hub connection manually, which can easily reach up to a number of approximately 20,000 (e.g. Sheringham Shoal wind farm), seems like a promising approach regarding cost, CO_2, and time reduction. The application of such a cutting tool implies challenges of technical and environmental nature which have to be addressed by further projects. In a second step, the approach of simulating the decommissioning process has been considered. Computational simulation is already in many industrial sectors an indispensable tool with the goal to optimize a variety of operational parameters (e.g. costs, time, required personnel etc.). It can be assumed that with simulation it is possible to evaluate different decommissioning methods in a safe and cost-effective way. The acquisition of reliable information as well as the huge amount of available input parameters will lead to very complex simulation models and can be seen as one of the main challenges within the simulation approach. Within this paper, a first conceptual simulation model has been developed with focus only on the dismantling process of the blades. This can significantly reduce the complexity of the simulation model.

The outcome of this paper is based on extensive literature study and discussions with companies involved in offshore oil and gas decommissioning as well as the cutting and sectioning industry.

Keywords: *blade cutting tool; wind turbine; decommissioning; offshore wind farms; $C0_2$ emissions; simulation; sustainability; cost reduction*

Acknowledgment

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I would also like to thank the companies that have been visited during this project for great collaboration. Through their experience and honest estimations it was possible to accumulate first impressions about the relatively young field of wind farm decommissioning from established key providers within the offshore decommissioning and the cutting/sectioning industry.

A very special thanks goes to my family who supported me in every stage of my life.

Nomenclature

ALARP	As Low As Reasonably Practicable
CAD	Computer Aided Design
HSE	Health and Safety Executive
LIVO	LEANWIND Installation Vessel Optimizer
LNG	Liquefied Natural Gas
MGO	Marine Gas Oil
MSL	Mean Sea Level
NSR	North Sea Region
OSPAR	Oslo Paris Convention
OWT	Offshore Wind Turbine
ROV	Remotely Operated Vehicle
WTIV	Wind Turbine Installation Vessel

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CHAPTER 1. INTRODUCTION

1.1 Background

In the last decades, power generated by offshore wind farms has grown exponentially. While in 2008 approximately 2GW of installed offshore capacity was providing sustainable power in Europe, in 2018 the installed offshore capacity in Europe rose up to roughly 19GW [1]. It is expected that the share of offshore wind power will keep increasing in the future. In 2016, already 10.4 percent of the European power demand has been covered by wind energy (onshore and offshore) [2]. The target for emission reduction expressed by the European Commission is to produce at least 27 percent of the final energy consumption of Europe from renewable energy sources in 2030. By expectations of Wind Europe, approximately 28 percent of the installed capacity until 2030 will be installed offshore [2]. Regarding the European Wind Energy Association (EWEA), an installed offshore capacity of 66GW in Europe could be achieved until 2030 [3].

The outstanding advantages of wind energy produced by offshore installations compared to their shore-based counterparts are typically the consistency of higher and more stable wind speeds. In addition, offshore installations are out of sight of potential stakeholders (e.g. local residents) and do not occupy land space which could therefore be used for other purposes such as agriculture. With an expected life time of around 20 to 25 years, most of the offshore wind turbines (OWT) have not been decommissioned yet. Since the first offshore wind farm has been erected in 1991 (Vindeby) and with an exponential rate of growth, a very busy future for the decommissioning market can be predicted.

It can be stated that most of the research work within the last decades went primarily into the production, commissioning, and operation & maintenance phase of the wind energy systems. Due to the fact that as of today only three wind farms has been decommissioned and with an expected life time of 20 to 25 years, the decommissioning phase received very limited attention until now.

To face the upcoming decommissioning projects, the DecomTools project has been initiated with the goal to develop solutions for more cost effective and more sustainable decommissioning operations, particularly in the North Sea Region [NSR].

1.2 Objective and research question

Since the entire decommissioning of a wind farm comprises a wide range of different tasks and operations, the focus of this paper lays on the optimization of the dismantling process of the blades in particular. The industry agrees that the current standard of dismantling the blades will be performed similarly to the installation activities (reverse installation). The intention of this paper is to consider alternative dismantling approaches, which will include the conceptual design of a blade cutting tool as well as brief introduction of simulation related to decommissioning. Always with the goal to reduce the costs and environmental footprint associated to these operations. Within this paper the following questions will be investigated:

- What are the advantages of using a blade cutting tool?
- Which cutting/sectioning method seems reasonable for the application?
- What could be a conceptual prototype for a blade cutting tool?
- Can simulation optimize the decommissioning process?
- How could a less complex simulation model be created?
- What are the challenges related to those alternative approaches?

1.3 Justification for the research

One of the main advantages of offshore wind energy systems is the provision of sustainable energy which does not produce greenhouse gases during energy production. In order to maintain the sustainable reputation it seems obvious to ensure sustainability throughout the entire life time cycle of those systems. This includes the commissioning as well as the decommissioning phase of the offshore wind farms. Another aspect is the desire of cost reduction to increase the overall profitability of offshore wind energy systems.

Currently used OWT with a power rating of approximately 3.5MW are using around 50 to 80 high-tension bolts to assure a proper blade-to-hub connection (for only one blade). This number highlights the amount of high-tension bolts that have to be loosened within the upcoming decommissioning projects. A number of bolt connections which can easily reach up to 20,000 and more (per wind farm), is reason enough to consider alternative approaches for the blade dismantling process.

1.4 Methodology

To be able to answer the research questions which are mentioned in chapter 1.3, different methods has been applied. A more detailed explanation of the used methodology is provided in chapter 3. Anyways, the methods that have been used are:

- Literature study
- Interviews with companies involved in offshore decommissioning
  and cutting industry
- CAD modeling

1.5 Structure of the paper

In this paper, the following structure will be used. In Chapter 2, a literature review is provided with a brief introduction of the DecomTools project followed by an overview of the current situation of offshore wind industry in the NSR and an explanation of the main components of an OWT. With a further explanation of the actual decommissioning process itself, Chapter 2 will be completed. A definiton of the used methodology within this paper will be given in chapter 3.

Chapter 4 will introduce two alternative approaches for optimizing the blade dismantling process and point out significant challenges which will occur by the application of those alternatives. A further discussion of these alternatives and the recommendation of further work will be conducted in Chapter 5. Subsequently, this paper will be completed by a conclusion in Chapter 6.

CHAPTER 2. LITERATURE REVIEW

2.1 The DecomTools Project

With the mission statement “Eco-innovation”, the European Regional Development Fund “Interreg” is managing different projects within the NSR. The NSR program supports transnational partnerships and brings together 49 regions from different countries, which are located around the North Sea Area, with the goal to address some of the most important challenges of that particular area [4].

The philosophy behind this project is that by sharing different expertise, ideas, experience as well as resources which are available in every participating country will help to improve existing technologies/solutions; and not negligible; to work out new solutions and technologies. The NSR program in general is based around four thematic priorities which are innovation and the knowledge economy, green technologies, climate change and other environmental challenges, and transport [4]. The target of those projects is to preserve and protect the environment and to promote resource efficiency. The two specific objectives of the projects are: [5]

1. Promote the development and adoption of products, services and processes to accelerate greening of the North Sea Region economy.
2. Stimulate the adoption of new products, services and processes to reduce the environmental footprint of regions around the North Sea.

One project backed by the Interreg NSR Program is DecomTools. DecomTools is supported with EUR 4.7 million and has gathered 13 European partners with the aim to develop eco-innovative concepts for the end-of-life for offshore wind farms. DecomTools is working on the logistical improvement of the dismantling process of deteriorated offshore wind farms while keeping the associated CO_2 emissions and costs as low as possible. As already mentioned, energy produced by offshore wind farms can be seen as one of the most sustainable ways of producing energy.

Therefore, it seems reasonable that the process of commissioning, decommissioning, as well as the afterlife of wind farms is supposed to be sustainable and as little as possible associated CO_2 emissions as well to maintain an environmental friendly climate outcome. With partners from Belgium, Denmark, Germany, Norway, The Netherlands, and the United Kingdom, the decommissioning costs are supposed to be reduced by 20 percent while the environmental footprint is supposed to be reduced by 25 percent (measured in CO_2 equivalents) [6]. The dean of the Faculty of Maritime Studies at Hochschule Emden Leer stated: [7]

"Whether repowering or decommissioning, the dismantling of the redundant parts should be carried out-cost-efficiently and with a minimized environmental footprint".

A special role within this project play the participating countries Norway and the United Kingdom, which possess a high amount of decommissioning experiences from their high developed offshore oil and gas industry.

2.2 The offshore wind industry in the North Sea Region

The potential for extracting power produced by offshore wind turbines are quite good within the NSR. Due to a wind velocity which is in average mostly high, relatively shallow waters, and low appearance of extraordinary storms are just some of the reasons why 62 percent of the installed offshore wind capacity (1,651MW) in Europe are located in the North Sea while just 15 percent are located in the Irish Sea, 14 percent in the Baltic Sea, and 9 percent are located in the Atlantic Ocean [2].

The first offshore wind farm that has been erected 1991 in the North Sea (Vindeby) was located in shallow waters just off the coast of Denmark [8]. Vindeby had an installed capacity of 5MW produced by 11 turbines with 450kW each. Compared to today's standards, the first offshore wind farm can be seen as a modest affair, while nowadays wind turbines with a capacity of 50MW are in discussion (e.g. SUMR50). Within this paper it is not essential which of the participating countries have how much share of the already installed or planned power capacities within the North Sea.

The aim is to get an overall overview about the situation in the NSR disregarding any belongings to countries. It can be stated that in 2018 a total number of 80 wind farms has been operated within the NSR. Figure 1 shows a simplified map of wind farms which are currently operating (red), approved (yellow), as well as wind farms that are planned (green).

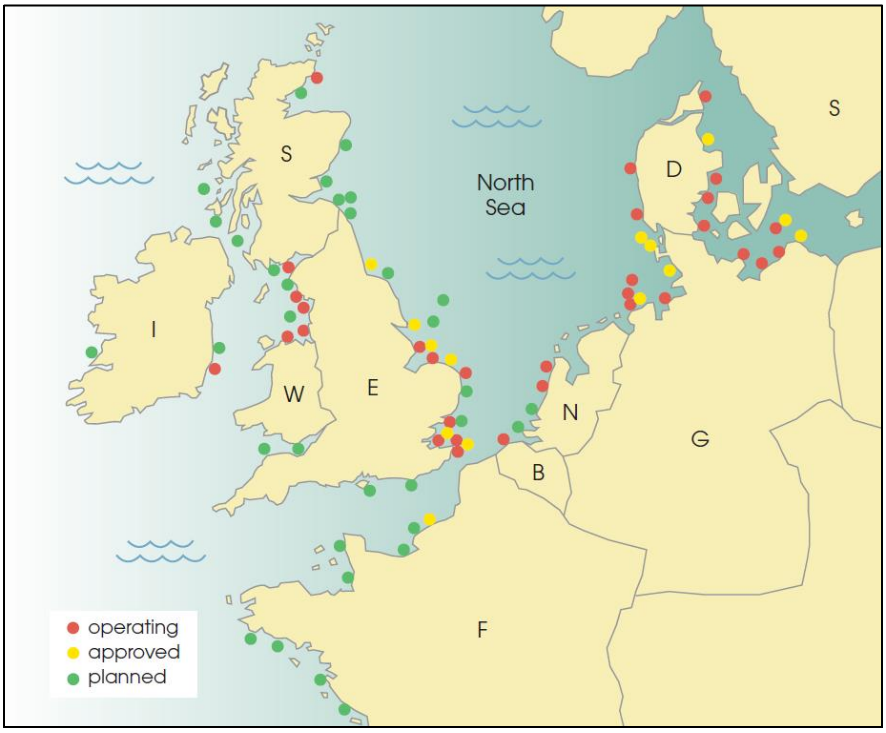

Figure 1: Wind farms within NSR [9]

In 2016 most of the worldwide countries signed an agreement with the goal to strengthen the global response to the threat of climate change by keeping a global temperature rise below 2 degrees Celsius for this century; The Paris Agreement [10]. To be able to reach the goals of the Paris Agreement; reducing the emissions of greenhouse gases; and the fact that our resources on earth are limited (e.g. coal, oil, gas) leads to predict a promising future for the offshore wind industry. Another contributing factor towards offshore wind is the fact that in the last few years it became more and more complicated for European countries with high population density to locate new sites for onshore wind farms [8].

The participating countries of the DecomTools project are planning to increase the installed offshore wind capacity by approximately 308 percent in average until 2030 [2]. This would result in an overall installed offshore wind capacity of around 47,000MW in the NSR [2]. At the present time, roughly 3,500km² of the North Sea, which is in total 750,000km², are covered by offshore wind farms. With the goal of 47,000MW installed offshore wind capacity, the area will increase to approximately 8,000km² [2]. The Norwegian multinational energy company Equinor just secured agreements with different oil companies for the first floating offshore wind farm development which is dedicated to the Norwegian Sea Oil and gas operations [11]. The wind farm is supposed to comprise eleven 8MW wind turbines based on the Hywind technology and will be located in water depths of 260 to 300m [11].

Due to a relatively young era of the offshore wind industry, a high increase of different development levels can be noticed within a short period of time. Whereas, in 2000 the average height of wind turbines installed in the NSR was around 70m, in 2018 the average height rose to 130m [2]. The same trend can be witnessed for the diameter of the rotors. While in 2000 the average diameter was approximately 70m, it rose to an average diameter of roughly 150m in 2018 [2]. It might be important to mention, that the data regarding the height of wind turbines and rotor diameter are based on numbers which reflect the average of all wind turbines finished in 2000 and 2018.

Another factor that increases constantly is the power rating of the wind turbines. As already mentioned, the first offshore wind farm (Vindeby) had 11 turbines with an electrical power output of 450kW each. The average size of grid connected turbines in 2012 can be stated with 4MW and increased to 4.8MW in 2016 [2]. Nowadays, 8MW turbines are already in use with a significant trend to even more capacity and exceeding design parameters in the near future. This year LM Wind Power produced the world's largest wind turbine blade with a length of 107m [12]. The 107m blade will be installed on the offshore wind turbine GE Haliade-X 12-MW, which is currently the most powerful turbine that provides electricity for 16,000 Dutch households [13].

In addition, the water depth as well as the distance to ashore is a decisive factor for the upcoming decommissioning process. The water depth is an essential factor for a sufficient selection of required vessels working on the commissioning as well as on the decommissioning process. The distance from the wind farm to the next suitable port side determines the logistical effort and time to return all dismantled parts and equipment. One big technical limitation factor regarding water depth of an offshore wind turbine is the foundation. Currently the maximum water depth is somewhere between 40m and 50m [2]. In 2000 the water depth where wind farms have been installed was between 0.8m and 4m while in 2018 the water depths increased up to 6m to 36m [2]. Different investigations revealed that on a European level approximately 80 percent of offshore wind resources are located in waters of 60m and even deeper [2]. As expected, the distance between wind farms and ashore reached higher levels during the last two centuries. The wind farm erected in 1991 was 1.5 to 3km off the southern Danish coast [14]. Wind farms which have been erected within the last century are reaching distances up to 85km (Gemini Winpark) or even up to 130km (Veja Mate) [2].

2.3 Components of an offshore wind turbine

The following chapter has the intention to describe briefly the technical components and the design of an OWT. Due to the goal of this paper, the blade in particular will be described in a bit more detail. In general, it can be stated that OWT and their support structures are facing a harsher environment compared to their onshore counterparts. This requires higher resistance to corrosion and wear in the marine environment as well as the ability to withstand very high wind speeds, squalls and heavy sea. The occurrence of waves induces unwanted dynamic loads on the whole structure and corrosive sea spray and salt water require an enormous durability of each component.

Another important factor is the necessity of high reliability because of the difficulties and costs of access, maintenance and repair at sea [8]. The main components of such an "offshore wind energy system" can be divided into three categories: support structure, wind turbine, and electrical supplies. The listing below gives an overview of all main components as well as the associated category.

• Foundation • Transition piece • Scour protection	Support structure
• Tower • Nacelle • Hub • Blade	Wind turbine
• Cable • Substation	Electrical supplies

2.3.1 Foundation

The foundation for wind turbines erected shore-side is usually "just" a big concrete slab which is heavy enough to create sufficient moment and holding force to withstand the bending moment and movements of the wind turbine caused by the wind acting on the blades. To design a sufficient foundation for an OWT the same factors as for a shore-side wind turbine have to be considered. Those could be for instance the highest possible wind speed, size, and weight of the whole wind turbine. For the foundation of OWT additional parameters including particular water depth, wave load, seabed conditions, and turbine-induced frequencies (turbine acts and counteracts with wave load; resonance frequency) have to be taken into account [15]. While planning and constructing a wind farm, each foundation is customized to the water depth at its particular location [15]. The most common used foundation types for OWT are monopiles, jackets, tripods, gravity base, and in a few cases the suction bucket. The use of floating foundations for OWT is in an early development stage but seem very promising for locations with greater water depth [16].

Figure 2 visualizes the five different most common foundation types. Due to the fact that almost 90 percent of the OWT in the NSR are based on monopiles structures [2], only the monopile foundation is supposed to be explained in a bit more detail.

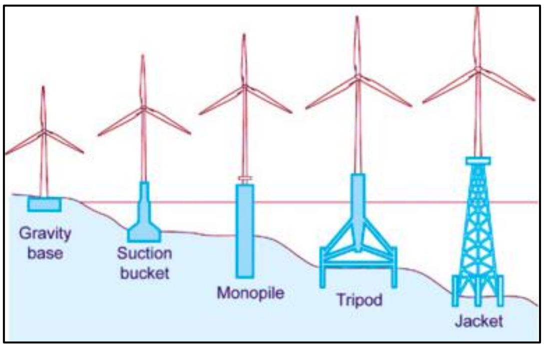

Figure 2: Foundation types [17]

A monopile is basically just a long steel tube which has been welded together from so called "cans". Cans are simplified steel plates of varying dimensions rolled into a round shape and welded together [15]. The outer diameter of those steel tubes ranges usually from 4 to 6m [18]. The advantages of monopiles are the simple design and construction effort, relatively inexpensive to manufacture, easy to handle and store, and relatively simple to install and maintain [15]. After the monopile has been manufactured, mostly barges or other vessel types will carry the pile offshore. Once the monopile has reached its final destination, hydraulic hammers are used to "stab" the pile typically 40 to 50 percent of its total length into the seabed. Figure 3 shows how such a monopile is gripped by the gripper and ready to be stabbed into the seabed.

Figure 3: Monopile stabbing [19]

2.3.2 Transition piece and scour protection

By stabbing the monopile into the seabed, the top of the pile can be forged due to the constant pounding with the hydraulic hammer. Those circumstances can lead to the metal becoming brittle and decrease the load bearing of the pile [15]. To enhance the load bearing capacity and to create a level platform on top of the foundation, transition pieces (yellow component; figure 5) are used. Already attached to the transition piece are for instance boat fenders, access ladders, access deck, cable tubings, and handrails. A transition piece can be seen as an additional oversize pile on top of the monopile. Afterwards, the monopile will be slotted into the transition piece over a distance of 6 to 8m [15]. In the following step the transition piece has to be adjusted to an exact horizontal level. The annulus between monopile and the oversized transition piece is usually filled with a high-density concrete, also called grout.

A phenomenon which can occur for a combination of a vertical pile (monopile) and a seabed with erodible characteristics is called scour. By definition: *"Scour is the removal by hydrodynamic forces of granular bed material in the vicinity of Coastal Structures"* [20]. Figure 4 illustrates the effect of scour in simplified way. To encounter scour, which can lead to a destructive structural instability, scour protection is applied. To protect the seabed around the foundation, a very common applied measure is to dump rocks of different grade and placing concrete mattresses around the foundation. Figure 5 shows the application of rock dumping around a monopile to encounter the occurrence of scour.

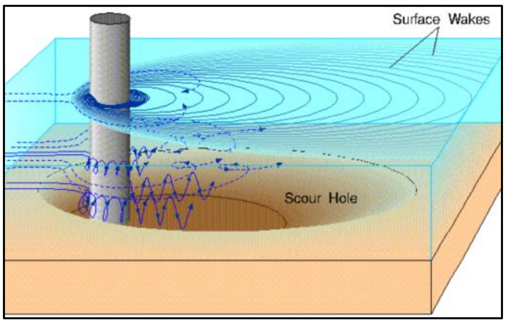

Figure 4: Scour effect [21]

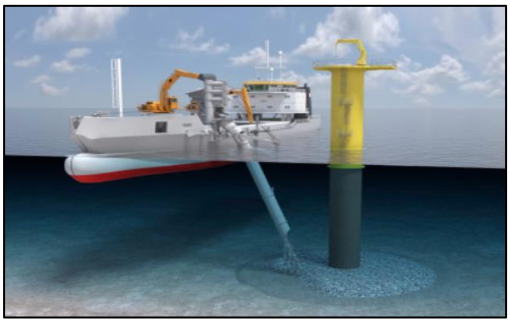

Figure 5: Rock dumping [22]

2.3.3 Tower, nacelle, and hub

The tower, same as the monopile, is a tubular structure that consists of cut steel plates which have been welded together. Figure 6 demonstrates the lifting operation while a tower is being placed on top of the transition piece. Main purpose of the tower is to provide a platform for the nacelle and is also used to accommodate a transformer in the base (if not located in nacelle), yaw motor at the top, ladder/elevating system, as well as communication and power cables [18]. The height of the tower is determined by the diameter of the blades. An approximate height of a tower for an OWT with 3.6MW (Siemens 3.6-107) is 90m with a weight of 255t [23].

Figure 6: Tower lifting [24]

The nacelle, in simple words, can be seen as the brain of a wind turbine. It is placed on top of the tower and contains the main technical parts of the wind turbine. It accommodates the low and high-speed shaft, the gearbox, the generator, the brake, monitoring systems, a hydraulic system for the blade pitch control (if applied), and the yaw drive which controls the position of the turbine relative to the wind. A trend can be noticed that for more and more OWT a helicopter platform is built on top of the nacelle. The nacelle's size and weight increase with a rising tendency to more and more powerful OWT.

While the weight for a nacelle of a turbine with a rated power of 3.6MW (Siemens 3.6-107) is roughly 125t, the nacelle of the new GE Haliade-X 12-MW weighs about 600t [25]. To illustrate the dimensions of the newest and most powerful OWT (GE Haliade-X 12-MW), the relative size of the nacelle is shown in figure 7.

Figure 7: Nacelle GE Haliade-X [26]

The hub connects the blade to the main shaft (low speed shaft) of the gearbox and thereby transmits horizontal wind loads from the blades into rotational energy. Hubs are usually made of steel and can be welded or cast. If considering the whole turbine itself, it can be stated that the hub is one of the most highly stressed components [27]. There are three basic types of hubs which have been applied in modern wind turbines: rigid hubs, teetering hubs, and hubs for hinged blades. A more detailed explanation of the hub would not meet the goal of this paper and would be beyond the scope.

2.3.4 Blade

The blades are the most fundamental components of the rotor. In technical jargon, the rotor is defined by the assembly unit of the blades and the hub. Since the goal of this paper is to optimize the dismantling process of wind turbine blades from offshore wind farms during decommissioning, it is essential to gain more knowledge about the blade itself.

Within the design process of a blade for wind turbines a lot of different factors have to be considered. Most of the factors can roughly be divided into two main categories: aerodynamic performance and structural strength [28]. A summary of relevant design considerations is given by the listing below: [28]

- Aerodynamic performance
- Structural strength
- Blade materials
- Recyclability
- Blade manufacturing
- Worker health and safety
- Noise reduction
- Condition/health monitoring
- Blade roots and hub attachment
- Passive control or smart blade options
- Costs

To address the research question mentioned in chapter 1.3, the following chapter will provide more detailed information about structural strength, used materials in blade manufacturing, and conclusively a few words about the principles of the blade to hub connection.

2.3.4.1 Structural strength

The hull and shape of the blade is designed to achieve the highest preferable aerodynamic results. The inner design and architectural structure of the blade is determined primarily by considerations of strength [28]. The inner structure must be designed to withstand extreme loads and to endure quite a certain amount of fatigue cycles [28].

Another important parameter of structural strength is the resistance to deformation. Even by the impact of high loads, the blade should not deform more than to a certain limit. A typical structure for wind turbine blades shall be visualized by a cross-sectional view in figure 8.

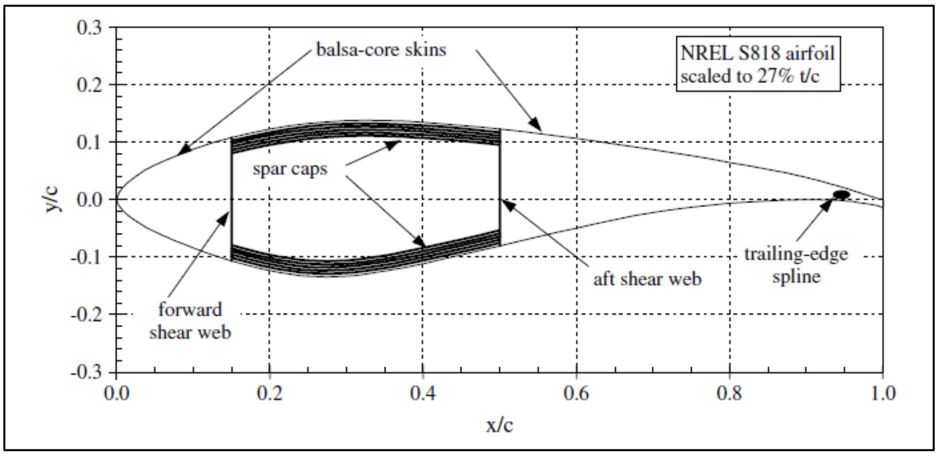

Figure 8: Blade cross-section [29]

As illustrated in figure 8, the interior strength is provided by shear webs (forward and aft) as well as spar cabs. Spar cabs are relatively thick laminates with mostly unidirectional fibres to carry the occurring bending loads (flapwise) [28]. The forward and aft shear webs take up the loads that have been transferred from the outer skin through the spar caps. In simple words, the shear web turns a pair of spars into an I-beam and thereby adds an enormous strength to the blade construction as well as preventing a spar from compression to the point of failure. The appliance of shear webs has been used in the aviation industry (wings) since it was in its infancy.

It can be stated that the blade's integrity is largely dependent on the quality of the bonding between the spar caps and shear webs [30]. With the help of figure 9 (p.16), the appliance of spar caps and shear webs is illustrated by the cross section of a wind turbine blade. At this time it remains unknown if the illustrated blade has been used onshore or offshore and for which power rating, but it seems fair enough to get a small insight.

Figure 9: Cross-section wind turbine blade [31]

2.3.4.2 Materials

Formerly, wood was the state of the art material to build wind turbine blades [28]. Steel was used to build blades of larger wind turbines until the middle of the 20th century [28]. From a historical point of view, it can be worth to consider different materials for the manufacturing process. Possible materials could be for instance aluminum, titanium, steel, fibre composite materials (glass, carbon, and aramide fibres), as well as wood [27]. A few different factors are essential to find the best suitable material for every field of application. Not only material properties are important, also the material costs, manufacturing costs, as well as the costs of development are significant parameters. Aluminum, the traditional aircraft material, does have sufficient material properties, but due to expensive production techniques the application of aluminum will be unprofitable [27].

With the beginning of the 1970s, blades for horizontal axis wind turbines have been made from composites [28]. Before discussing composites in a bit more detail, an overview of the most important material properties shall be provided. The most important material properties for a first assessment are: [27]

- Specific weight ($10N/dm^3$)
- Strength limit (N/mm^2)
- Modulus of elasticity (kN/mm^2)
- Breaking strength related to the specific weight; breaking length (km)
- Modulus of elasticity related to the specific weight (10^3km)
- Allowable fatigue strength after 10^7 to 10^8 load cycles (N/mm^2)

Figure 10 provides a table with essential strength and stiffness parameters of materials which can in principle be used for wind turbine blades. Even though only composite materials are used nowadays, the table gives a good overview of considerable materials.

Parameter / Material	Spec. weight γ	Strength limit σ_B	Modulus of elasticity E	Spec. breaking strength σ_B/γ	Spec. modulus of elasticity E/γ	Fatigue strength $\pm\sigma_A$
	10 N/dm³	N/mm^2	kN/mm^2	km	10^3 km	10^7 N/mm^2
Steel St 52	7.85	520	210	6.6	2.7	60
Alloyed steel 1.7735.4	7.85	680	210	8.7	2.7	70
Aluminium AIZnMgCu	2.7	480	70	18	2.6	40
Aluminium AlMg5 (weldable)	2.7	236	70	8.7	2.6	20
Titanium alloy 3.7164.1	4.5	900	110	20	2.4	—
Glass Fibre/ epoxy*	1.7	420	15	24.7	0.9	35
Carbon fibre/ epoxy*	1.4	550	44	39	3.1	100
Aramide fibre/ epoxy*	1.25	450	24	36	1.9	—
Wood (Sitka Spruce)	0.38	approx. 65	approx. 8	approx. 17	approx. 2.1	approx. 20
Wood/epoxy*	0.58	approx. 75	approx. 11	approx. 13	approx. 1.9	approx. 35

* EP-matrix 40 vol.%

Figure 10: Material parameters [32]

As already mentioned, almost without any exception, fibre composite materials are the most common materials for manufacturing blades of wind turbines. To say it simple words, a composite material is a material, which on a macro-scale is “composed” of multiple non-homogenous materials [33]. Glass fibre is the main fibre material, while carbon fibre is more and more used as reinforcement at critical locations [27]. The two compounds of “fibre-reinforced composite material” (GFRP) is synthetic resin and fibres [27].

The task of the fibres is to absorb stress in the material whereas the resin is responsible for embedding the fibres and create the right shape. Due to a wide range of different compounds, a large variety of resins and fibres can be combined, but just a limited amount of combination can be considered for high-strength lightweight structures for wind turbine blades [27].

2.3.4.3 Blade to hub connection

The connection between the blade and the hub is very important when it comes to the optimization of the dismantling process of OWT blades during decommissioning. For the application of possible blade cutting tools, it is essential to know how the area around the blade to hub connection is constructed. If considering the appliance of cutting tools, it has to be understood which kind of materials are used around the flange area as well as the length of possible embedded metal flanges. Currently there are four different concepts to realize a modern blade to hub connection: [27]

- Steel flange connection
- Cross-bolt connection
- Bonded-in lightweight flanges or sleeves
- Bonded-in bolts

The “steel flange” connection has been used more at older blades with polyester matrix material and by the application of heavy dual steel flanges. Within this type of connection, the blade root is clamped between an inner and outer metal flange which are bolted together by heavy duty tension bolts [27]. Figure 11 (p.19) illustrates the “heavy duty steel flange” in earlier blades. For a proper connection of the blade to the hub, the hub is equipped with an external flange ring which is the base plate for the bolted connection. One big disadvantage of this type is the relatively high weight of the blade flange, which can frequently constitute up to one third of the total blade weight [27].

Another more lightweight connection type is the “cross-bolt” connection (see figure 12, p.19). The appliance of this connection type was a step towards weight reduction of the blade and reduction of manufacturing costs at the same time [27].

Formerly used for helicopter blades, this connection type has found its way into commercial blade production for wind turbines. There is just one restriction, since polyester materials tend to plastic deformation when high load is concentrated on one point; the blade has to be made out of epoxy resin composite materials [27]. Since a well-known manufacturer for self-assembly furniture uses an almost identical connecting technique, the “cross-bolt” type is sometimes called “IKEA Joint” [27].

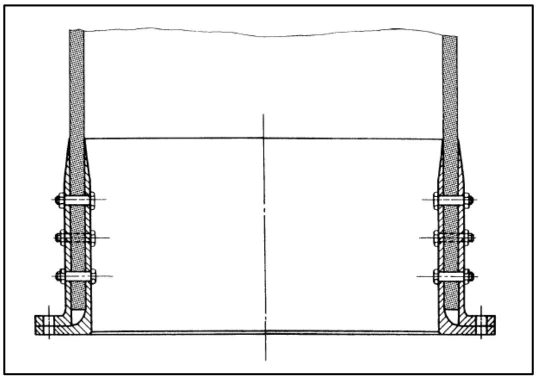

Figure 11: "Heavy duty steel flange" [34]

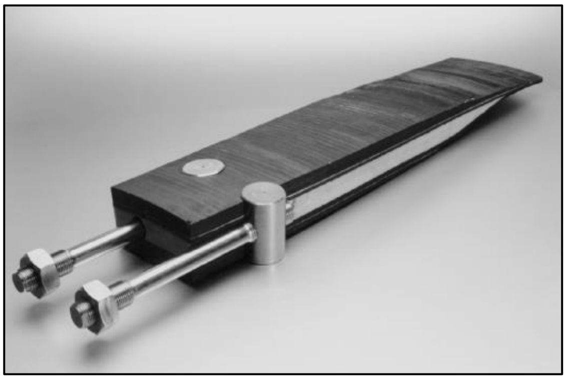

Figure 12: Cross-bolt connection [35]

An alternative to the “cross-bolt” connection has been developed by Vestas; the “bonded-in lightweight flanges” connection. Figure 13 (p.20) shows a blade root with flanges made of high-strength aluminum, which are bonded into the structure of the blade root. Another type is the “bonded-in sleeves” connection (see figure 14, p.20), designed by LM [27]. The metallic sleeves, which are bonded-in into the blade root, act as an “anchor plate” to fasten the blade to the hub. This is accomplished by using high-strength bolts which are screwed into the sleeves.

One of the simplest blade-to-hub connection types is the “bonded-in bolts” connection (from a design point of view) [27]. Because the bolts are bonded-in straight into the structure of the blade root, this approach can achieve a high level of weight reduction [27]. At the same time, this approach is evaluated to be risky [27]. Maybe further improvements regarding strength and reliability give rise for hope that this approach can be used for mass production.

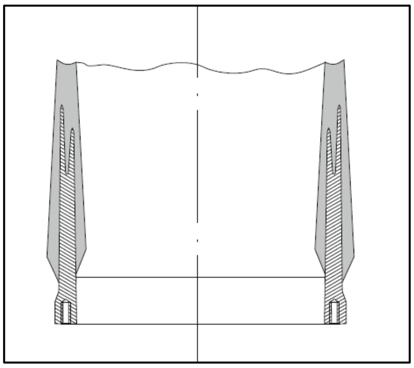

Figure 13: "Bonded-in lightweight flange" [36]

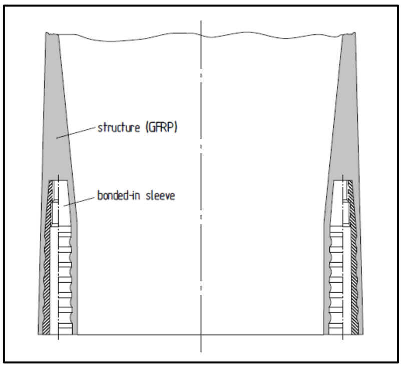

Figure 14: "Bonded-in sleeve" [37]

2.3.5 Cables and Substation

To transfer electrical power, produced by OWT, different cables from the OWT to the substation as well as to the electrical grid ashore are necessary. A typical layout of the installation of cables can be seen in figure 15. Two cable types which are usually used in wind farms are:

- Inter-array cable
- Export cable

The inter-array cables have the purpose to connect each wind turbine with an offshore substation (if present). The voltage output of the generator which is located in the nacelle is usually relatively low with 500 to 600V [18]. This voltage is not high enough for a direct interconnection to other turbines. That is the reason why every wind turbine accommodates a transformer, that transforms the voltage up to 10 to 36kV [18]. The burial process of inner-array cables is, compared to export cables, more challenging due to the required "pull-in" process to each OWT foundation within the wind farm.

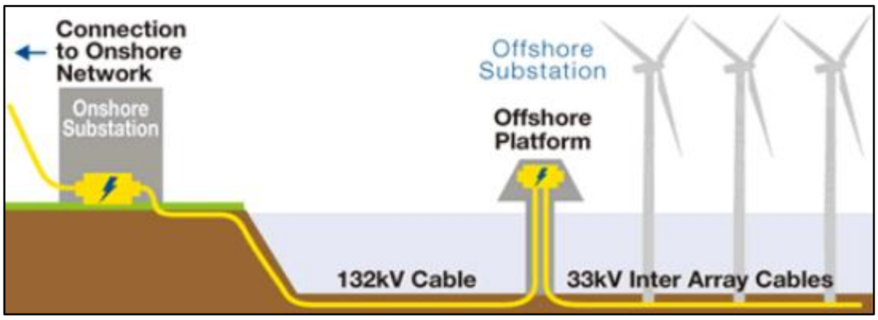

Figure 15: Cable installation layout [38]

The export cable can be seen as the connecting link between onshore facilities and the wind farm/offshore substation. The cables are composed of three insulted conductors which are protected to each other by galvanized steel wire [18].

Export cables can be classified into medium voltage (24 to 36kV) cables if no offshore substation is installed and high voltage (110 to 150kV) cables when substation is installed [18]. An advantage of high voltage cables is obviously the capacity to transfer higher amounts and larger distances of power compared to medium voltage cables. With higher capacity, the weight and diameter of the cable increases. While a medium voltage cable has a mass of roughly 20 to 40kg/m, the high voltage cable can have a mass up to 50 to 100kg/m [18]. Those exports cables are usually installed as a single length of cable and therefore larger vessels with higher storage capacity are required [39].

Offshore substations are an essential part of an offshore wind farm, which collect the power generated by each OWT (via inner-array cables) and export the power with an increased voltage to onshore facilities to minimize transmission losses. Besides the main task of increasing the efficiency of wind farms by converting the power from alternating current (AC) to direct current (DC), the substation also increases the voltage output from for instance 33kV to 132kV with the goal to reduce transmission losses. The substation plays also an important part for the stabilization of the power output as well as the monitoring function of the whole power generation process. The offshore substation of the wind farm Nobelwind, which has been installed in 2017 (47km off the coast of Belgium) can be seen in figure 16. The substation is installed on a monopile structure and has a total weight of 1,100t [40].

Figure 16: Offshore substation Nobelwind [41]

2.4 The decommissioning process of offshore wind turbines

The process of wind turbine decommissioning comes along with quite a lot of different considerations. As an initial step it has to be clarified if the OWT will be partial removed or if a total removal of the OWT including the foundation has to be done. Hans Kerkvliet from the University of Uppsala found 21 criteria which could influence the results for a multi- criteria decision for the decommissioning of offshore wind farms [42]. These criteria can be classified into the categories economic, environmental, social, and technical [42].

A closer look into all the criteria mentioned by Hans Kerkvliet would not meet the goal and expectation of this paper. Nevertheless, it is worth to mention that all methods and operations which can be related to decommissioning should be considered with regards to HSE (Healthy Safety and Environment) [43]. All requirements regarding HSE are at least equally important as the cost and time consumption for a decommissioning operation. It is essential that all parties involved in the decommissioning operation understand all potential risks related to the operation and that those risks are properly addressed [43].

2.4.1 General aspects

The commissioning of wind farms is comparatively speaking a young industrial sector where the majority of owners and operators are mainly concerned to improve installation techniques as well as the operational efficiency of the installed capacity [44]. At the present time, decommissioning has not received the attention which it might deserve. Decommissioning is the last phase of every project and a significant part of the project which should be taken into account from the very beginning. If the decommissioning process is not being considered from the beginning, impacts can become more severe and costs will probably be higher than expected. Figure 17 (p.23) shows the time scale of any technical project with a predetermined lifetime and a possible lifetime extension. But at the end of every project will come the decommissioning phase.

Offshore wind farms that have been installed within the last couple of decades have an expected lifetime of 20 to 25 years [44]. In case of technical issues or economic reasons, it might happen bringing forward the date of decommissioning.

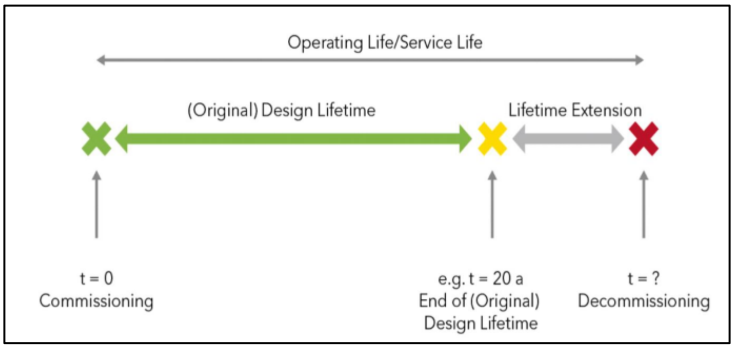

Figure 17: Operating time scale [45]

Another important subject that has to be considered within decommissioning is Article 60 adopted by the "United Nations Convention on the Law of the Sea" (UNCLOS). With respect to abandoned or disused installations or structures in the countries exclusive economy zone Article 60 states: [46]

"Any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation, taking into account any generally accepted international standards established in this regard by the competent international organization. Such removal shall also have due regard to fishing, the protection of the marine environment and the rights and duties of other States. Appropriate publicity shall be given to the depth, position and dimensions of any installations or structures not entirely removed".

Usually, the process of decommissioning OWT can be expected to be the reversal of the commissioning process [18]. The process of decommissioning is divided into several steps. The planning phase can be seen as the first step. Within the planning phase, contractual obligations as well as the requirements from lease, operating, production, sales, regulatory requirements will be examined [18]. Based on this examination, the development of a plan for the subsequent phases and for allocating the required hardware (e.g. vessels, tools) will be initialized [18].

As soon as the planning phase has been completed, the OWTs will be disconnected from the power grid and de-energized. A next stop would be the removal of liquids such as gas and lubrication oil as well as other chemicals. In some cases, liquids or chemical materials won't be removed due to reduction of a possible spillage. The following step would be the dismantling process of the OWT in its main components and the backhauling to available port facilities nearby.

The concept of the removal/decommissioning process can be carried out in many different ways and totally depends on the commissioning operation if the reverse installation process has been chosen. To give an overview of those different concepts, figure 18 shall be used. The table in figure 18 assumes that every OWT consist of two tower sections, nacelle, hub, and three individual blades. It presents six different removal options with a varying numbers of lifts required.

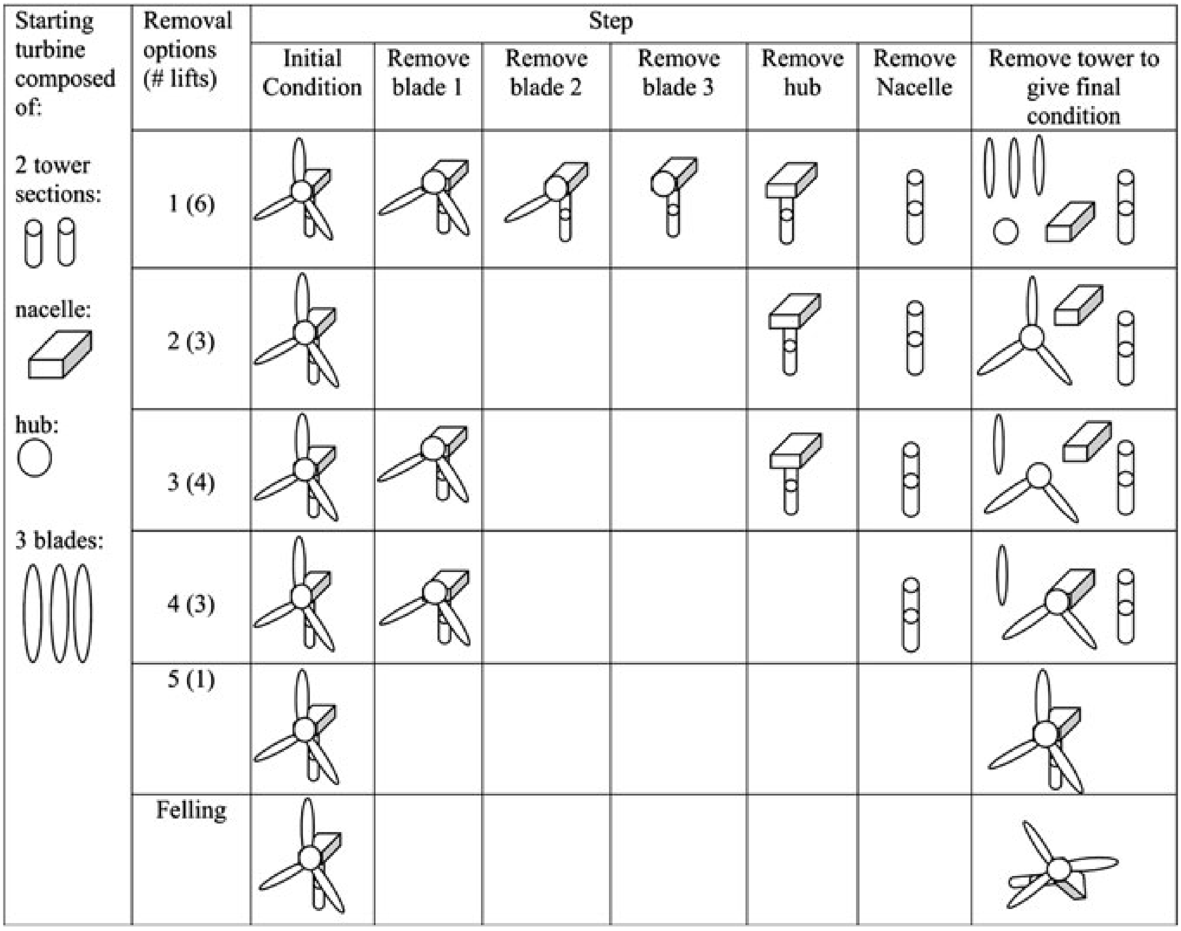

Figure 18: Dismantling concepts [47]

2.4.2 Wind farms already decommissioned

Within the last decades only a handful of wind farms have been decommissioned which is caused by the fact that the offshore wind industry is relative young. Consequently, very little experience has been gained in decommissioning wind farms and therefore in the decommissioning of the blades itself. The past has shown that each wind farm faces different environmental conditions, which makes every decommissioning process in some way unique. This leads to the assumption that there is no "one-size fits all" approach to decommission wind farms due to different factors such as water depth, distance to next available port facility, number of installed wind turbines etc. All those factors in total influence the choice of equipment and the availability as well as the operational capability of different demobilization units/vessels. In the following, a closer look to already decommissioned farms shall be taken.

2.4.2.1 Yttre Stengrund

The offshore wind farm Yttre Stengrund had an installed power capacity of 10MW and has been decommissioned in 2015 [48]. This makes Yttre Stengrund to the first decommissioned wind farm worldwide [49]. The wind farm comprised five NEG Micon 2MW wind turbines which were located roughly 4km off the coast of Sweden in the Baltic Sea. Just after an operation life time of 14 years the decision has been made to decommission the wind farm due to limited availability of spare parts and high costs of a possible upgrade of the wind turbines [48]. In figure 19 it can be seen that at Yttre Stengrund the decommissioning process of the blades was carried out in one lift with the hub and all three blades attached.

Figure 19: Rotor lift Stengrund [50]

2.4.2.2 Lely

In 2016, four turbines of 500kW each has been decommissioned in the Ijsselmeer (Lake Ijssel) named Lely offshore wind farm. The wind farm had an overall capacity of 2MW and operated for 22 years. The small wind farm was located approximately 800m off the coast of The Netherlands [48]. The operation of the whole farm has been stopped shortly after one turbine lost its rotor head and blades due to metal fatigue in 2014 [48]. Lely used a design with just two blades per turbine. The decommissioning of the blades has been carried out within one lift with nacelle, hub, and rotors in one unit (see figure 20).

Figure 20: Rotor lift Lely [51]

2.4.2.3 Vindeby

After 26 years of operation the world's first offshore wind farm Vindeby, just off the coast of Denmark, has been decommissioned in 2017. The total capacity of 5MW was delivered by 11 turbines with a capacity of 450kW each. A closer look to the process of the blade decommissioning reveals that at Vindeby the "bunny-ear" approach has been used. Within this approach, just one blade will be removed before the nacelle, hub, and the two remaining blades will be lifted down within one lift (see figure 21).

Figure 21: Rotor lift Vindeby [52]

2.4.3 Wind farms planned for decommissioning

In the following chapter a closer look shall be taken to future decommissioning projects that already have been planned, respectively proposed. It can be assumed that by the accumulation of more experience within decommissioning a constant level of improvement and modification can be witnessed. Available literature reveals that approximately 62 wind farms have to be decommissioned in a time span from 2020 to 2038 [44]. Figure 22 demonstrates a diagram of the expected numbers of wind farms in Europe to be decommissioned for the upcoming years.

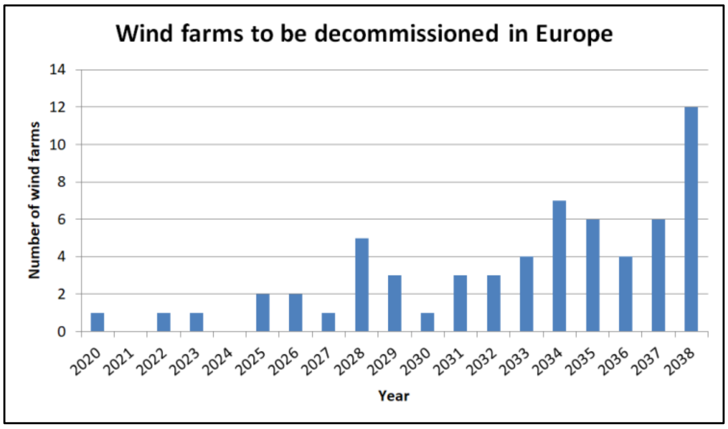

Figure 22: Wind farms to decommissioned Europe [53]

Additional literature estimates that in a time range from 2020 to 2038 approximately 4,500 OWT are supposed to be decommissioned within the NSR [54]. Figure 23 provides a diagram with the number of OWT to be decommissioned and highlights the rapid increase of upcoming decommissioning projects within the next two decades.

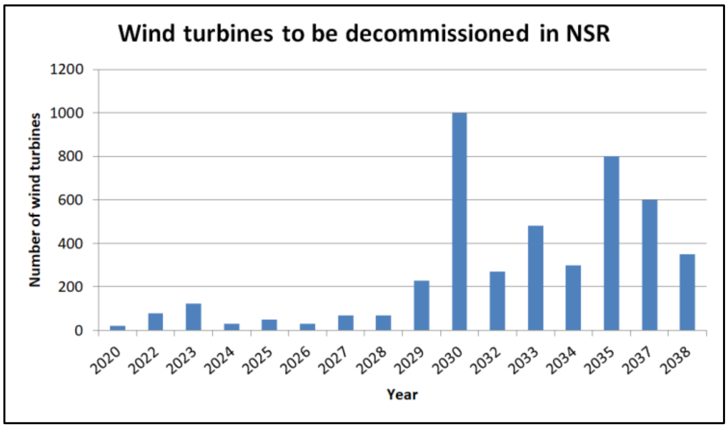

Figure 23: Wind turbines to be decommissioned NSR [55]

To get an idea of how the concept of already planned/proposed decommissioning projects will be carried out, it seems reasonable to have a closer look to their published decommissioning programs. The following offshore wind farms and the process of blade decommissioning in particular are supposed to be considered:

- Sheringham Shoal
- Lincs
- London Array

2.4.3.1 Sheringham Shoal

In 2010, Statoil revealed a decommissioning program for the Sheringham Shoal Offshore wind farm which comprises of 88 3.6MW wind turbines with a total capacity of 316.8MW [56]. The offshore wind farm is approximately 17 to 23km off the coastal town Sheringham on the north Norfolk coast and covers in total 35km² [56]. The commission of Sheringham Shoal started in 2010 and therefore it can be assumed that the earliest possible year for decommissioning is 2030 [56]. Statoil determines in its program the decommissioning of the blades will be carried out in a reverse installation process. The installation of the blades has been carried out with 3 lifts, where every single blade was attached to the hub within one lift.

2.4.3.2 Lincs

The Lincs wind farm is located 8km off the east coast of The United Kingdom and has a capacity of 270MW. In 2010 the construction phase begun and has been completed in 2013 with 75 turbines [57]. The decommissioning plan for the Lincs wind farm proposes, as well as for Sheringham Shoal, a decommissioning process as a reversal commissioning/installation process. The plan proposes the removal of the three individual blades within the decommissioning process of the turbines [57]. Compared to Sheringham Shoal, the Lincs wind farm project has a planned lifespan of 40 years, realized by a planned repowering of the turbines after 20 years [57].

2.4.3.3 London Array

With 175 Siemens SWT-3.6-107 OWT, London Array is currently the second largest offshore wind farm on Earth [58]. The wind farm with an overall installed capacity of 630MW is located approximately 20km off the North Foreland on the Kent coast (United Kingdom) [58]. In 2013, all OWT of London array where connected to the grid. The design life of the turbines is assumed with 20 years [59]. The decommissioning program published by LONDON ARRAY LIMITED stated that the decommissioning process for the OWT will likely be a reversal of the installation process [59]. The installation process of the OWT blades at London Array has been carried out by three single lifts where each blade has been installed at the hub individually.

A comparison of the last three decommissioning programs reveals that the most common practice is the concept of reverse installation. It is worth to mention that most of the reviewed decommissioning programs are mentioning that their suggested decommissioning concepts are based on a “best practice” approach regarding experiences from decommissioning projects in the past. Due to very little experience in the decommissioning of offshore wind farms, it can be assumed that during the next decade remarkable improvement as well as different concepts of removing OWT will become effective.

2.4.4 Decommissioning costs

As in almost every industrial sector, costs are one of the main drivers of every project. The costs for decommissioning an offshore wind farm are approximately 2 to 3 percent of the total capital costs [44]. The operator/owner of the wind farm has to ensure that during operating the wind farm enough assets have been accumulated to be able to pay for the decommissioning process. A breakdown of the decommissioning costs for an offshore wind farm can be seen in figure 24.

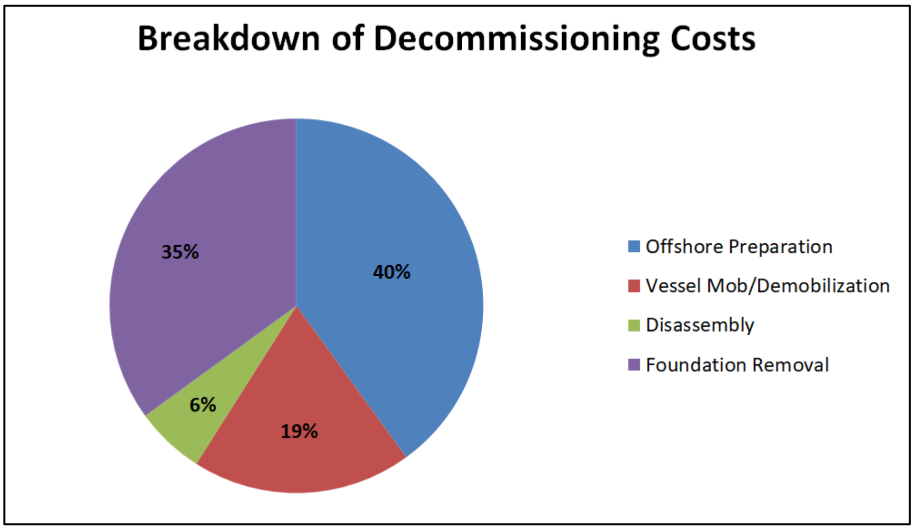

Figure 24: Breakdown of decommissioning costs [60]

As shown in figure 24, approximately 40 percent of the costs belong to offshore preparation, 19 percent to vessel mob- and demobilization, while only 6 percent belong to the disassembly of the wind turbine itself. The mentioned 6 percent of the disassembly process includes the removal of blades, hub, nacelle, tower, as well as the transition piece. A large percentage of the decommissioning costs belong to the removal of the foundation with 35 percent.

One very important factor for the determination of costs is time, while a great influencing factor of time is weather. The weather offshore can change rapidly. The work environment can turn into a hostile and unsafe condition for the working personnel, which is very common in windy areas where wind farms have been erected.

Additional influencing factors are for instance the distance to port, used vessels, logistical solutions, and of course the number of turbines and foundations of the wind farm. If one compares the estimated decommissioning time for the Greater Gabbard wind farm (140 turbines) and Lincs (75 turbines), it can be questioned that for Lincs the expected time is twice the one predicted for Greater Gabbard [44]. As already mentioned, not only the number of wind turbines has to be considered, but it shows that there has to be some improvement to reach realistic schedules and thereby a reliable estimation of costs. First estimations of expectable decommissioning costs for offshore wind farms were around £40,000/MW. Those first estimations have become outdated in the meanwhile [44]. Newer studies conducted by DNV GL estimated decommissioning cost for wind offshore energy somewhere between €200,000 and €600,000/MW [44]. It can be assumed that these costs will decrease as soon as more experiences in the field of decommissioning have been gained.

2.4.5 Recyclability

At the current time, one of the biggest challenges within the offshore wind industry is the uncertainty which comes along with the process of recycling the blades of OWT [48]. As mentioned, composite materials are mainly used to manufacture wind turbine blades. This gives the opportunity to increase performance and length while reducing the relative mass of the blade. Currently it is not possible to recycle the composite material and break it down into its initial components.

One approach to reuse the blade material is to shred it and “recycle” it through cement co-processing. Within cement co-processing, the glass fibres and fillers of the composite replacing partially the raw materials of cement production while at the same time organic materials of the blade (e.g. balsa) are used as a fuel to replace coal which is necessary for the production of cement [61]. By applying the approach of cement co-processing, the CO_2 output of the cement manufacturing can be significantly reduced (up to 16 percent if composites represent 75 percent of cement raw material) [61].

It is worth to mention that this approach can be handled on a commercial scale with a number of blades to be recycled at the current time, but figure 23 (p.27) demonstrates the vast amount of blades which have to be recycled within the next decades. Another point that has to be considered is the innovative application of carbon fibres for reinforcement of critical locations. The problem of the used carbon fibres is compared to glass fiber the relatively high specific breaking strength, specific modulus of elasticity, as well as fatigue strength (see figure 10, p. 17). Those material characteristic makes it impossible to shred a whole blade just by sectioning it in smaller pieces. Currently, before a blade being sectioned and shredded for the cement co-processing approach, the carbon fibres have to be cut out, which increases the operational time significantly.

Besides recycling through cement co-processing or using the blades as design elements, alternative approaches are being developed. The European Chemical Industry Council (Cefic) and the European Composites Industry Association (EUCIA) have initiated a project to advance new approaches of recycling wind turbine blades [62]. Two very promising recycling approaches which will be advanced within this project are solvolysis and pyrolysis [62].Whereas solvolysis is a chemical reaction of a solvent and solute that results in the formation of new compounds, the process of pyrolysis is a thermal decomposition of materials at elevated temperatures in an inert atmosphere [63]. A closer look into the chemical principles of these two approaches would be beyond the goal of this paper. Nevertheless, those two approaches seem very promising and due to some literature review, quite a lot of attention has already been paid due to upcoming research projects which could bring up a sustainable way of recycling wind turbine blades.

CHAPTER 3. DATA AND METHODS

3.1 Introduction

In the following chapter a further explanation of methods and data, which have been applied to answer the research questions of this paper, shall be provided. As already mentioned in chapter 1, a variety of methods has been used with the goal to achieve results that are as much as possible practically orientated and reflect the realities within the offshore industry. It is worth to mention that through the early stage of wind farm decommissioning, the experience gained in the fields and therefore the available literature was very limited.

3.2 Literature study

A very essential part of the preparation work for this paper was the familiarization with common practice/methods applied within the offshore wind industry. Extensive literature study was the first step to gather relevant information about the offshore wind sector with main focus on decommissioning operations. Due to the limited amount of available literature about decommissioning of wind farms, a useful subject to accumulate more profound knowledge was the field of wind farm installation as well as the decommissioning of offshore oil and gas structures. The main focus for relevant literature study was based on the following resources:

- Textbooks
- Published decommissioning programs
- Scientific articles
- Former master and doctoral theses
- Final reports of relevant projects

A decisive element within finding and reviewing literature was to evaluate the reliability of the information/data that has been found. To do so, a number of tests have been carried out. The most significant considerations that have been made during the evaluation process of the found information/data were:

- Comparison with other sources regarding great deviation
- Check of the authors and associated institution/company
- Existence of bias
- Date of publication
- Etc.

To find profound and reliable information/data to each subject, a wide range of services has been used. The listing below provides an overview of the most eminent services used within the literature study:

- HVL library (Oria)
- Online catalogue HS Emden/Leer
- Internal documents of the DecomTools project
- Google Scholar
- Online databases (e.g. Science Direct, Scopus, Research Gate etc.)
- Web pages (e.g. DNV GL, Wind Europe etc.)

3.3 Company visits and interviews

To visit and interview companies involved in offshore decommissioning and a variety of cutting/sectioning operations was a significant enrichment for this paper. The opportunity of receiving first-hand information regarding offshore decommissioning as well as the application of a variety of cutting/sectioning methods, and in particular about the diamond wire saw, was a huge enrichment for this paper. By the help of long-time experience of each individual company within their area of expertise, it was possible to broaden the horizon with respect to offshore operations and to identify bottlenecks which could possibly occur during the elaboration of the research questions within this paper.

It has to be mentioned, that the author did not participate the meeting with DeepOcean, Kvaerner and AF Offshore Decom. Before every visit, a paper with questions related to the company was handed over to allow proper preparation time. A comprehensive summary and the takeaways of each visit can be found within the “Minutes of Meetings” in appendix A to E. With access to hose “Minutes of Meetings” it was possible to extract the most useful information for this paper, even though the author did not participate in person [135].

Despite the fact that the visited companies have not been involved in wind farm decommissioning in particular, the practical experience gained within decommissioning of oil and gas structures as well as the application of diamond wire saws was a great asset for this paper. Within the framework of the DecomTools project and in preparation of this paper, the following companies have been visited:

- DeepOcean, Haugesund; Norway
- Reach Subsea, Haugesund; Norway
- Kvaerner, Stord; Norway
- AF Offshore Decom, Haugesund; Norway
- CEDIMA, Celle; Germany

In the subsequent chapters, a brief introduction of the visited companies and their areas of expertise will be provided.

3.3.1 DeepOcean

DeepOcean is one of the leading subsea service providers and has already great experience in the offshore field late-life and decommissioning market [64]. The field of experience ranges from wellhead removal, development of new remotely-operated vessel (ROV) tooling to decommissioning by burial (e.g. pipelines) [64]. For the decommissioning of different subsea structures, the diamond wire saw has been several times applied by DeepOcean.

3.3.2 Reach Subsea

Reach Subsea is a relatively young subsea-operation provider with comprehensive knowledge about subsea operations. The company is well known for state of the art ROV's and extensive engineering work [48]. Reach Subsea has been involved in decommissioning of monopiles, removal of trawl protection structures and removal of concrete subsea structures [48]. Depending on the scope of work, Reach Subsea used amongst other methods the diamond wire saw for several decommissioning tasks.

3.3.3 Kvaerner

Kvaerner has extensive experience from decommissioning of offshore oil and gas commissioning as well as decommissioning. The company has been involved in offshore decommissioning, onshore demolition, and disposal since the mid-1990s [65]. A wide range of cutting/dismantling technologies has been used within their decommissioning operations (offshore and onshore). For subsea structures, water and water grit cutting technology are used as well as diamond wire saw and special shear cutters.

3.3.4 AF Offshore Decom

AF Offshore Decom is a specialized contractor within decommissioning of offshore installations [66]. Since 1994, the company is working constantly on new solutions for the removal and recycling of offshore installations. AF Offshore Decom has been a big stakeholder in the North Sea related to decommissioning for the last 15 years. Removal and recycling of jackets and platforms is the main source of work. To the present day, AF Offshore Decom has not been involved in decommissioning of OWT.

3.3.5 CEDIMA

For more than 30 years, CEDIMA has been developing diamond tools and machines for the construction industry [67]. One area of expertise covered by CEDIMA is the diamond wire saw technology. CEDIMA develops automatic diamond wire saws in-house and participated already in the development of a mobile sectioning unit for wind turbine blades.

3.4 CAD modeling

For the design of a first conceptual blade cutting tool prototype, the software AutoCAD has been used. AutoCAD is a computer-aided design (CAD) software which allows creating 2D and 3D drawings. It is possible to draft and edit 2D geometries as well as 3D models with solids, surfaces, and mesh objectives. It is worth to mention that the goal of the designed tool was to demonstrate the idea and the concept of the tool. Given to the objective of this paper and caused by poor availability of proper 3D geometries (wind turbine blade), realistic dimensions of the first conceptual design has been neglected.

3.5 Challenges

It can be stated that the acquisition of more profound information regarding used wind turbine blades within the NSR was very dissatisfying. Almost every manufacturer (e.g. Siemens Gamsea, Vestas, Senvion, LM WindPower etc.) of blades which are involved in projects within the NSR have been contacted (via phone and mail), but not even one responded. Under those circumstances it was impossible to accumulate accurate numbers of for instance root diameters, number of used high-tension bolts, or material composition. To some extend it was possible to gather very basic information (e.g. length and mass) through advertising booklets of different blade types published by the manufactures.

CHAPTER 4. ALTERNATIVE APPROACHES

4.1 Introduction

To be able to reach the goals established by the DecomTools project, more strategies have to be developed within the unexperienced and blooming field of offshore wind farm decommissioning. To do so, a variety of approaches can be considered. At a current state DecomTools considers the decommission process in reverse to the installation process as the base case. It is worth to mention that his paper does not have the intention to estimate a potential cost and pollution saving percentage. An estimation of possible savings compared to the base case would not reflect reliable numbers due to the fact of no published ultimate costs for the decommissioning of the three wind farms in 2015, 2016, and 2017. If referring to estimations that have been made in the past, the range of decommissioning costs for the base case ranges from €200,000 to €600,000/MW dependent on a variety of characteristics of each wind farm. To be able to compare the costs of different methods, more profound information of realistic costs as well as the performance of alternative approaches is required.

Nevertheless, in the following chapters the approach of a blade cutting tool as well the approach of simulation will be introduced. The overall goal of those alternative approaches is to optimize the dismantling process of offshore wind turbine blades. To make sure that the given research goal is understood in the right way, a brief definiton of the word "optimization" shall be given. An official definiton for the word "optimization" provided by Cambridge Dictionary is: [68]

> *"The process of making something as good or effective as possible"*

Before having a closer look into alternative approaches, a discussion of essential criteria which have to be taken into account for the development of new decommissioning methods will follow in the subsequent chapter.

4.2 Criteria

A simultaneous reduction of costs and CO_2 emissions can be seen as quite challenging. With respect to cost reduction it has to be ensured that there will be no trade-off between benefit and health as well as safety conditions for the workers or the environment. To achieve the best conditions to reasonable costs, effort, or resources, the United Kingdom Health and Safety Executive (UK HSE) defined the ALARP (As Low As Reasonably Practicable) principle. The basic idea behind ALARP, which has already been applied in the oil and gas industry, is to determine the point of ALARP where the level of risk is “as low as reasonable possible” and a further reduction in risk would create outstanding costs [69]. The basic principle of ALARP is shown in figure 25.

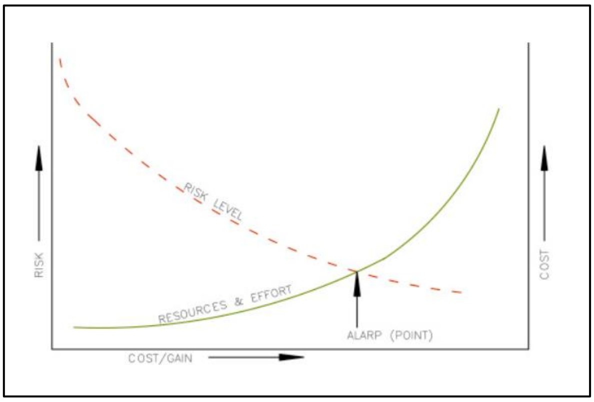

Figure 25: ALARP principle [70]

Within the determination of a suitable decommissioning method, not only costs and working safety have to be considered. The listing below gives a brief summary of one of the most significant key principles which have to be taken into account in a short as well as in a long term perspective: [59, 71]

- Safety for all at all times
- Minimize environmental impact
- Consideration of the rights and needs of legitimate users of the sea
- Promote sustainable development
- Maximize reuse of material
- Stick to the polluter pays principle
- Technical feasibility

4.3 Blade cutting approach

The idea behind the blade cutting approach is to cut the blade as close as possible at its root instead of loosen all high-tension bolts of the blade-to-hub connection. To be able to loosen the high-tension bolts very powerful hydraulic or pneumatic torque tools are required. An example of such a tool used within the offshore industry is the hydraulic torque tool HYTORC AVANTI, which can provide up to 187.6kNm in its strongest version [72]. A specification sheet of the HYTORC AVANTI can be found in appendix F. Seizure as well as deterioration and corrosion of the blade-to-hub connection can make it challenging to loosen the bolts with the standard used tools. In this case the application of grinding tools or plasma cutters can be seen as common practice [56].

The Siemens Gamsea blade B52 which is attached to the Siemens wind turbine SWT-3.6-107 (erected at Sheringham Shoal), is made out of a fiberglass-reinforced epoxy material with a length of 52m and a mass of 20t [73]. To provide a sufficient mechanical connection between the hub and the blades, approximately 80 high-tension bolts are used [74]. For the decommissioning of Sheringham Shoal a total number of approximately 21,000 high-tension bolts would have to be loosened manually. With a number of 175 OWT, approximately 42,000 high-tension bolts have to be loosened only for the blade dismantling of the London Array wind farm [75]. These numbers are significant enough to give a first idea of the resources (e.g. time, personnel, equipment) needed to perform this part of the decommissioning phase.

For relatively small wind farms such as Lely (4 OWT), Yttre Stengrund (5 OWT), and Vindeby (11 OWT) an evaluation of designing a blade cutting tool might not be considered as profitable. Due to a higher demand of more offshore wind energy, a constant increase of wind farm size can be detected. A closer look to younger wind farms such as Sheringham Shoal (88 OWT), Horns Rev II (91 OWT), Thanet (100 OWT), and London Array (175 OWT) reveal ever increasing power ratings as well as numbers of OWT [76]. With an increasing turbine rating, the diameter of the rotor will increase as well.

More mechanical stress on the hub due to higher moments and increasing mass of the blades will require more high-tension bolts to provide a sufficient blade-to-hub connection. With respect to this long-lasting trend, a discussion of designing a cutting tool to reduce the blade dismantling time can be considered as very promising.

4.3.1 Potential cutting methods

Designing a blade cutting tool can be realized by a totally new development as well as applying and adjusting already present methods. A first step would be the consideration of different cutting/sectioning methods already available. To determine the right cutting/sectioning method, different parameters have to be taken into account. Significant parameters which have to be defined beforehand are for instance:

- Material composition and characteristics of item to be cut
- Required cutting speed
- Durability
- Risk occurrence
- Operating costs
- Environmental impact (e.g. dust, noise, debris etc.)

As mentioned in chapter 3, as part of the DecomTools project and in preparation of this paper, different companies in Norway and Germany were visited to discuss their experience regarding offshore decommissioning as well as cutting operations. It can be stated that the provided information are a tremendous enrichment for the DecomTools project and in particular for the accumulation of potential and already well-established cutting/sectioning methods within the offshore sector.

A very useful summary of different cutting/sectioning methods has been created by Børre Mæland (Western Norway University of Applied Science). The summary is visualized by figure 26 (p. 42) and gives a brief description of the basic principles of each method followed by significant benefits and drawbacks.

Cutting method	**Principle**	**Pros**	**Cons**
Saw	A circular or straight blade with teeth removes material.	Wide range of blades can cut almost everything. Easy setup.	Relatively slow.
Diamond wire saw	Wire with diamond segment are dragged over/trough the object being cut and remove material.	Easy setup. Doesn't need extra operators or deck space. Can cut everything softer than diamond. Fine straight cut.	Must start from scratch if wire snap in middle of cut. Relatively slow.
Oxy-fuel	Using fuel-gas and pure oxygen to oxidize the metal in an exothermic reaction.	Cost effective. High cutting speed.	Need experienced operators or automated system for fine cut. Can cut only low carbon steel and low alloy.
Laser	Using a focused laser beam to heat the metal, the heated metal is either blown away with air or N_2 or oxidized with the use of pure Oxygen.	Can cut materials not possible to cut with oxy-fuel. Can cut complex patterns. Small area affected by heat. No wear out of cutting equipment.	Not developed enough for subsea operations.
Plasma	Using heat from gas in the plasma state to melt and vaporize the electrically-conductive material.	Can cut all electrically-conductive material and materials not possible to cut with oxy-fuel. Can use clean air as gas.	Rough cut with handheld equipment.
Grinding	Friction from a circulating blade scratches away material, both the blade and material are scratched away.	Simple construction. Same tool can be used with different blade.	Used in small cut operation Slow speed. Used for maintenance.
Water jet	Using high-pressure water with abrasives to cut materials.	Is a very versatile and effective process and can cut through almost any material. Can cut thick materials, up to 1500mm concrete.	Need dedicated operators and deck space. Orifice wear out. Uncertainty regarding cut verification.
Guillotine/	Using hydraulic power to push a knife against an anvil. Use hydraulic power to cut materials between two knives.	Effective. Can be used as safety release device.	Deformation of the object being cut.
Shear-cutter	Use hydraulic power to cut materials between two knives.		
Explosives	An explosion is a very rapid exothermic chemical reaction where the explosive material is converted to very hot, dense, high-pressure gas that can cut through materials.	Effective, can blow away everything. Effective and safe on big structures.	Dangerous if used wrong. Transport with strict safety measures.

Figure 26: Summary of possible cutting methods [77]

As a continuation of the summary, a brief discussion of the different cutting/sectioning methods will be conducted to get an idea which method could be used for the application of a blade cutting tool. It is important to mention that the evaluation of the usability of those different methods is based on the author's technical understanding and his point of view.

4.3.1.1 Saw

The application of a circular or jig saw might be questionable for a blade cutting tool. Due to the fact that the root of a modern OWT blade can reach a diameter of more than 4m, a prolonged operation of a saw will come along with a variety of challenges. By using a circular saw, the sawblade must have a radius of at least the maximum diameter of the blade root, which makes a safe operation at a height of 80m and more uncertain. A reduction of the sawblade diameter would cause less installation space, but requires a support structure around the blade root to ensure a cut all the way through the material and to meet the exact initial starting position. From a technical point of view this would lead to a quite complex and most likely expansive method and is therefore not taken into account. The same is valid for utilizing a jig saw. Figure 27 shows the application of a circular saw sectioning blades of an onshore turbine. For sectioning smaller blades while lying on solid ground, the circular saw can be seen as a suitable method.

Figure 27: Circular saw [80]

4.3.1.2 Diamond wire saw

Within this method, a reinforced steel wire with diamond segments is dragged over the object to be cut. Diamond wire saws already gained a lot of reputation in the offshore oil- and gas industry as well as in the process of sectioning wind turbine blades ashore. At the first glance, the diamond wire saw method has the highest potential for the application as a blade cutting tool. Therefore a more detailed explanation of the working principles, advantages and disadvantages, as well as a first conceptual prototype can be found in chapter 4.3.2 and 4.3.3.

4.3.1.3 Oxy-fuel

The basic principle of oxy-fuel cutting is a chemical/thermal reaction occurring with iron and iron alloys only [79]. A small area of the metal (from the workpiece) is preheated to reach a certain temperature. As soon as the desired temperature has been reached, a confined stream of oxygen is blown onto this area. This leads to a narrow band of oxidized iron, where the melted oxide and metal are removed by the kinetic energy of the oxygen stream [79]. Based on those principles it is obvious that oxy-fuel can be used for metals only and is therefore not applicable for composite materials.

4.3.1.4 Laser

A big advantage of laser cutting is the wide range of materials that can be cut. While a laser beam is focused on the workpiece to heat it up, an additional gas is used to blow away the heated material [78]. A laser cutter is a high-tech piece of equipment designed with fragile parts like mirrors and lenses. Due to high complexity combined with filigree components, an application within the offshore industry and its harsh environmental conditions does not fit. Another cut-off criterion is given by the principle function of the laser cutting method. Since the laser is using lenses to focus the laser beam into a focal point where the material has to be cut, the position of the focal point is related to the focal length. Figure 28 shows different positions of the focus which are usually determined by material characterisics and thickness. To make sure that the focal point will always be at the right spot, the laser would have to be guided around the blade while following the exact shape. Those points as well as the appearance of the inner architecture of the blade (shear webs) make the application of a laser for this tool hardly possible.

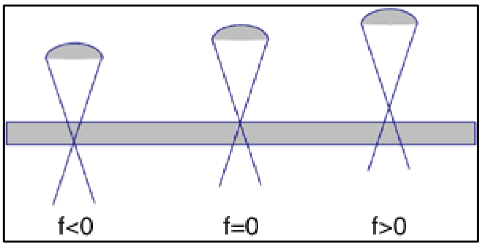

Figure 28: Laser focal points [81]

4.3.1.5 Plasma

To describe the principles of plasma cutters, it is necessary to briefly discuss the appearance of plasma. Plasma in simple terms is the fourth state of matter. The terms solid, gaseous, and liquid are usually well known while plasma attracts little attention. The introduction of energy, such as heat, will cause a change of matter. H_20 as an example, if heated, will change from ice (solid) to water (liquid). An increase of the introduced heat will turn the water into steam (gas). In case the level of heat increases on and on, the steam gases will become ionized and electrically conductive, it changes to plasma. The plasma cutter is using the electrical conductive gas to transfer the energy from the power supply to any kind of conductive material. Right there the cut-off criterion for a blade-cutting tool application can be found. The blade itself is made out of non-conductive materials and therefore cannot be cut with plasma.

4.3.1.6 Grinding

The process of grinding is part of the abrasive cutting discipline and can be carried out by a variety of machines such as hand-cranked grindstones, handheld power tools (e.g. angle grinder) as well as expensive industrial machine tools. Grinding practice is a huge and diverse area of manufacturing within the engineering industry. The main goal of grinding is usually to create a fine finish, accurate dimensions etc. It can be stated that grinding is primarily used for small cut and maintenance operations [78]. The cutting speed of grinding can be considered as relatively low [78]. Conclusively, the latter mentioned characteristics of grinding result in an exclusion for the application as blade cutting method.

4.3.1.7 Water jet

Water jet cutters use a very high-pressure jet of water or a mixture of water and an abrasive substance. With water jets a variety of materials such as marble, granite, stone, metal, plastic etc. can be cut [82]. For the sectioning of turbine blades the water jet has already been used within different onshore applications. On the first glance, the method of water jet cutting appears somehow promising for an application as a blade cutting tool, but due to great occupation of valuable deck space for the needed equipment on board the working unit, it will be not considered within this paper.

4.3.1.8 Guillotine

The invention of the guillotine goes back a couple of centuries, where people got sentenced for execution by beheading [83]. Back in the days the gravitation force of the knife was sufficient enough to complete the job. Nowadays, usually hydraulic power is used to push a knife against an anvil to cut the material/workpiece which is placed in between [78]. One drawback of the guillotine is the vast deformation of the material being cut which can possible cause a significant amount of debris by parts of the blade breaking away. In addition, this approach needs a sufficient support structure and base plate where the introduced force can be absorbed. This would create a relatively big structure. Due to these reasons the guillotine method will not be considered as a method for a cutting tool.

4.3.1.9 Shear-cutter

The shear-cutter uses hydraulic power to cut material between two knifes. A report published by Wind Europe in 2017 stated that the shear-cutter/jaw-cutter is currently the most common method for sectioning wind turbine blades before recycling ashore [84]. The cut-off criterion for not considering this method for the cutting tool is a steady increase of the blades' diameter which would result in disproportional big shears/jaws to be able to cut the blade. Another significant factor is the uncontrolled emission of fibres as well as big loose parts which can break-off by cutting the blade. Figure 29 demonstrates the application of the shear-cutter and the vast amount of loose parts during sectioning.

Figure 29: Shear-cutter [85]

4.3.1.10 Explosives

The application of explosives is common standard for decommissioning offshore oil platforms in the Gulf of Mexico and is recognized as a safe and effective method [78]. The working principle of explosives is a rapid exothermic chemical reaction where explosive material converts to very hot, dense, and high-pressure gas. The effect that is used for decommissioning purposes, is the shockwave caused by a rapidly expanding gas with a high velocity [78]. In water, the use of explosives might be a reasonable solution, but using explosives during crane operation with a mass of 20 to 25t on the hook does not seem as a safe work environment. Another argument against explosives is the mounting process of explosive material on the blade. If not remotely performed, a worker would have to strap it manually to the blade which makes it necessary to operate in a work basket at a height of usually more than 80m (e.g. Siemens SWT-3.6-107). At this height the workers are facing high risks and potentially harsh environmental conditions. Additional problems can occur if it is not possible to verify a complete cutting/sectioning operation on the first glance. This would require a worker in the vicinity of the cut to assure successful cutting by visual inspection. Residuals of explosives that did not go off represent a serious risk for worker in the close surrounding. Those factors are leading to the decision that explosives as a method for a blade cutting tool is not taken into account.

4.3.2 The Diamond wire saw

Approximately 2000 before Christ, the Egyptians were the first one who started to cut blocks of stone with the help of wires and a mixture of water and sand [86]. In the 19th century the industrial application of cutting stone by wires and ropes in stone quarries begun. This method is to some extend still used in different stone quarries. Figure 30 (p.48) shows the assembly of different cutting wires guided by wire guide pulleys in a stone quarry. Whereas in the past the abrasive medium was accomplished by admixing silica sand and later carbide, in the 20th century the utilization of diamond rolls threated to the wire has prevailed [86].

A steady development of wire saws made this method to an all-rounder which became indispensable in many industrial sectors with the possibility to cut almost every shape and material. In the following chapters a brief introduction of different diamond wire saw designs, significant working principles and components, and conclusively a summary of relevant benefits and drawbacks are provided.

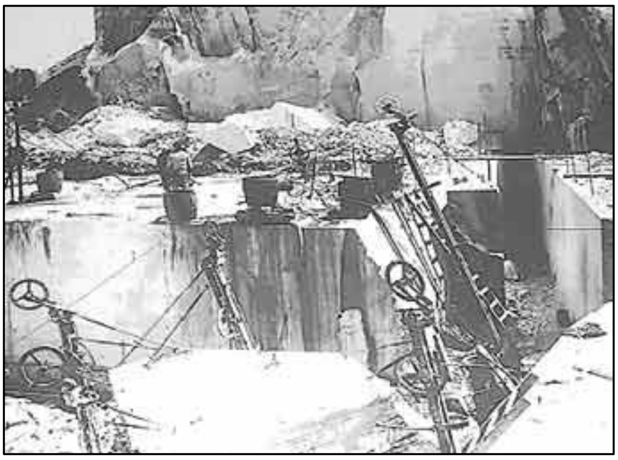

Figure 30: Wire saw in stone quarry [87]

4.3.2.1 Different wire saw designs

As mentioned before, quite a few different types of diamond wire saws are present in a variety of industrial applications. Within the offshore oil and gas industry the diamond wire saw is used to cut pipelines, platform legs, piles, wellheads etc.

Another major industry utilizing the diamond wire saw is the construction and deconstruction industry. Within these sectors the saw is used for the reconstruction of walls as well as for the demolition of buildings, nuclear power plants, etc. A very famous diamond wire saw application was the salvage operation of the Russian submarine K-141 Kursk in the Barents Sea in 2000. The submarine, with a length of 154m, presumably experienced technical malfunction resulting in an explosion which caused the sinking of the nuclear powered K-141 [88]. Before K-141 salvaged from seabed, divers used diamond wire saws to detach the bow from the rest of the submarine because of unexploded torpedo warheads and the risk it could break off and destabilize the lifting operation [88].

The latter mentioned examples emphasize the wide range of applications and by that it can be assumed that already a certain amount of experience and expertise has been gained. In conclusion, a few examples of different diamond wire saw types shall be presented. The variety of different types can range from mobile circular saws (figure 31), mobile saws mounted on support structure (figure 32), stationary saws (figure 33), to mobile units with temporary support structure (figure 34).

Figure 31: Mobile circular saw [89]

Figure 32: Mobile saw on support structure [90]

Figure 33: Stationary saw [91]

Figure 34: Mobile unit with temp. support structure [92]

4.3.2.2 Working principle and components

The overall working principle for diamond wire saws can be seen as very comprehensible and is valid for every type of diamond wire saw. An exception to this is the circular wire saw (figure 31), but this can be neglected for now.

To demonstrate the working principle of a diamond wire saw in a bit more practical way, a simplified visualization has been chosen. As shown in figure 35, the diamond wire saw consists in general of the following parts:

- Motor (power unit)
- Diamond wire
- Driving and guiding pulleys
- Feeding mechanism

The main goal of a diamond wire saw is to accelerate the wire up to a desired speed and maintain the necessary tension of the wire which is essential for the cutting operation. Some sort of motor drives the driving pulley which is looped around by the diamond wire. By the movement of the wire and the introduced wire tension, material abrasion can be detected at the contact points of the wire and the workpiece. Appropriate wire tension is required to ensure effective cutting speeds as well as protecting the wire from thermal and mechanical overload. To be able to maintain constant wire tension, different kinds of feeding mechanisms are used. Figure 35 shows the application of a hydraulic cylinder which is connected to one of the guiding pulleys. An extension of the cylinder would decrease the wire tension while retracting the cylinder would cause an increasing wire tension. Another method to adjust the wire tension could be the relative movement of the wire saw supporting structures to the workpiece (figure 32, p. 49).

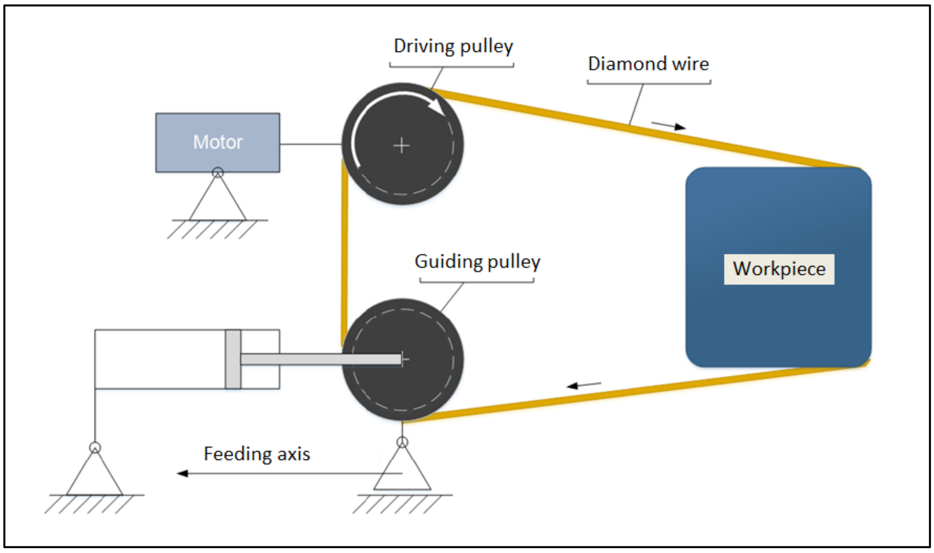

Figure 35: Diamond wire saw concept [93]

Due to strong heat development in the cutting area it is recommended to cool down the diamond wire during operation. Common practice is to apply water by water lances right into the cutting area. Different investigation revealed that with sufficient cooling the lifetime of the wire can be significantly extended [94]. In the subsequent chapters, the main components of the diamond wire saw as well as the importance of sufficient water supply shall be discussed in a bit more detail. Caused by a great number of different feeding mechanism and different levels of complexity, the feeding mechanism will be discussed in chapter 4.3.3.1 with respect to the conceptual prototype.

In the following, a bit more insight of the actual cutting process of a diamond wire saw shall be provided. Simply said, the spinning diamond wire is being attached to the workpiece with a predefined initial tension. The cutting speed and direction (Vc) in combination with a given direction of feed (Vf) will result in an effective direction (Ve). By the help of figure 36 the process kinematics of a diamond segment in interaction with the workpiece during a cutting operation can be visualized.

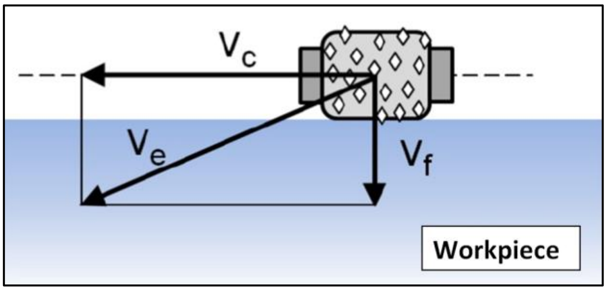

Figure 36: Process kinematics [95]

All the cutting forces which act on the diamond segment during the cutting operation are applied by form closure to the workpiece. The overall cutting force acting on the diamond segment can be divided into the following components: [94]

- Normal force F_n: effective direction in wire curvature
- Tangential force F_t: effective direction contrary to cutting direction
- Lateral Force F_a: effective direction orthogonal to F_n and F_t

Figure 37 constitutes all process forces which act on the diamond segment during the cutting operation. A deeper analysis and explanation of the relevant forces is left out and would not meet the expectation of this paper.

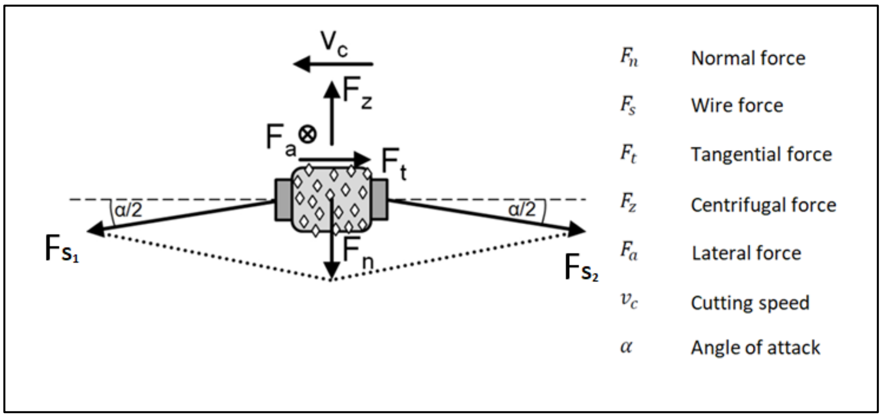

Figure 37: Process forces [96]

4.3.2.2.1 Power unit

The power unit includes a motor which is responsible to provide the requested power to any given time. Usually most of the wire saws are driven by hydraulic or electric motors, but an application of small sized combustion engines can be also conceivable under given circumstances. The power output of the motor is directly connected to the wire driving pulley. For the ease of operation a user-friendly control panel is needed to adjust and control wire speed as well as wire tension. The location of the control panel can be chosen by demand. The offshore oil and gas industry has proven that within the last decades a diamond wire saw operation can be remotely controlled up to a water depth of a couple of thousand meters [97]. Experiences gained by the sectioning process of wind turbine blades has shown that a power output of 15 to 20kW is sufficient enough to cut a blade root with a diameter of 2m and a material thickness of roughly 330mm in less than 15 minutes [98].

4.3.2.2.2 Diamond wire

The diamond wire can be seen as the most essential part of the diamond wire saw. One of the biggest advantages of a wire saw are given by the ability to cut every material softer than diamond and a theoretical infinite length of the wire which gives the opportunity to cut large structures.

The basic element of the diamond wire is the support wire (see figure 38). The support wire is usually made out of steel with fine strands and a high breaking load (>19.000N) [98]. The coated diamond rings/segments are the actual cutting elements which are threaded to the support wire. The diamond coating is applied to the support rings by a galvanic or active soldering process or eventually the process of sintered diamond impregnation [98].

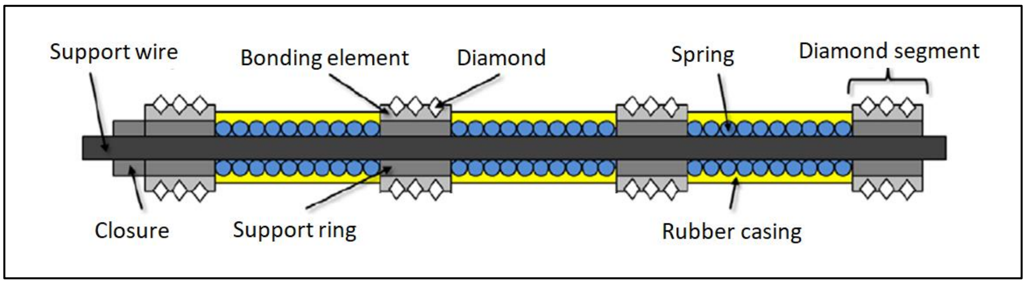

Figure 38: Diamond wire structure [99]

To protect the support wire, reinforced springs are used as a spacing element between the diamond segments. A rubber casing is used to secure the diamond segments on the thread as well as an anticorrosive agent for the support wire. To be able to repair, open, and close the wire a closure is applied. Due to the construction of the closure, it is from an utmost importance to make sure that the wire is operated in its determined running direction. To achieve the best trade-off between cutting time, cut quality, and tool wear, the cutting speed of the wire has to be adjusted to each material and structure to be cut. Experience has shown that for the different materials the following cutting speeds are adequate: [98]

- Solid rock ca. 20 m/s
- Reinforced concrete ca. 25 m/s
- Abrasive materials ca. 30 m/s
- Composite materials ca. 30 m/s

4.3.2.2.3 Wire guiding pulleys

The main task of the wiring guiding pulleys can be derived from its name. Guiding pulleys are supposed to guide the diamond wire to assure proper aligning for a straight cut. The application of wire guiding pulleys gives the opportunity to cut even structures which are difficult to access without sacrificing cut quality. Furthermore, at some cutting operations the pulleys are used to reduce the angle of attack of the diamond wire. Even though a certain angle of attack is required, a buckling diamond wire with a too great angle of attack will cause high stress for the fine metal strands of the support wire. High stress of the fine metal strands will lead to fatigue and consequently reduce the operational lifetime of the cutting wire. Figure 39 demonstrates the angle of attack between the diamond wire and the plane cutting level of the workpiece. A rule of thumb for a required angle of attack in order to achieve sufficient cutting results is a minimum of 15° [98].

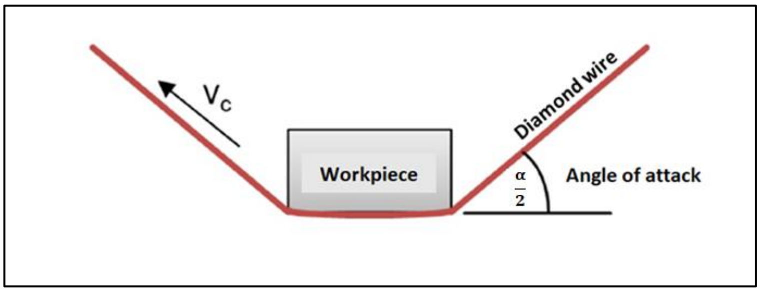

Figure 39: Angle of attack [100]

The occurrence and the issues of a too great angle of attack shall be demonstrated by the help of a brief example. Figure 40 (p.55) shows a pipe which is cut by a diamond wire and where the entwined approach is used. Entwined; this means that the diamond wire has to be attached around the pipe before the cutting operation can start. Even though the entwined approach is not supposed to be used for the conceptual prototype of this paper, a small explanation seems reasonable. As shown in figure 40 (p.55), the angle of attack during the cut of a tubular shaped workpiece can reach almost up to 80 to 90°. It is easily comprehensible that an angle of attack of almost 90° will cause tremendous stress for the diamond wire.

To avoid those great angles of attack, support brackets with additional wire guiding pulleys are used. The application of supports brackets as well as an increasing bending radius and therefore a decreasing angle of attack can be seen in figure 41.

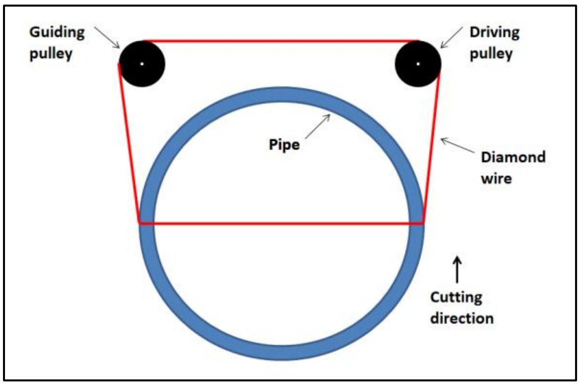

Figure 40: Diamond wire saw w/o support brackets

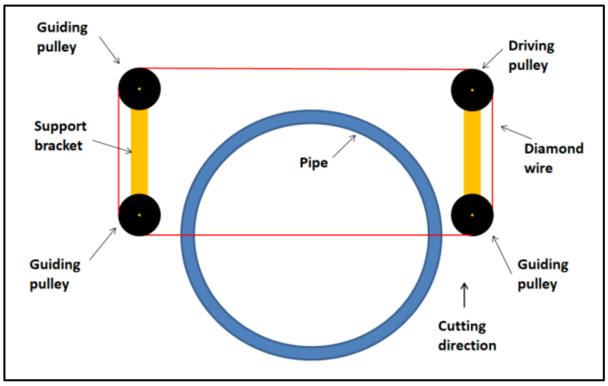

Figure 41: Wire saw with support brackets

4.3.2.2.4 Water supply

By cutting composite materials it is required to provide a sufficient amount of water during the entire cutting operation. Water acts as a coolant for the diamond wire as well as for the cutting area. Through the contact and relative movement between the diamond wire and the blade, the existing friction between those two surfaces will convert kinetic energy into thermal energy (heat). Thermal hotspots in the cutting area can lead to melting material. The past has shown that the material of wind turbine blades (composite materials), if cut with a diamond wire saw and without sufficient water supply, will start to melt in the cutting area and clogs the cutting elements (diamond segments) [98].

Clogged cutting elements will increase operation time, decrease cut quality, and requires the replacement of the diamond segments which will increase the operational costs. To avoid thermal hotspots the diamond wire and the cutting area have to be cooled down. Figure 42 (p.56) demonstrates the appearance of thermal hotspot of an engaged diamond wire during cutting operation of a concrete sample.

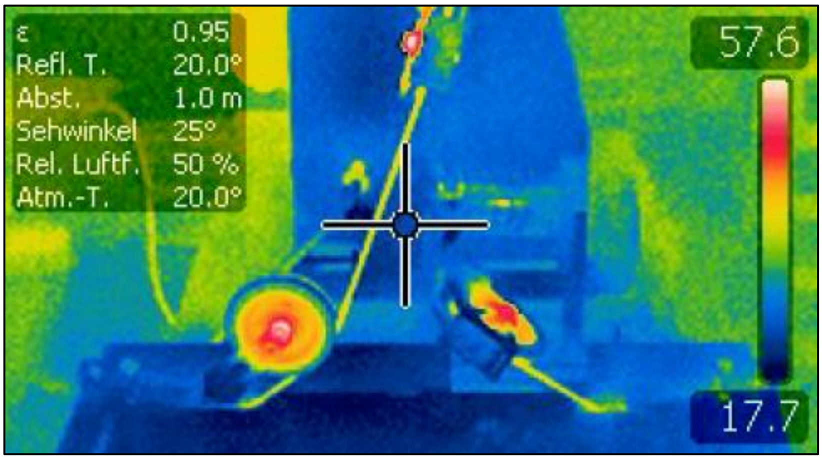

Figure 42: Thermal hotspots [101]

An additional consideration of applying water is dust prevention. This is particularly relevant for blade sectioning which will be performed ashore with workers and sensitive environment in the vicinity. The development of dust at a height of approximately more than 80m in open waters seems one the first glance negligible, but has to be considered as well as the collection of generated waste water. The issue of waste water can be seen as a great challenge and will be discussed in chapter 4.3.3.5.

4.3.2.3 Benefits and drawbacks of a diamond wire saw

The wire saw technology has like every other cutting/separation method a variety of benefits and drawbacks. The listing below shows the fundamental benefits and drawbacks of the wire saw technology. A more detailed discussion of each point does not seem necessary in the context of this paper. The following points are to be mentioned: [94]

Benefits

- High flexibility of applications
- No limits regarding cutting depth and shape of work piece
- Cuts practically all materials
- Requires low driving power
- High accuracy of the cut
- Low set-up times and low size and weight of mobile units
- Low noise emissions
- Little heat generation due to more cutting elements (diamonds)
- Low personnel costs
- Easy machine handling
- Remotely controllable

Drawbacks

- Relatively large cut width
- Relatively coarse cutting surface
- High risk through snipping diamond wire
- Workpiece has to be firmly affixed to avoid pinching the wire
- Relatively high costs for cutting elements
- High tool wear
- High amount of secondary waste compared to other cutting methods (e.g. dust and contaminated water)

4.3.3 Conceptual prototype

Based on the information gathered by the help of the previous chapters, a conceptual prototype of a blade cutting tool was designed. In the following chapter a closer look to the conceptual prototype shall provide an overall idea of the concept. The concept of the prototype is not a total redevelopment; it is more a combination of already existing technologies and methods.

In addition, necessary measures to operate the tool in a safely manner and the requirement of sufficient redundancy at those operations will be mentioned and discussed. By the help of roughly estimated calculations a first impression about present forces, required pump power, and amount of waste during cutting will underpin the idea of the concept. Within the last chapter, the environmental challenge that appears by the application of a cutting tool which will operate at a height of approximately 50 to 80m will be explained. It is very important to mention that the designed prototype can be considered very much just as a conceptual sketch with the intention to demonstrate the author's idea behind his approach of a blade cutting tool.

4.3.3.1 Design approach

A first conceptual design of a blade cutting tool can be seen in figure 43 (more CAD drawings can be found in appendix G). The idea is to create a detachable connection between the lifting frame and the diamond wire saw. It can be assumed that for different blades (e.g. manufacturer, size) an individual frame is used for lifting operations within the commissioning and decommissioning phase. If during the designing stage of the frame a possible attachment layout for the diamond wire saw will be considered, the frame only can be used for all other lifting operations and just for dismantling, the saw can be attached to the frame. The application of such a modular system comes along with the big advantage of flexibility. If the frames are designed within a standardized system, the saw could be used for dismantling a great variety of blades regardless manufacturer and size. Due to a great deviation of blade diameters (especially the root) of older OWT (500kW) and current standard OWT (3 to 6MW) a series of different saws would have to be designed. A rough division of potential saws with different cutting diameter capacities could be for example: PrototypeX (500 – 900mm), PrototypeY (900 – 1700mm), and PrototypeZ (1700 – 2400mm). With these dimension a wide field of currently used OWT blades would be covered.

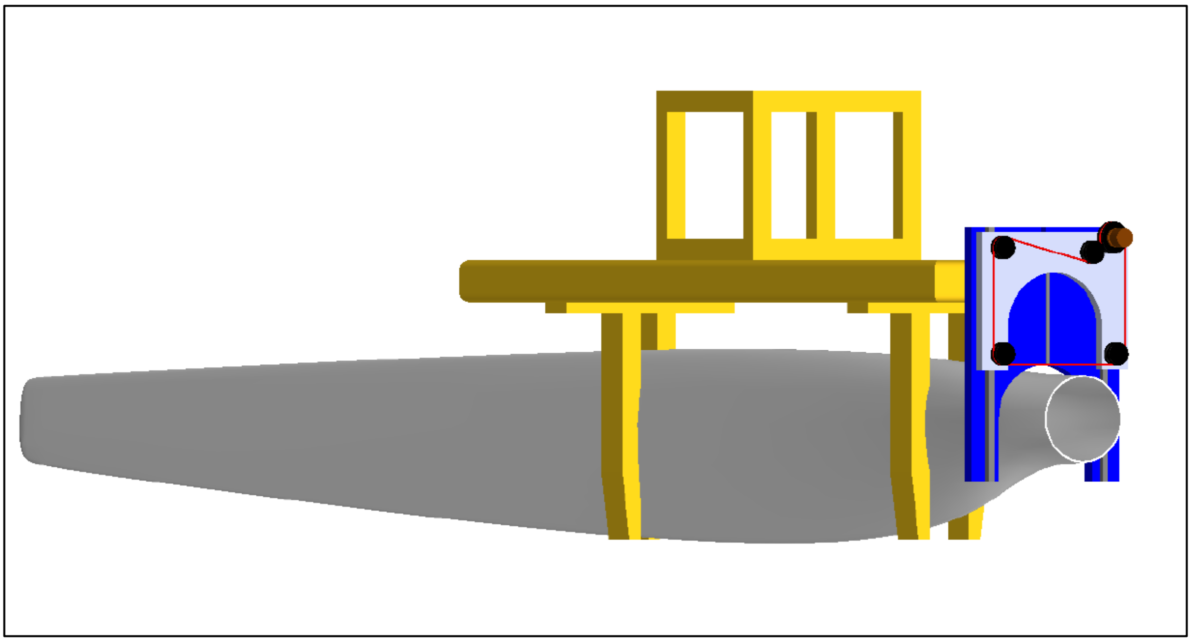

Figure 43: Conceptual blade cutting tool prototype

In the following section an overview of all components of the conceptual blade cutting tool shall be provided. A detailed explanation of the operating principles of each component is not necessary since the majority of the used components have been discussed in chapter 4.3.2.2. It can be stated that within the next section all mentioned references are made to figure 44.

Figure 44 shows the blade (1) with the blade cutting tool already attached. The basic structure of the cutting tool is the lifting frame (2) which is necessary for each lifting operation of the blade. The lifting frame consists of a basic structure, hoisting device, and four clamp jaws. The four clamp jaws are responsible to grab the blade and assure sufficient contact pressure between the jaws and the blade. It can be assumed that those clamp jaws are hydraulic controlled, which requires a safety measure in case of a hydraulic pressure loss. A loss in hydraulic pressure could result in a decreasing contact pressure between the jaws and the blade and the risk of a fall-down. A simple safety measure could be realized by a connection-rod/bar that mechanically engages with the clamp jaw and its opposite counterpart and therefore avoids the down-fall in case of a hydraulic pressure-drop.

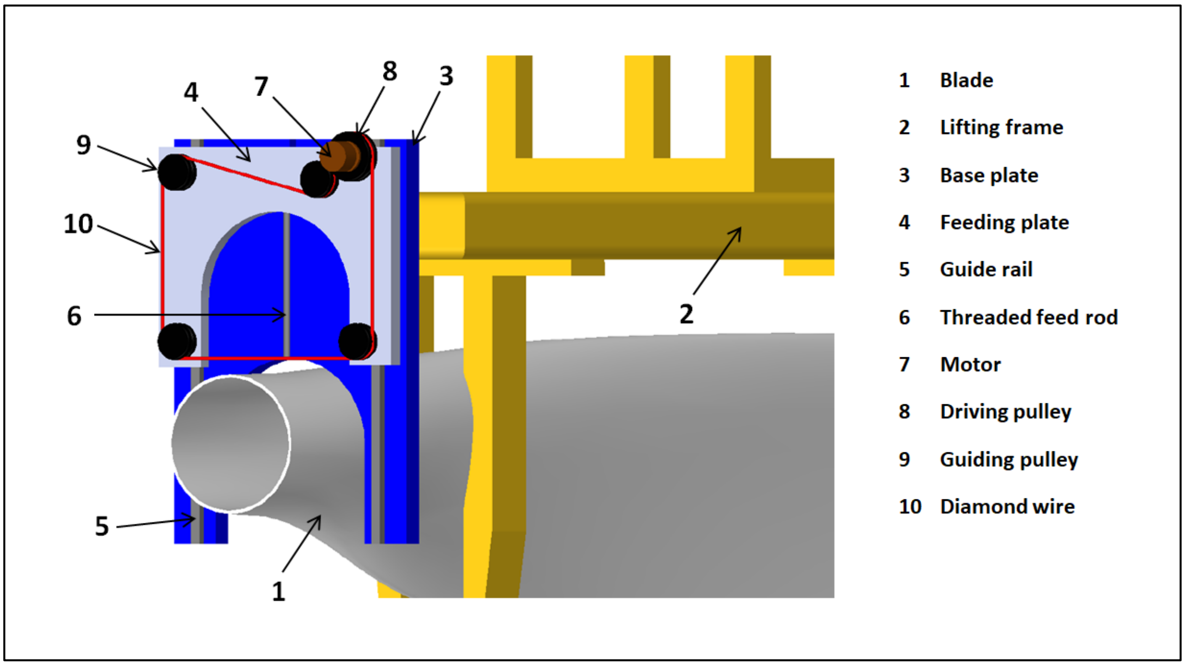

Figure 44: Blade cutting tool components

Directly attached to the lifting frame is the base plate (3). The base plate can be seen as the basic structure of the diamond wire saw and gives support for the guiding rails (5) and the threaded feed rod (5). Due to the conceptual prototype stage, the base plate in figure 44 (p.60) seems very bulky and consists of solid material.

In an advanced level of development, the most suitable material for the base plate would be an aluminum alloy with decent mechanical properties, good ductility, high strength, and sufficient resistance to fatigue and corrosion for the harsh offshore environment. On the first glance, the aluminum alloy 7075 could be a suitable material due to a wide field of application within the offshore oil and gas sector as well as the aviation industry [102, 103]. A datasheet of the aluminum alloy 7075 can be found in appendix H. The structural shape of the base plate will be obviously optimized with respect to weight reduction and stability.

To be able to perform a cut, a feeding mechanism is required which allows a relative movement between the diamond wire (10) and the blade. This is realized by the feeding plate (4). The feeding plate utilizes the main components of the diamond wire saw such as motor (7), driving pulley (8), guiding pulleys (9), and attached to pulleys the diamond wire. A controlled relative movement of the feeding plate is given by the two guiding rails and the threaded feeding rod. The "Fingerspitzengefühl" of the feeding movement is dependent on the motor that drives the rod (not yet included) and the pitch of the rod itself. A full cutting operation is demonstrated by three sequences in figure 45.

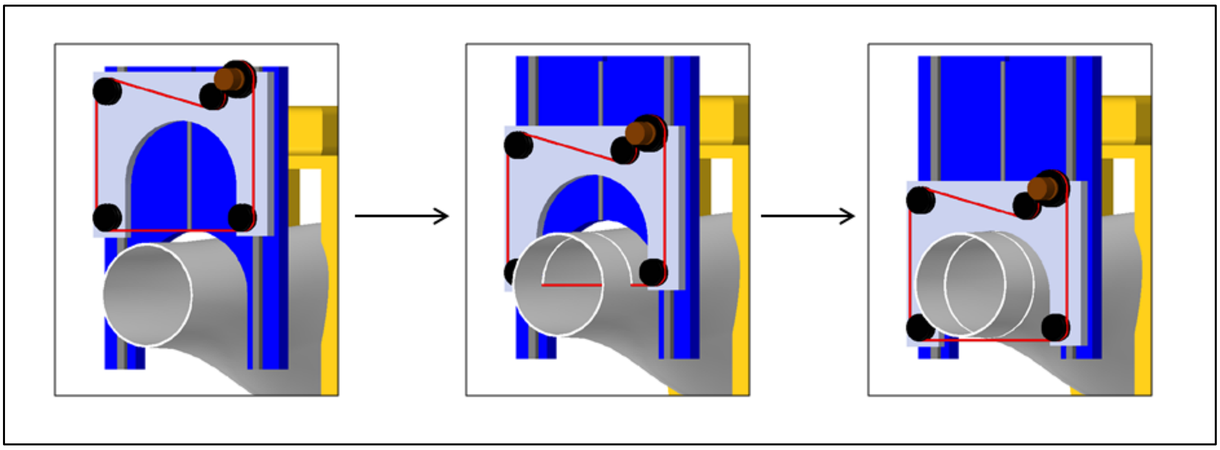

Figure 45: Cutting sequence

For the accomplishment of sufficient wire speed, a motor is attached to the same shaft as the driving pulley. Placing the motor to the same shaft reduces mechanical losses by the avoidance of redirecting the required rotational energy delivered by the output shaft of the motor. For the application of a suitable motor type, a motor which works on the hydraulical or electrical principle should be considered.

The same applies for the motor that drives the threaded feeding rod. Alternatively, a hydraulic cylinder can be used to control the feeding force. In a further development stage of the entire blade cutting tool a closer examination has to be conducted to select the most suitable type of drive. A first very simplified estimation revealed that a feeding force of approximately 320N can be expected during the cutting operation (with a drive power of 20kW). Appendix K demonstrates the assumptions and simplifications which have been made.

To reduce the loss of power and therefore increase the efficiency of the cutting operation, the relative motion between the driving pulley and the diamond wire, also called slip, has to be diminished. Within this model two obvious methods are used to reduce slip. As shown in figure 44 (p.60), the diameter of the driving pulley compared to the guiding pulleys has been enlarged. In addition, a special locational arrangement of the driving pulley relative to the closest guiding pulley was chosen to achieve the best possible angle of wrap. A greater angle of wrap increases the area of contact and at the same time a rise of the clamping force can be detected. Even though a variety of additional parameters are contributing slip, by a proper enlargement of the driving pulley diameter and an increased angle of wrap the occurrence of slip can be seen as manageable.

For sufficient wire guiding a number of four wire guiding pulleys has been chosen. Important to mention is the heavy impact caused by the diamond segments on the pulleys, which is valid for the guiding as well as for the driving pulley. Since the diamond segments cut in every direction, the guiding and driving pulleys are facing very high contact pressures.

To counteract those high contact pressures, the application of a simple rubber inlay can extend the lifetime of the pulleys significantly. Such a rubber inlay can be seen in figure 46.

Figure 46: Wire pulley with rubber inlay [104]

4.3.3.2 Machine operation

In the following subchapter the conceptual idea of operating the blade cutting tool is described a bit more thoroughly. As demonstrated in figure 45 (p. 61), it is intended to cut the blade as close as possible to the blade root. This would simplify the handling of the hub for the upcoming dismantling operation as well as the storage arrangement onboard the demobilization units. Another aspect of cutting at root vicinity is the shape of the blade. Most of the blades will increase in diameter towards the center point on the longitudinal axis (see figure 47). An increasing diameter and the change of shape can maybe affect the clamping ability of the lifting frame in a negative way, but this point in particular is subject of further investigations in a proceeded level of development.

Figure 47: Blade shape [105]

The actual handling of the saw can be seen as pretty straightforward. The operation of the saw will be performed remotely from the demobilization unit. It has to be investigated if there is need for a special control room in form of a container on deck or an actual room in the vessels accommodation. Maybe a simple mobile remote controlled operator panel is enough. For the operator is important that all relevant cutting parameters are displayed to be able to adjust the feed to assure a safe and efficient cut. A more detailed explanation of relevant parameters for a safe and efficient cut are discussed in more detail within chapter 4.3.3.3.

Potential methods for the transmission of operation commands could be for example a hard-wired signal line which is embedded into the umbilical (saw power supply) or one of the two standards for crane remote control systems; radio frequency signals/waves and infrared light [106]. An example of a potential remote control panel with the possibility to display a variety of parameters is given by figure 48.

Figure 48: Remote control [107]

Another important part of the operation is the constant supply of a sufficient amount of water around the cutting area. As described in chapter 4.3.2.2.4, it is necessary to cool down the diamond wire and the cutting area to avoid unnecessary wear and tear of the cutting gear and to assure high efficiency of the entire cutting operation. In addition, water spray in the surrounding of the cut reduces the environmental pollution through rising dust which is contaminated with particles of composite material.

To provide a sufficient amount of water even in windy situations, a water pressure of 1 to 6bar shall be maintained at the position of the cutting tool (within the cutting area) [86]. The temperature of the water should not exceed 25° C to assure sufficient cooling capacity [86]. An application of fresh water as well as sea water can be taken into consideration, but it is more likely to use sea water due to its natural occurrence in the surrounding of the whole decommissioning process.

A first investigation revealed that a water pump with a power rating of approximately 1.3kW is required to provide sea water with a desired pressure of 3.5bar and a constant volumetric flow rate of 0.8m^3/h at a height of 85m. A detailed calculation with all its assumptions can be found in appendix I. To avoid frost damage in the system, either the addition of anti-freeze agent has to be considered or the water has to be extracted from the entire system immediately after the job has been completed. If some kind of anti-freeze agent will be used is heavily depended if the water will be reused or how the waste water will be collected.

One more essential aspect for the blade cutting operation is the consideration of mass distribution. Since the intention is to cut the blade as close as possible to its root, the cutting tool must be positioned in the vicinity of the cut as well. It can be assumed that the position of the cutting tool and therefore its center of gravity will not precisely meet the center of gravity of the blade. This will result in a moment of force which will act on the blade after the cut has been accomplished. It can be assumed that the mass of the cutting tool, compared to the blade and lifting frame, is insignificant low. Nevertheless, the distribution of mass has to be considered and should be subject of further work.

4.3.3.3 Operation and conditioning monitoring

The subject operation monitoring is a major component for safe and efficient cutting operations. The aim of operation monitoring is the acquisition of measured variables during and after each cutting session to ensure a safe and a cost effective way of operation.

In addition, a sufficient monitoring method will reduce required redundancy due to higher operational safety and premature failure detection. The subject redundancy in this context will be discussed at the end of this subchapter. To be able to achieve higher operational safety and some sort of premature failure detection, the following parameters could be significant:

Operational parameters:

- Wire speed
- Wire tension

Conditional parameters:

- Diameter of diamond segments
- Vibrations
- Apparent defects

One of the most essential parameters is the speed of the diamond wire during operation. This parameter must be visible for the operator at any given time. By the fact that every pulley, guiding as well as driving pulley, rotates with the same speed (disregarding slip) as the wire, a decent way to detect the wire speed would be the application of an inductive rotation sensor.

The working principle of such an inductive rotation sensor is based on “Faradays Law”. A simple inductive sensor (see figure 49, p.67) usually consists of a housing (1), permanent magnet (2), induction coil (3), and soft iron core (4). The sensor has to be attached to the gear wheel (5) within a defined distance (G). The gear wheel has to be mounted to one of the pulleys where the rotation speed is supposed to be measured. Through the rotation of the gear, at some point the sensor will face a metallic tooth of the gear wheel (situation is given in figure 49) and the magnetic flux through the coil will increase. If the sensor faces a tooth gap the magnetic flux will decrease. This will result in a time-dependent sinus curve (or PWM) which changes the output voltage over time (see figure 49). Appropriate electronics can then evaluate the rotational speed of the pulley and therefore for the diamond wire.

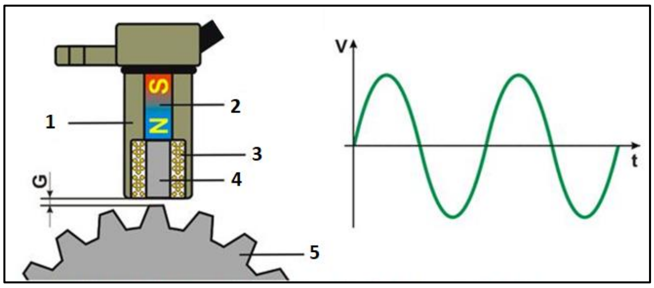

Figure 49: Inductive sensor [108]

The tension of the diamond wire is also one of the most important parameters for a safe and efficient cutting operation. To little wire tension causes insufficient cutting rates while at the same time too high tension would stress the diamond wire as well as the bearing of the pulleys. Exceptional stress on the components leads to additional wear and decreasing changing intervals. The wire tension is dependent on the angle of attack and could be determined by the application of force transducers. As shown in figure 37 (p.52), the force that acts perpendicular to the workpiece is the normal force (F_N). The counterforce of F_N will act on the diamond wire and has to be absorbed by the mounting arrangement of the pulleys. Due to the introduced force, the mounting arrangement is likely to deform, even though it is hardly visible (depending on the design).

A potential type of force transducer could be the piezoelectric force transducer. Piezoelectric materials have the characteristics to produce an electric charge under mechanical stress. The big advantage of those sensors is the proportionality of obtained electric charge to applied mechanical stress. A simplified demonstration of such a piezoelectric transducer is given by figure 50.

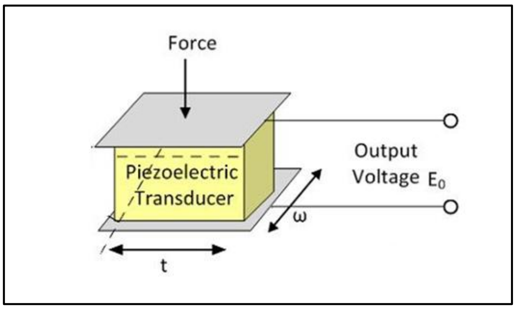

Figure 50: Piezoelectric transducer [109]

A simple determination of force distribution within the pulley arrangement as well as its effective direction of force gives the opportunity to identify the normal force (F_N) and thereby the important parameter of wire tension.

The diameter of the diamond segments provides information about the stage of wear. Due to wear, the diameter of the diamond segments will decrease during operation. Caused by the specified running direction of the wire, the diamond segments will change from a ring-shaped segment to a conical-shaped segment. Figure 51 shows the comparison of a new (upper) and a used (lower) wire that reached the maximum level of conicity.

Figure 51: Wire saw comparison [110]

Another parameter that has to be monitored is the non-circular wear of the diamond segments. The limit of wear (for diameter and conicity) has been reached if the difference in diameter between d1 and d2 exceeds 0.4mm [86]. Figure 52 shows the way of measuring out-of-roundness while figure 53 (p.69) demonstrates the measurement for assessing the occurrence of conicity.

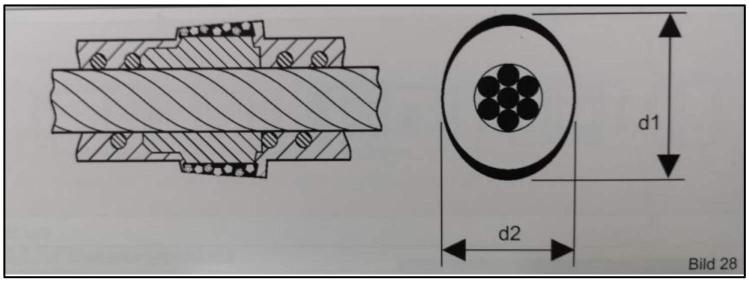

Figure 52: Measurement of non-circularity [111]

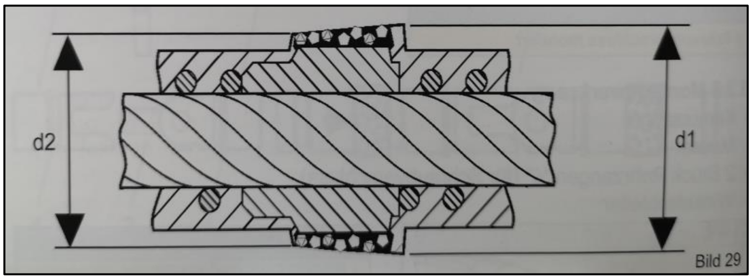

Figure 53: Measurement of conicity [112]

Available literature suggests a verification of the latter mentioned parameters approximately after two hours if concrete materials have been cut [86]. The measurement of the relevant diamond segment parameters can be conducted by ordinary caliper gauges which are able to display the required measuring range. To reduce the risk of measurement errors and improve the operational safety of the wire saw, an automatic acquisition of measuring values during operation should be considered. This would give the operator the possibility to analyze the condition of the wire during the entire cutting process and could therefore extend the machine uptime.

One possibility to acquire automated measuring values could maybe be realized by the application of laser-based wire displacement sensors (figure 54). If this approach can be applied to accomplish the required data with respect to the design parameters of diamond wires in particular, is currently subject of a research project at the Leibnitz University Hannover, Germany.

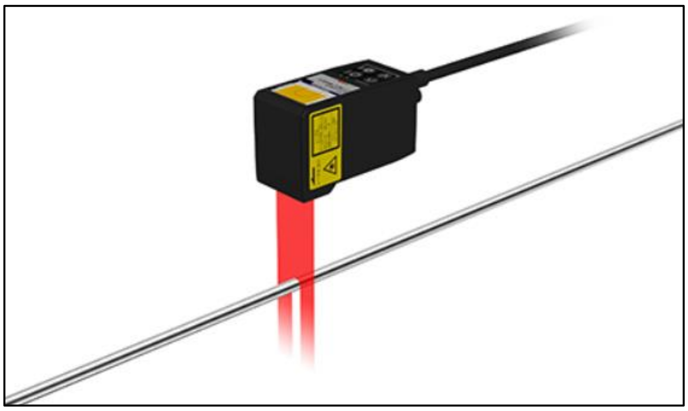

Figure 54: Laser-based displacement sensor [113]

A very advanced monitoring method could be the acquisition of vibration data during the cutting process. The idea to use vibration signals to identify the level of degradation and the stage of wear was born out of the need to reduce unexpected machine downtime and enhancing product quality of complex installations. An unexpected downtime of an assembly line within the automotive industry can easily reach losses of $20,000 per minute [114]. Considering day rates of resources used within commissioning and decommissioning operations, time can be seen as a very valuable parameter and any unexpected downtime would create great losses also within this industry. The listing below gives an idea of approximate day rates for required offshore units: [115]

- WTIV $150,000 – 250,000
- Jack-up barge $100,000 – 180,000
- Crane barge $80,000 – 100,000
- Cargo barge $30,000 – 50,000

To be able to use the very complex method of vibration monitoring, the rotating parts of the blade cutting tool have to be monitored. The application of vibration monitoring requires a vast amount of empirical data (e.g. frequency ranges) in relation to different degradation stages and parameters such as cutting force, material inhomogeneity, ambient conditions and tool wear [114].

A further explanation of the working principle of vibration-based monitoring is not supposed to be part of this paper, but it is worth to mention that the Leibnitz University Hannover, Germany is currently evaluating the approach of using vibration data for evaluating the stage of degradation and tool wear for diamond wire saws.

A more conventional way to assure safe cutting operations is given by visual checks of the whole blade cutting tool to be able to detect apparent defects. Visual checks shall be performed after every cutting session with the goal to detect already existing visible damages to avoid a tool breakdown during the next cutting operation. Visual checks could be also performed during the cutting operation by the help of camera technology.

For every kind of operation it is always desired to get a live picture of the situation instead of relying just on parameters which are display on the operators control panel. If the blade cutting tool is attached to the blade at a height of 80m, it is very likely that the operator does not have sufficient sight to comfortably control the tool (even worse in foggy or murky weather).

As already mentioned in previous research work, sufficient redundancy for the assurance of safety of involved workers and resources at any time is from an utmost importance [48, 78]. The fact that the tool is usually used around a height of 70 to 80m will increase the need of sufficient and profound redundancy. It can be assumed that required redundancy is depending on how good the failsafe performance of the cutting tool can be. An application of all the above mentioned monitoring parameters would increase the safeguard against failure tremendously, but anyways, a breakdown of the machine can happen at any time without any signs of fatigue or malfunction. In this case a technician would have to conduct a visual inspection by the help of a lifting basket if the used camera does not reveal the cause of failure at the first glance. By the use of a lifting basket, the technician is able to conduct a first inspection as well as to change broken parts if possible. In case a repair in the attached condition is not possible, the modular construction system of the lifting frame and diamond wire saw would give the opportunity to change to a backup wire saw which should be on board the demobilization unit. To carry along a spare unit can sometimes be observed within the offshore industry and the utilization of ROV's. To be able to replace the diamond wire saw while the cutting tool is still attached to the blade, a backup crane with lifting basket would be required.

This is only necessary if it is not possible to retrieve the entire cutting tool, which could be the case due to a cut that has already progressed too far and would not allow releasing the lifting frame. It can be concluded that reliability and redundancy are one of the most important parameters for the operation of such a cutting tool and should be subject of further investigation to make the application of a blade cutting tool possible.

4.3.3.4 Hazard identification

The term hazard identification can be described as part of the process to evaluate if any particular situation or operation may have the potential to cause harm [116]. The term that is often used to describe the whole process is “risk assessment” [116]. Before discussing the application of hazard identification in a bit more detail, the definition of the words “harm” and “hazard” with respect to workplace health and safety shall be mentioned. The Canadian Standards Association for occupational health and safety gives the following definiton: [116]

- *Harm – physical injury or damage to health*
- *Hazard – a potential source of harm to a worker*

Hazard identification has the overall goal to identify and record possible hazards that could occur in our workplace. In the context of this paper it would be the identification of possible hazards which could occur during the operation of the blade cutting tool. The process of hazard identification can be divided into three steps: [116]

- Hazard identification
- Risk analysis and risk evaluation
- Risk control

In a first step it is necessary to identify every potential hazard that could occur while operating the cutting tool. This could be for instance a breaking diamond wire during operation, worker falling from high level out of the working basket during repair or inspection, or an electrical short circuit/earth leakage.

The second step would be an analysis and evaluation of risks associated to each particular hazard. The risk of a broken diamond wire at a height of 80m could have fatal consequence for workers located on the working platforms beneath the blade cutting tool. A falling worker from a height of 80m would probably end fatal and at the same time it poses a great risk for workers located on deck. The occurrence of an electrical short circuit or earth leakage can cause serious electrical injuries. In a third step, appropriate ways to eliminate the hazard or to control the risk if the hazard cannot be eliminated have to be defined.

To eliminate the risk of a falling diamond wire could be the attachment of a safety net or the definition of restricted areas on board the working platform beneath the cutting tool. Risk elimination for a falling worker could be sufficient safety measures (e.g. safety cable) as well as restricted areas on deck to protect the workers on deck as well. The use of residual-current devices (RCD) and appropriate safety measures could eliminate the risk of electrical short circuits and thereby the risk for electrical injuries. It is worth to mention that the given examples are only a few out of many possible hazards for the application of a blade cutting tool. The performance of a complete hazard identification would go beyond the scope of this paper.

Conducting a hazard identification is not only required during the design and implementation phase of a new product or operation. It should be seen as a continuous process before, during, and after every operation. Special attention should be given during inspection of the blade cutting tool and after incidents. To assure that every possible hazard of each particular operation is found, the listing below provides some examples suggested by the Canadian Centre for Occupational Health and Safety: [71, 116]

- Consider all aspects of the operation and include non-routine activities (e.g. maintenance, repair, cleaning etc.)
- Include the procedure of operation
- Review injury and incident records regarding diamond wire saw application
- Interview workers of the particular industry
- Look at foreseeable unusual conditions (e.g. power outage, wind gusts etc.)
- Review the physical work environment, equipment, materials, products, etc. that are used during the operation

4.3.3.5 The environmental challenge

The biggest environmental challenge of the blade cutting tool operation will be the collection of the required cooling water. As described in chapter 4.3.2.2.4, water is needed to cool down the diamond wire/cutting area during the whole cutting operation. The waste water (after cooling) will obviously be contaminated with cutting waste of the blade.

Due to the application of glass fiber reinforced plastics as a main component within blade manufacturing, the waste water has to be collected and can under no circumstances be disposed into the ocean. Plastic pollution can be seen as one of the most widespread problems affecting the marine environment [117]. Cutting a blade of a Siemens SWT-3.6-107 OWT would generate a volume of plastic-based waste of approximately 13.6dm³ with a mass of 11kg. For a wind farm decommissioning with 88 OWT (e.g. Sheringham Shoal), plastic-based waste with a volume of approximately 3.600dm³ and with a mass of roughly 2.9t would be generated. A detailed explanation of the calculation can be found in appendix J.

The Convention for the Protection of the Marine Environment of the North-East Atlantic ('OSPAR Convention') is the current legislative instrument regulating international cooperation on environmental protection in the North-East Atlantic, which includes the NSR. The convention was signed by every participating country of the DecomTools project [118]. Annex III of the convention regulates the prevention and elimination of pollution from offshore sources. The 1992 OSPAR Convention annex III Article 3(1) implies: [119]

"Any dumping of wastes or other matter from offshore installations is prohibited"

Due to Article 3(1) and the desire for more sustainable offshore operations will require the collection of the waste water. Limited extend of this paper does not allow a concrete design of such a water collection method, but a first overall concept shall be shared. The idea is to collect the water maybe by using a collecting bag (e.g. made out of tarpaulin) which can be placed around the saw arrangement. The collection arrangement should be equipped with a drain hose which allows the waste water by the help of gravity to be collected on deck of the demobilization unit. The drain hose could be implemented into the umbilical of the cutting tool which already accommodates power and water supply. Merging those cables/hoses will contribute to simplification of the entire operation. The collected water on deck can be filtered and the residual cutting waste can be properly disposed. Again, it is worth to mention that this idea is just a first concept and requires much more investigation and should be object of further research to determine the technical feasibility.

4.4 Simulated decommissioning approach

Another approach to optimize the dismantling process of OWT blades is a simulation of the decommissioning process. A simulation of the blade dismantling process and all its associated variables can be considered as "well-targeted" if the goal is to optimize the costs and the environmental footprint of this particular subtask. A breakdown of the entire decommissioning costs (see chapter 2.4.4) shows that the blade dismantling process is only a minor amount of the whole costs. To achieve the best possible reduction of costs as well as emitted CO_2 emissions, it seems reasonable to have a look at the whole decommissioning process, which obviously includes the blade dismantling process. A greater insight of the whole decommissioning process can widen the horizon and has more potential for decreasing costs as well as the reduction of CO_2 emissions.

Before starting to deepen into the subject of simulation, a brief definition of the word "simulation" shall be given. Simulation can be considered as the evaluation of a large number of different alternatives under a great variety of realistic scenarios [120]. Those realistic scenarios have to be defined by decision-makers. It is essential to understand that every result provided by simulation is based on the evaluation of predefined options which are created by the decision-makers [120]. It should be mentioned that simulation is not able to generate the best possible solution [120]. A simulation only gives the best possible solution among the predefined strategies (determined by the decision-makers). This generates the risk of output parameters based on the bias of the decision-makers.

Simulation models are supposed to be used to measure the achievable performance of a project under defined flexibility and a high degree of realism provided by decision-makers [120]. To be able to create the best possible outcome of a simulation model it is important that all involved decision-makers have comprehensive knowledge within the field of operation to ensure the correct selection of predefined strategies/options [120]. A small introduction of simulation is provided in the next chapter.

4.4.1 Introduction

As already mentioned, optimization by simulation is defined as a process of finding the best input variable values among all conceivable and available input variables without evaluating each possibility into detail. The main objective of simulation is to minimize the resources while maximizing the information found in a simulation experiment [121].

The introduction of computer based simulation dates back to World War II when the two mathematicians Jon von Neumann and Stanislav Ulam were faced with the puzzling problem of the behavior of neutrons [122]. Even at this time, the experimentation method "hit and trial" was too costly and the given problem was too complicated for common analysis. Therefore, the "Roulette wheel" technique was proposed by von Neumann and Ulam [122]. At this time, the basic data regarding the occurrence of different events were known and the probabilities of separate events were merged into it by a step by step analysis to be able to predict the outcome of the sequence of events [122]. This method achieved remarkable results on neutron problems and soon it became popular and found many applications in several business and industrial sectors [122].

For solving computer based simulations the most common approach is the application of mathematical models. If mathematical models are used to study a simulation, it is called a *simulation model* [121]. The definition of a *simulation experiment* can be stated as a test or where meaningful changes of the input variables of the simulation model are made with the goal to observe and identify the reasons for changes in the output variable(s) [121]. A simulation model in general consists of n input variables (x_1, x_2,….,x_n) and m output variables (y_1, y_2,…,y_m) [121]. A simulation model with n input variables and m output variables can be seen in figure 55.

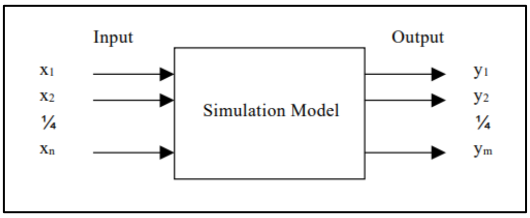

Figure 55: Simulation model [123]

4.4.2 Input parameters

As described in chapter 4.4.1, a variety of input variables have to be defined to start a simulation. Those input variables in combination with predefined options (defined by decision-makers) represent a simulation model that will generate different output variables. Output variables generated by the simulation model have to be understood, evaluated, and verified by the decision-makers.

With respect to the decommissioning of OWT's, a vast amount of input parameters could be considered. The extreme amount of possible input parameters can easily become unmanageable with the result of too complex simulation models. For the application of decommissioning, the input variables that are significant can be divided into the following categories: [71, 124]

- Vessel and equipment
- Wind farm details
- On-land transport
- Project personnel
- Costs and revenue

In the following sub-chapters each of the above mentioned categories shall be further discussed.

4.4.2.1 Vessel and equipment

One very essential category of input parameters with respect to the decommissioning of OWT blades is *vessel and equipment*. Within this category all vessels that are suitable and available for the pre-determined operation have to be considered. Possible vessels for the decommissioning operation can vary from simple crew transfer vessels (CTW), offshore support vessels (OSV), offshore barges, tug boats, heavy-lift vessels, heavy-lift jack-up vessels, up to especially for this purpose designed wind turbine installation vessels (WTIV). To be able to accomplish profound simulation results regarding the most suitable vessels, different properties of each individual vessel have to be considered.

This would include for instance basic design parameters such as speed, draught, length, and breadth. Significant parameters like fuel consumption, fuel capacity, day rates, as well as time for mobilization/demobilization have to be taken into account. For particular decommissioning work parameters with respect to capacity (weight and personnel), maximum time offshore, lifting capacity, deck space, deck strength, operational limits (e.g. significant wave height, wind speed, dynamic positioning), as well as the number of required technicians to perform the job are from an utmost importance.

Another essential point of choosing the right vessel is the capability of applying a cutting tool which has been introduced in chapter 4.4.3. A summary of the mentioned parameters for the category *vessel and equipment* is given by the following listing: [124]

- Basic design parameters (e.g. speed, draught, length, breadth)
- Fuel consumption, fuel capacity, day rates
- Required deck space
- Capacity (weight and personnel)
- Maximum time offshore
- Operation durations (positioning, access, lifting)
- Operational limits (wave height, wind speed, access, lifting)
- Costs for mobilization/demobilization and sea-fastening)
- Number of technicians required
- Capability of applying a cutting tool

4.4.2.2 Wind farm details

The input parameters that are associated to the wind farm which is supposed to be decommissioned are representing the most influential parameters. As already mentioned several times within this paper, the wide range of different on-site conditions for each individual wind farm makes every decommissioning project unique with new upcoming challenges related to each particular work site. In a long term perspective this highlights the benefits of computer-based simulation due to the fact that not for every wind farm the planners have to start from scratch with planning the decommissioning process.

A vision for the future would be the presence of a reliable fully developed tool where all relevant input parameters as well as predefined strategies are specified and the tool creates an output with all conceivable options and suggestions regarding the most beneficial and most sustainable decommissioning approach. One of the easiest and most straight forward input parameters is the number of OWT within the wind farm.

More specific data regarding the OWT would include general specifications such as number of components (e.g. 3 blades, nacelle, and two-piece tower), height, weights etc. Additional input parameters are distances from the location of the wind farm to each potential port/landing stage as well as the inner-array distance of the OWT within the wind farm. By the choice of potential ports it can be distinguished between ports for different activities. While one port is used only for bunkering, crew change, and maintenance, other ports can be used for discharging dismantled components. Due to geographical circumstances it is possible that the most beneficial and sustainable way of decommissioning results in discharging blades, nacelle, and tower in three different ports. A very illustrating example is given by figure 56. Figure 56 shows all possible ways for retrieving dismantled components by different types of vessels and the variety of potential ports as well as landfill/dumping areas.

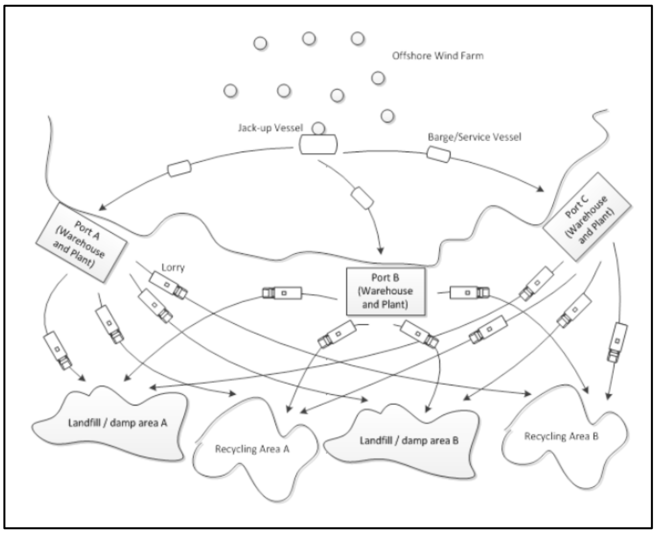

Figure 56: Possibilities of decommissioning [125]

Another very important section of input parameters considers the meteorological and oceanographic (metocean) data at each individual work site. Metocean data is usually presented as statistics which includes seasonal variations for the description of water movement (e.g. water levels and flows), offshore wind conditions, as well as sea states (e.g. wave conditions) [126]. With the help of these data, the simulation model can predict the best vessels for each work site. Without the help of a simulation tool the project planner would have to compare each work site parameter (e.g. water depth, seasonal mean wave height, and seasonal mean wind speeds) with every available vessel regarding draught and operational limits for certain wave heights and wind speeds.

It is obvious that the latter mentioned aspects are only a few parameters among many others. For the simulation model it is also essential to determine the available time frame to complete the decommissioning process and a specification of a date where the project starts (seasonal changes). A brief summary of significant parameters regarding *wind farm details* is given by the listing below [124]:

- Number of turbines
- General specification of OWT (e.g. components, height, and wave)
- Distance from work site to each potential port/landing site
- Inner-array distance
- Metocean data
- Time frame

4.4.2.3 On-land transport

Even though the OWT has been dismantled and retrieved to the chosen port facility, the decommissioning process cannot be seen as completed. It can be assumed that the subsequent treatment (e.g. scrapping, “recycling”, or alternative utilization) of the blades will not be carried out within the port facility or in its immediate surrounding. It is very likely that the blades; as well as other OWT components; will be further transported on land to reach their final process station. In order to achieve a holistic insight of the possibility of time, cost, and CO_2 reduction within the whole decommissioning process, the on-land transport has to be considered as well.

To simulate the on-land part of the decommissioning process, the means of transport plays an important role. The transport on land can be realized by truck, train, as well as inland waterway vessel. The choice of the most suitable mean of transport will be influenced by input parameters of each individual mode of transportation such as speed, day rates, fuel consumption etc. Transport connection (e.g. highway, railway, and river) of potential ports as well as the distance from port to reprocessing facilities plays also a pivotal role within the simulation. With respect to street navigability, it has to be taken into account if the blades will be sectioned at port or if the blades will be transported in one piece.

A transport of the blade without pre-sectioning would generate limits for the exceptional transport (e.g. narrow villages, street signs, traffic light, sharp turns, etc.). Already at this stage it becomes visible how complex the process of simulation can become by considering all relevant input parameters. The listing below gives a small summary of the mentioned input parameters for the category *on-land transport* [71, 124].

- Available transport options (e.g. truck, train, and inland waterway vessel)
- Transport connection of potential ports (e.g. highway, railway, or river)
- Transportation costs (e.g. fuel consumption, day rate, etc.)
- Transport navigability (e.g. narrow villages, sharp turns, street signs, bridges etc.)

4.4.2.4 Project personnel

The number of personnel required for each step of decommissioning will of course also influence the decommissioning process and costs. While for some tasks only a minimum number of technicians are required, other tasks will become more efficient to utilize more technicians instead of having a WVIT on hold to proceed with a particular operation. One simple example could be the process of loosen the high-tension bolts of the blade-to-hub connection. If three workers work at the same time on loosening the bolts, the job will be done in one-third of the actual time and the operational time of the WTIV would decrease for each blade as well.

A small summary of significant parameters that have to be considered within the category *project personnel* is given below: [124]

- Number available (including proper resting hours)
- Salary costs

4.4.2.5 Costs and revenue

Besides the fact that a significant percentage of decommissioning costs is already covered by the categories *vessel and equipment, wind farm details, on-land transportation, and project personnel,* a project with this magnitude will generate additional costs which have to be considered. Fundamental costs within every project are caused by the management of the project and the requirement of contingency plans. Additional costs related to project management are costs to monitor the project progress and the necessity of conducting surveys to gain knowledge that gives the opportunity to improve for upcoming decommissioning projects.

Other significant cost factors are port fees which accrue for the use of infrastructure and services offered and provided by each potential port as well as the costs for disposal and recycling revenues for each dismantled component. Depending on the complexity and the goal of the simulation model, additional input parameters such as a re-sale calculation and re-conditioning factors can be taken into account.

A re-sale calculation would determine the revenue of a re-sale price based on a useful remaining life time approximation while the re-conditioning factor is used to determine the costs to restore or upgrade a particular component (e.g. blade). A closer look into those input parameters would be beyond the scope of this paper and can be seen as more relevant for a strictly financial cost determination or the assessment of repowering OWT.

As for every other category, a brief summary of the mentioned input parameters can be found in the listing below: [124]

- Project management and contingency
- Survey and monitoring
- Port fees
- Costs for disposal
- Recycling revenues
- Determination of re-sale and re-conditioning factors

4.4.3 Predefined strategies and output parameters

Predefined strategies are a substantial part of every simulation model. As described in chapter 4.4, the predefined strategies/options have to be determined by specialized decision-makers who have sufficient knowledge about the project environment. In simple terms, the predefined strategies can be seen as a rule book for every decommissioning task. Strategies determined by the decision-maker include all components that have to be removed within a given task as well as the number of components to be removed [124]. For the accomplishment of profound simulation results it is necessary that for every component a dismantling time as well as the mass of each component to be lifted is defined. It also has to be defined how many technicians or vessels are required to complete the tasks and in addition, the necessity of on-land transport has to be chosen.

The output parameters are the results of the simulation. As already mentioned in chapter 4.4, the results provided by the simulation are based on the predefined strategies and based on the input given by the decision-makers. Resulting output parameters have to be defined beforehand and can portray a wide range of factors. These factors can range from cost and time schedules as well as the amount of generated CO_2 emission for particular vessel constellations. An example of possible output parameters for a simulation of blade dismantling in particular can be found in chapter 4.4.7.3.

4.4.4. Validation and verification

The overall goal of conducting a simulation is the accomplishment of profound and reliable output parameters. Significant output parameters of a decommissioning project could be for instance a detailed breakdown of decommissioning costs, duration of particular operations, availability etc. The development of a simulation model with the goal to generate output parameters is just useful if the model represents true behavior which is close enough to a "real-world" system. If the model does not reach a certain degree of true behavior, the model has to be considered as invalid. To assure validity of any kind of simulation, the following steps have to be taken into account:

- Validation
- Verification

Validation evaluates the accuracy of the conceptual model's representation of the "real-world" system [127]. This can be simply done by comparing two results. Figure 57 shows the interaction for validation and verification between the real world system, conceptual model, and simulation program. Different techniques can be applied to perform high validity of a simulation model. Therefore it is essential that the model is discussed among experts of the particular industrial sector during designing stage as well as the supervision of the generated outputs by the experts [128]. The interaction between the model and the client throughout the project is an additional step to increase validity of the simulation model. Furthermore, the model can be tested with assumption data where the output is compared with the expected results of the assumption data [128]. Performing a sensitivity analysis indicates the effect of changes in the results while changing significant input parameters.

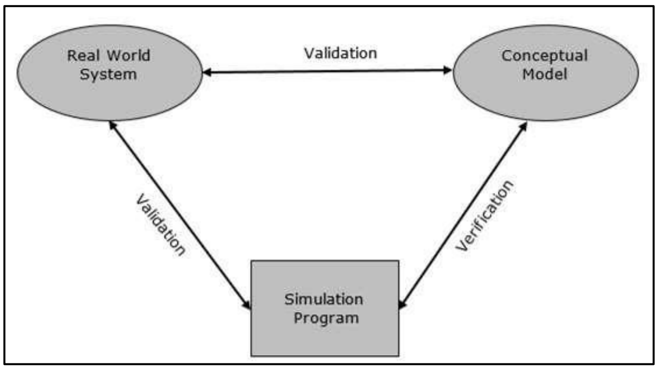

Figure 57: Validation and verification [129]

A last step to increase validity of the simulated model is the evaluation of the represented output parameters [128]. This can be achieved by comparing how close the simulated output parameters are compared to the “real-world” system. The latter mentioned step can be challenging due to very little experience in wind farm decommissioning.

To emphasize the major differences between validation and verification the following definitions shall be used: [130]

- *Validation: Are we building the right system?*
- *Verification: Are we building the system right?*

In other words, verification is concerned if the simulation model is well-engineered and works without errors [130]. With the help of verification, it can be determined if a simulation model is of high quality, but it cannot evaluate if the model is suitable for the desired application [130]. A simulation model can accomplish sufficient verification by following the subsequent steps: [128]

- The simulation program should be written and debugged in sub-programs
- Applying a “Structured Walk-through” policy to make sure that more experts will read the program
- Intermediate results shall be traced and compared with output parameters
- Using various input parameters to check the simulation output
- Comparing analytical results with final simulation results

4.4.5. Challenges of simulation

As with any other method or approach, the application of simulation will face different kind of challenges. One challenge will be the constant maintenance of validation and verification of the simulation model. Even though the simulation tool has been developed and considered as valid and verified, the offshore wind sector is developing with an enormous speed which requires permanent adjustment.

The challenge of data availability includes the accessibility of the always newest data (e.g. vessel database, changing port layouts, changing on-land infrastructure etc.). The great amount of interconnectedness creates a huge challenge with respect to validation, verification, and up-to-datedness.

Another challenge is the creation of additional expenses. Expenses related to maintain the simulation tool as well as for the application. As already mentioned in the previous chapter, a profound and reliable application of simulation tools requires a great amount of effort as well as a certain degree of expertise to set the right input parameters, predefine possible strategies, and to evaluate the output parameters. The necessity of a high expertise will accumulate costs which have to be justified towards the customer.

In addition, non-negligible challenges will also occur within the development stage of a simulation tool. The development of such a simulation tool requires a vast amount of data regarding every aspect of decommissioning which will result in very complex simulation models. The required data ranges from technical and geographical details of the wind farms, vessel specifications, to data regarding potential ports and associated on-land conditions. To be able to face those challenges, a cooperation of all bordering countries of the NSR and important industry partners is absolutely necessary. For this reason, the DecomTools project and its 13 European partners who are privileged with high expertise, experience, as well as resources is incredibly important to address those challenges.

4.4.6. The LEANWIND project

A pioneering role within the field of simulating decommissioning work played the LEANWIND (**L**ogistics **E**fficiencies **A**nd **N**aval architecture for **W**ind **I**nstallations with **N**ovel **D**evelopments) project. The project started in 2013 and was scheduled for 4 years [131]. LEANWIND has been guided by a consortium of 31 partners and has been awarded with €10 million by the European Commission. The high participation of influential industrial partners, as for instance Siemens Wind Power A/S, DNV GL, The Crown Estate, Statkraft, Senvion SE, and Statoil, contributes to a high degree to the progress of the project by an immense amount of bundled expertise regarding offshore operations [131].

The main objective of the project was to provide cost reductions across the wind farm life cycle and supply chain through the application of lean principles and the development of state of the art technologies and tools [131]. The idea of lean principles was originally developed by the automotive giant Toyota to enhance the process of manufacturing [131]. It can be stated that those lean principles have been already successfully adopted within many industrial sectors to remove wasteful stages and streamlining processes [131]. Regarding LEANWIND, the offshore industry has not yet applied lean principles regarding logistical operations of the wind farm in all stages of its life cycle [131].

Evaluated by LEANWIND, simulation/modelling can be seen as a safe and cost-effective way to evaluate and optimize operations within the offshore industry. The project revealed the occurrence of deficiencies related to comprehensive decision-support tools that are precise enough to provide insight of technological innovations as well as novel strategies.

To encounter those deficiencies, LEANWIND developed a suite of logistics and financial tools. By the aid of these tools the end-user should have the possibility to optimize the entire supply chain and conducting simulations of the full wind farm lifecycle as well as the provision of in-depth cost and time analysis [132]. The methodology of the project was to divide the full wind farm lifecycle into three categories: [133]

- Installation
- Operation and maintenance
- Decommissioning

Due to the goal of this paper, the categories *installation and operation and maintenance* will be neglected while *decommissioning* is supposed to be reviewed in a bit more detail. The final report of the LEANWIND project "*Driving Cots Reductions in Offshore Wind"* published in 2017 gives insight of the results achieved by the project. The majority points regarding decommissioning can be found in chapter 3 (Logistics & Supply-Chain) of the final report [132]. As already mentioned in previous chapters, the logistical part and the associated supply-chain should be considered as significant factors of the decommissioning process. To reduce costs by optimization, LEANWIND developed different tools to address those challenges. One essential step within every planning stage of wind farm decommissioning is the selection of the most suitable port facilities. To support the decision-makers, LEANWIND proposed a tool named "Port Selection Tool". This tool can be seen as a decision-making model based on an analytical hierarchy process. Different criteria taken into account by the tool are physical port characteristics (e.g. seabed suitability, quay length, port depth etc.), connectivity of the port (e.g. road networks, heliports, distance to wind farm etc.), as well as the layout of the port (e.g. storage area, component fabrication facility, recycling facilities etc.) [132]. The application of the tool is to determine the most important port characteristics for each phase of the wind farm development. Investigations have shown that for the installation and decommissioning phase the physical port characteristics have been the most important factors for the decision-makers [132]. The connectivity of the port was the most significant factor for the operation and maintenance phase [132]. Another application of the tool was to compare the suitability of all potential ports for a given wind farm by using the above mentioned criteria. For each port a suitability score was given and the port with the highest score could be considered as the most suitable among all potential ports [132].

LEANWIND identified that within the *installation* as well as *operation and maintenance* phase the resources of the vessels are one of the most significant cost factors [132]. A literature survey has shown that only a few studies exist that deal with logistical challenges concerning the maritime supply-chain within the installation phase. To face those challenges, the project and its 31 industrial partners developed the LEANWIND Installation Vessel Optimizer (LIVO) tool.

Figure 58 shows the concept of LIVO and the output parameters which are related to the choice of input parameters. Even though this tool in particular is tailored for the installation phase, it can be assumed that the layout and structure of the tool can be adjusted for an application within the decommissioning phase as well, without the necessity of developing a tool from scratch. Further explanation of the LIVO tool does not seem necessary due to the self-descriptive visualization of figure 58.

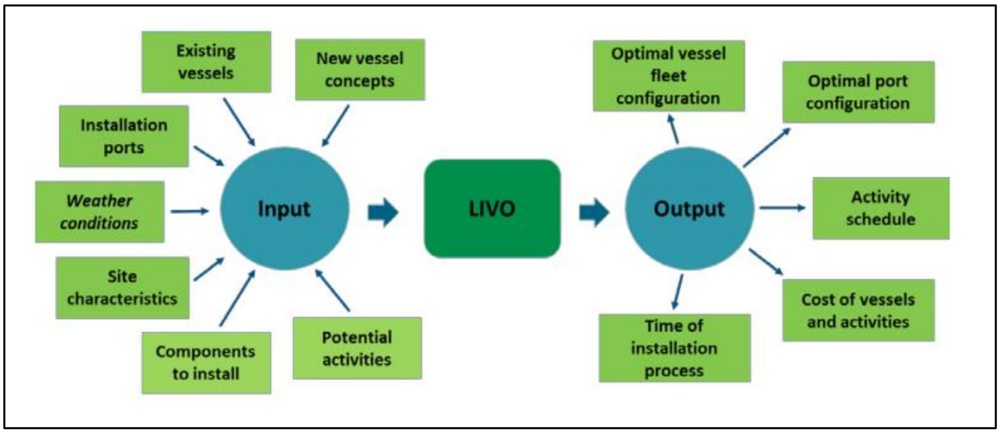

Figure 58: LIVO concept [134]

Further work has been done to give the decision-makers the opportunity to assess the different decommissioning options and logistical requirements. An additional financial model of the decommissioning process allows the decision-maker to consider a variety of wind farm dismantling strategies (reverse installation or other methods), as well as the related impact on the overall project costs and timeline [132]. For this purpose, the developed model includes the dismantling process of the OWT and foundation, vessels, technicians, on-land transport, as well as inputs for the location of recycling and disposal facilities and ports [132]. The output of the model is a derivation of estimated decommissioning costs, salvage revenue and the required time to complete the task [132].

The structure of the decommissioning model is an Excel input file which contains the required input parameters to define a decommissioning and post-decommissioning simulation strategy [132]. The actual main simulation is developed in MATLAB.

The MATLAB model runs the scenarios that are specified in the Excel file over an hourly time series with the goal to estimate logistical costs of vessels, technicians, as well as on-land transport [132]. The generated output parameters are again stored in an Excel file.

A proper validation of the generated results (output parameters) can be seen as difficult due to the fact of lacking experience in this particular field and is therefore highly dependent on methods for cost estimation given by different literature. Nevertheless, a case-study performed by LEANWIND resulted in decommissioning costs of €513,000 /MW while DNV GL estimated a cost range of €200,000 to €600,000/MW.

To increase the validation of the simulation model a sensitivity analysis has been performed. With the help of a sensitivity analysis it can be assured that the used model works as expected. By the help of the sensitivity analysis LEANWIND was able to highlight different areas with potential for optimization within the decommissioning phase: [132]

- Costs of additional resources (e.g. vessels, technicians etc.) could outweigh the savings of time. Therefore, the optimal balance should be determined for a specific scenario
- The impact of operational limits and durations is relative to the site location where for instance harsher conditions will increase the importance of optimizing activities as well as the investment in vessels with extended operational capabilities
- With an increase of distance between port and wind farm, the utilization of feeder vessels will be less useful due to longer transit windows. Activities without feeder vessels took longer but reduced costs. Nevertheless, the decision has to be made regarding the priories of the project management and the specific work site
- Proportionate savings in costs by an increasing size of wind farm or wind turbine capacity are evident

4.4.7 Conceptual simulation model

While in the previous chapters the approach of simulation has been introduced with the goal to consider the entire decommissioning process, given by the high degree of interrelations, this chapter focuses more on the actual blade dismantling process. This is a first approach to divide the entire simulation process into smaller sub-simulations and therefore reduce the complexity of the simulation model. The simulation model is based on potential input parameters, predefined strategies, and desired output parameters. Goal of the simulation model is to evaluate and compare the existing dismantling methods (e.g. base case or modified method) with the application of a blade cutting tool.

The requirement of choosing and defining a mathematical model which is able to simulate the presented model would be beyond the scope and therefore is not considered within this paper. A first conceptual sketch of the simulation model can be seen in figure 59 (p. 96). It is worth to mention that this simulation model is just a first conceptual sketch and requires more in-depth work to evaluate the priority of each individual available input parameter, predefined strategies, as well as the desired output parameters.

4.4.7.1 Input parameters

The choice of the input parameters will significantly influence the generated output parameters. Within this model it is attempted to consider only parameters related to the actual blade dismantling process. This would exclude parameters such as on-land transport, port layout, etc. It is obvious that for an entire decommissioning perspective it is not feasible to consider the dismantling of the blades as an individual independent process. Dismantling of the blades will always be a part of the entire decommissioning process with a high degree of interdependency.

With the goal to reduce the complexity of the simulation model and to get a first idea of the actual blade dismantling process, the applied input parameters can be divided into the following categories:

- Blade-to-hub arrangement
- Wind farm details
- Operational parameters
- Vessel characteristics

4.4.7.1.1 Blade-to-hub arrangement

The blade to hub-arrangement contains essential parameters about the connection between the blades and the hub and all characteristics of those components. An ideal conception of a simulation model would be the possibility if an accurate definiton of the material composition as well as the dimensions of the blade, could estimate the required cutting time. Same concept could be used for estimating the time to loosen one high-tension bolt by consideration of the used connection type (e.g. materials, size, pitch etc.). To be able to apply such a concept it is necessary to achieve empirical field data of cutting rates for each material composition and some kind of deterioration/corrosion coefficients for used connection types. For now, the following input parameters with respect to the blade-to-hub arrangement are:

- Mass of the components (blade and hub)
- Dimensions (e.g. length, diameter)
- Material composition
- Number of used high-tension bolts

4.4.7.1.2 Wind farm details

A precise definiton of existing wind farm details will to a great extend contribute to the generated output parameters. While for example the acquisition/leasing costs for a blade cutting tool are too high for a project with only 20 OWT, the costs could have already paid off for a project with 25 OWT. The chosen input parameters concerning wind farm details are:

- Number of OWT
- General specification of OWT (e.g. height)
- Inner-array distance
- Metocean data

4.4.7.1.3 Operational parameters

To create a simulation model which corresponds with the “real world scenario”, it is necessary to define a variety of operational parameters which are related to the predefined strategies. It is obvious that a reverse installation process requires different input parameters than for the application of a blade cutting tool. For this simulation the operational parameters are divided into the category “blade cutting approach” and “reverse installation approach”. While the parameters for the “blade cutting approach” are exclusively valid for the application of a blade cutting tool, the parameters of “reverse installation approach” will cover all strategies where the high-tension bolts will be loosened manually. The chosen operational parameters for the conceptual simulation model are:

- Blade cutting approach
    - Required cutting time
    - Acquisition, operation, and maintenance costs of the cutting tool
    - Transport and set-up times of the cutting tool
    - Mass of the cutting tool
    - Number of available personnel
    - Personnel costs

- Reverse installation approach
    - Required time to loosen one high-tension bolt manually
    - Acquisition, operation, and maintenance costs for required tools
    - Transport and set-up times for required tools
    - Number of available personnel
    - Personnel costs

4.4.7.1.4 Vessel characteristics

The input of characteristics regarding available vessels will include or exclude already a few vessels for some of the particular predefined strategies. As an example, a vessel with a lifting capacity of only 50t will be able to lift one blade, but it is not able to lift the entire rotor in one go (strategy S_2). The required input parameters regarding vessel characteristics are almost equal to chapter 4.4.2.1 and again listed below:

- Basic design parameters (e.g. speed, draught, length, breadth)
- Fuel consumption, fuel capacity, day rates
- CO_2 emission due to used fuel (e.g. MGO, LNG, hydrogen, electric etc.)
- Required deck space
- Capacity (weight and personnel)
- Maximum time offshore
- Operation durations (positioning, access, lifting)
- Operational limits (wave height, wind speed, access, lifting)
- Costs for mobilization/demobilization and sea-fastening)
- Number of technicians required
- Capability of applying a cutting tool

4.4.7.2 Predefined strategies

As already described in chapter 4.4, every simulation needs predefined strategies which describe all possible procedures within an operation. With respect to optimization of the blade dismantling process, all possible ways of dismantling the blades would have to be defined. This would include the reverse installation procedure as well as the application of a blade cutting tool. Even though the installation process was carried out by one particular method (e.g. each blade individually), the simulation gives the possibility to accomplish a safe and cost-effective evaluation of all existing methods. Within a lifetime of 20 to 25 years it can be assumed that best-common practice, available tools, and regulations will change which leads to the opportunity to perform the dismantling process more cost and time-efficient. Quite a few different strategies for the blade dismantling process can be found in figure 18 (p. 24). Within this simulation model the different strategies (S) to dismantle the blades and therefore representing the predefined strategies are:

- S_1 Loosen each individual blade manually
- S_2 Lift down the entire rotor assembly in one go
- S_3 Loosen one blade manually and lift down hub with 2 blades attached
- S_4 Cut one blade and lift down hub with 2 blades attached
- S_5 Cut all blades
- S_x ….

4.4.7.3 Output parameters

The goal of this simulation model is to generate sufficient output parameters which correspond with the “real-world” scenario to provide a decision-making tool for the selection of the most suitable dismantling method. The desired output parameters which are supposed to be generated by the simulation model are:

- Time schedule of each strategy
- Cost overview of each strategy
- Pollution through CO_2 emissions
- Optimal vessel configuration for each strategy

By the help of generated output parameters and a transparent listing of each strategy with respect to time and costs, it is possible to identify time or cost consuming bottlenecks within each strategy and create suggestions for improvement. One scenario could be that the simulation model reveals for example that the cutting time of the blade cutting tool is the bottleneck within one particular strategy and therefore the exclusion criteria for the application of such a tool. But at the same time, this gives the opportunity to examine possible improvements of the blade cutting process to accomplish an even higher reduction of costs and CO_2 emissions.

It is also possible for the decision-maker to try out different settings of potential input parameters and see what consequences it will have for the generated output parameters. It could be possible that for one wind farm, with one given set of input parameters, the most suitable strategy for dismantling the blades is to lift the entire rotor in one go. But maybe only a small increase of the significant wave height and wind speed will lead to the exclusion of using the heavy lift vessel which is able to lift the entire rotor in one piece. To avoid the risk of interruptions and reduce possible standby time, the application of another more "weather-resistant" strategy might be more suitable for this particular wind farm.

Figure 59 demonstrates a sketch of the first conceptual simulation model for blade dismantling in particular with all mentioned input parameters (green), predefined strategies (blue), and output parameters (orange).

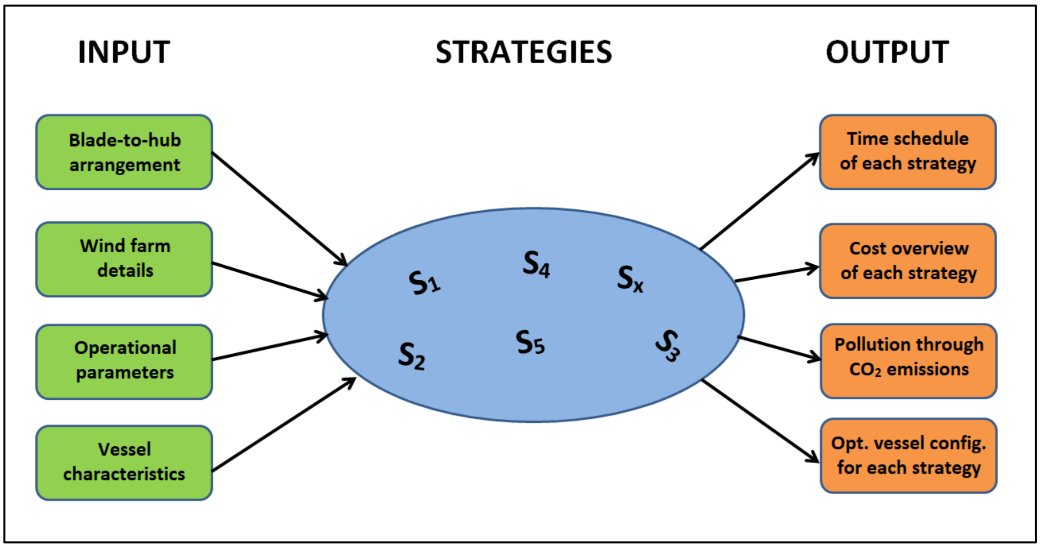

Figure 59: Conceptual simulation model

CHAPTER 5. DISCUSSION

5.1 Introduction

In the following chapter the two alternative approaches for the optimization of the dismantling process of OWT during decommissioning shall be discussed a bit more thoroughly. The discussion is supposed to address the challenges that occur for the application of those approaches within the current level of development. In the subsequent chapters of each approach follows a brief summary of recommended future work with the motivation that the existing ideas may turn it into viable solutions to achieve the goals set by DecomTools.

5.2 Blade cutting tool

Due to an incredible number of high-tension bolts which have to be loosened within the decommissioning phase of a wind farm, the application of a blade cutting tool seems very promising. As already mentioned in a previous chapter, for the decommissioning of Sheringham Shoal a number of approximately 21,000 bolts are used only for the blade-to-hub connection. Before making the decision to design and develop such a tool into its last detail, quite a few factors should be considered beforehand. Since the goal of the DecomTools project is to reduce costs and the emission of $C0_2$, it is inevitable to determine the actual time that is needed to dismantle one blade by the reverse installation process.

Only with the actual time needed for the dismantling process it is possible to compare the two different approaches and therefore to justify the development of a blade cutting tool. It can be presumed that a simple way to determine the time required to loosen such a blade-to-hub connection would be the creation of a replica of the used connection type and to perform different tests under laboratory conditions. Maybe it is possible to gain experience from former decommissioning projects. One very essential appearance of bolt connections is deterioration/corrosion or seizure. Deterioration or seizure is a very gradual process and can lead after 20 to 25 years (design life of an OWT) to non-detachable connections.

To accumulate profound and meaningful data it is necessary to get first-hand information which requires close collaboration with companies responsible for this particular decommissioning work. It would be a great enrichment for a comparison to know how long the workers need to loosen the bolts (in average) as well as the preparation and follow-up times (e.g. tool lifting in tower, tool set up times etc.).

A next step would be the collection of data regarding time needed to cut the blades with a diamond wire saw. Only by a direct comparison between those two approaches a useful decision can be made. Hereby it is important to consider different blades with respect to root diameter, material thickness, material composition etc. It can be stated that already a certain number of disposal companies use the diamond wire saw to section the blades at this time. Another very essential factor with respect to the application of a blade cutting tool is redundancy. Most likely no company would consider the application of a blade cutting tool without sufficient redundancy. Day rates up to $250,000 and a load of 20t on the hook at a height of 80m does not leave room for uncertainties. As described in chapter 4.3.3.3, the utilization of extended condition monitoring would increase the reliability of the tool and at the same time decrease the need for redundancy. Nevertheless, in case of an unexpected breakdown it must be possible to proceed or change the tool without the risk of a fallen blade. It can be stated that further investigations regarding redundancy is highly recommended to accomplish sufficient reliability of the cutting operation and therefore trust for the “end-user” (operator).

The need of collecting the waste water, which contains the plastic-based cutting debris, during the entire cutting operation can be seen as the biggest environmental challenge for the application of such a cutting tool. It can be assumed that within almost every cutting/sectioning method a certain amount of cutting waste will appear. A first idea of how to collect the waste water has been described in chapter 4.3.3.5. To realize the idea of a blade cutting tool it is mandatory to do more precise examination of different approaches to collect the waste water and its technical feasibility.

One very outstanding problem of the preparation and working stage on this paper was the difficulty to gather first-hand information in any kind of way. As soon as the above mentioned points can be seen as manageable, the next step would be the design of a cutting tool in more depth. Designing a cutting tool in more depth tailored to all relevant parameters (e.g. required power, type of drive, cutting diameter capacity) gives the opportunity to determine total costs of the tool as well as physical data such as size and its mass. To be able to design a tool in more depth, a lot of information regarding the blade design is required. This includes a variety of parameters such as the mass of each particular blade, mass distribution, material composition, dimensions etc. Information regarding the use of carbon fibres as reinforcement material is also from utmost importance since carbon will due to its high strength increase the cutting time significantly. But this is exactly where the problem lies, at least for now no manufacturer who had been tried to contact was willing to share information regarding the design of their blades. It was not even possible to gather information regarding the number of used high-tension bolts within the blade-to-hub connection or a simple root diameter. The motivation of more collaboration between the decommissioning industry and the actual manufacturing industry is one very important point that should be addressed by the DecomTools project. Only collaboration among the different involved partners will lead to more cost efficient and sustainable offshore operations and the ability to reach the milestones set by the Paris Agreement in 2015.

In addition, to exploit the big advantage of the modular concept for simple attachment and detachment of the diamond wire saw to the lifting frame, it is required to accomplish some kind of uniformity of the lifting frame. Uniformity gives the opportunity to use the diamond wire saw not only for one type of lifting frame which is designed for one particular blade. This challenge has to be addressed in an early stage to avoid the same difficulties that are present in automotive industry where every manufacturer is designing a different charging connector for their electric vehicles.

5.2.1 Recommended future work

To realize the application of a blade cutting tool in a cost effective and sustainable manner requires still a lot of effort. The appearance of additional challenges to assure safe and environmental friendly cutting operations is from high importance and shall be addressed in future work of the DecomTools project. In the previous chapter the most significant challenges with respect to the use of a cutting tool has been discussed and lead to essential recommendations for future work. The listing below is supposed to summarize the recommend further work and is presented by order of decreasing importance. It is important to mention that the order of importance is chosen by the author and is based on his opinion. The following tasks for further work are recommended:

- Identification and comparison of time frames for dismantling/cutting the blade
    - Required for the approach of reverse installation
    - Required for the approach of cutting the blade
- Defining strategies to ensure sufficient reliability by design and condition monitoring with the goal to reduce the need of redundancy. Determine alternative ways of increasing redundancy in a technical feasible way
- Development of a proper method to collect the waste water to ensure operations according to existing law as well as a high degree of sustainability
- Design of a blade cutting tool in more detail to determine actual costs as well as dimensions of the tool. To be able to do so it is essential to gather more first-hand information of the blades to be cut (e.g. material composition, mass distribution, dimensions etc.)
- Conducting hazard identification to assure safe cutting operations at any time. Conducting hazard identification in an early stage allows making design changes within the designing and planning phase of the blade cutting tool and avoids expensive design changes in a later stage.
- Motivation of all involved parties for more collaboration to achieve overall goals (e.g. more sustainability on planet earth)

5.3 Simulation

The application of simulation has proven its right to exist already in a variety of industrial applications. A simulation model for the decommissioning of wind farms, as described in chapter 4.4, will bring assumingly a variety of benefits which will help to achieve the goals set by the DecomTools project. But at the same time, the application of simulation will create huge challenges which have to be faced to be able to accomplish profound and reliable simulation results.

It can be stated that every simulation model is just as good as its validation and verification. Results created by simulation are just useful if the behavior of the model represents a true behavior which is close enough to the “real-world” system. To achieve a satisfactory level of true behavior a lot of effort has to be brought up. This starts with the accumulation of the required data. Based on the scale of simulation this would include all kinds of information regarding vessels and equipment, wind farm details, on-land transport, project personnel, as well as costs and revenues. Due to the vast amount of available and considerable data which influences the different stages of decommissioning, two main difficulties occur:

- How to gather and store all the required data?
- How to minimalize the complexity of the simulation model

The above mentioned points give a first idea how complex the simulation model can become by considering all possible information. A first step to reduce complexity would maybe be a division into sub-simulations with the goal to reduce the required computational capacity as well as the computational time required for the simulation. At the same time it has to be assured that the available data is always up-to-date and reflects the current situation (e.g. metocean data, available vessels etc.).

While a lot of experience and knowledge for the cutting tool approach can be gained from the offshore oil and gas industry, first experience regarding simulation of offshore wind farm decommissioning can be gained from the previous LEANWIND project.

Even though the focus of LEANWIND was more towards the installation and operation & maintenance phase of an offshore wind farm, it is not necessary to create a simulation model from scratch. It is definitely worth it to have a closer look at the simulation procedure chosen by LEANWIND to maybe get an idea or even to take over different approaches within the field of simulation.

The development of a conceptual simulation model that focuses only on the dismantling process of the blades has shown the possibility to reduce the complexity of the model by not considering all aspects involved in the entire decommissioning process. Now it is important to evaluate the practical suitability and if the generated output parameters still correspond with a “real-world” scenario. It cannot be denied that the entire decommissioning process of an OWT is a very complex and interdependent task, where quite a few parties are involved. Former decommissioning projects have shown that there are no separate “decommissioning teams”, where for example team 1 is responsible for the blades and team 2 deals with dismantling of the nacelle and tower. Especially with the application of WTIV’s, which are able to carry all components of the OWT at once, the commissioning and decommissioning will be performed by only one unit. This is obviously just possible if the water depth allows the WTIV’s, which usually have a relatively high draught, to enter the worksite. And so the wheel turns full circle, bringing us back to the beginning, where each work site requires separate evaluation with respect to its environmental conditions. Nevertheless, the creation of sub-simulations could be a very helpful decision-tool for different sub-tasks (e.g. blade dismantling) and should be evaluated with respect to its feasibility/reliability by further projects.

5.3.1 Recommended future work

To implement the approach of simulation into a relatively new and inexperienced field of wind farm decommissioning requires the investigation of different aspects. The listing below is supposed to summarize the recommend work for further tasks within the simulation approach and is presented by order of decreasing importance. It is important to mention that the order of importance is chosen by the author and is based on his opinion. The following tasks for further work are recommended:

- Reactivation of possible contact persons of the LEANWIND project
    - Collect information of simulation principles used by LEANWIND
    - What kind of challenges was facing LEANWIND while simulating?
    - Are there already any existing databases?
    - Are there any developments after the phase out of the project?
- Reduction of complexity caused by a vast amount of possible input parameters
    - Can the amount of information be reduced?
    - What kind of information is really important for the simulation process?
    - Feasibility/Reliability of sub-simulations within OWT decommissioning?
- Define strategies on how to gather all relevant information
    - Who is the right contact person/institute/company for required information?
    - Is there sufficient knowledge/expertise to determine the predefined strategies?
    - Verification of gathered information regarding up-to-dateness and reliability
- Development of a simulation tool that can handle a great amount of data
    - Which simulation software can be used (e.g. Excel, MatLab etc.)?
    - How to ensure sufficient validation and verification of the simulation model?

CHAPTER 6. CONCLUSION

Driven by the demand for more and more sustainable power delivered by OWT, the field of offshore decommissioning is becoming increasingly important. The actual decommissioning process is after only three decommissioned wind farms still in an early prototype stage. Due to little experience, no data about the actual costs of decommissioning offshore wind farms are available. First cost estimations are provided by available literature and show significant ranges for the decommissioning phase of different wind farms. One explanation could be the little experience gained in these operations, as well as the huge environmental differences of each wind farm which have to be faced by the decommissioning teams. Nevertheless, the past has shown that the costs for decommissioning have usually been assessed as too little and the actual process was more expensive than expected.

At the moment, the industry agrees that decommissioning operations will be performed similarly to the installation activities (reverse installation). With the goal to reduce decommissioning costs by 20 percent and the environmental footprint by 25 percent, the application of alternative approaches have to be considered. With respect to the dismantling process of the blades the application of a blade cutting tool as well as the approach of simulation seems indeed very promising.

The development of a first conceptual blade cutting tool combines already existing technologies in the offshore decommissioning sector with the goal to reduce the dismantling time of the blade and therefore costs and CO_2 emissions related to this task. Besides all potential reduction possibilities, the application of a blade cutting tool will generate challenges which have to be addressed. By the help of DecomTools it is possible to combine the experience and competences of each of the 13 participating partners, which can be seen as an enormous enrichment for the outcome of this project. The experience of diamond wire saw applications within the decommissioning of offshore oil and gas structures will significantly influence and accelerate the development of such a blade cutting tool.

With the introduction of simulation which is supposed to simulate different pre-defined strategies within the entire decommissioning process of an OWT, it quickly became clear that there is a vast amount of available input data. A first approach to reduce the complexity of the simulation model was the development of a sub-simulation model that focuses only on the blade dismantling process. To apply sub-simulations within a very complex and interdependent task, it is necessary to evaluate in a next step if the model still corresponds with the “real-world” scenario. The approach of simulation will as well generate big challenges due to inexperience within the decommissioning process, but with a rapid technological progress in computer technology, this approach could be a very helpful decision-tool in the near-future.

Within the pilot project for simulating the installation, operation and maintenance, and decommissioning phase of offshore wind farms (LEANWIND), the evaluation of a case-study revealed promising results regarding cost estimation which were much closer to the costs estimated by DNV GL than stated in most of the current decommissioning programs. A more profound and precise estimation of costs leads to more areas with potential for optimization which will include the supply-chain and logistics of the whole decommissioning project. Experience and knowledge already gained by LEANWIND can be seen as a great foundation to develop and refine the already existing structures towards the particular needs and goals of the DecomTools project.

The decommissioning boom era of offshore wind farms will still take some time, but the time should be used wisely to achieve the set goals. This includes the goals set by the DecomTools project and in an overall perspective the goal of a sustainable life for humans as wells as animals on planet earth for the upcoming generations.

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[112] **Figure 53:** Measurement of conicity, Reference [86], p. 68

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Appendices

Appendix A

Minutes of Meeting, DeepOcean 25th of January 2019

This document is a summary of minutes of meeting at DeepOcean on the 25th of January 2019.

Present:

Geir Helge Bachmann, Operations Director Subsea Services, DeepOcean

Rune Haraldseid, Lead Commercial Engineer, DeepOcean

Jens Christian Lindaas, HVL

Andres Olivares Lopez, HVL

Børre Mæland, Master student, HVL

Martin Urnes, Master student, HVL

Questions related to company visits (subsea operation- /construction companies):

- **Which decommissioning projects (oil and gas) have your company been involved in?**
  DeepOcean have been involved in many projects subsea and offshore; steel removal, two different loading buoy removals, debris removal, drill string recovery, two times wellhead decom, mattress recovery, structural removal, drill cutting, pipeline decom.
- **What has been your Scope of Work in these projects?**
  DeepOcean has done engineering, project management for the subsea operation. Operations include all types of dredging, a variety of lifting operations, cutting horizontal and vertical, cutting internal and external, pre-operation survey and post-operation survey, recovery of items into baskets and directly onto deck.
- **What methods and tools have been used for cutting/dismantling the structures (subsea and topside)?**
  Company 1 ONLY subsea. Mostly diamond saw/diamond blade cutting. However, HP water jetting grit/abrasives also used. Guillotine cutting has also been used. Whatever method, it is ALWAYS depending on the cost, SoW and material being cut.
- **What is your experience using these methods/tools?**
  Diamond wire – relatively slow, but reliable. Easy transport/mobilization.
  Diamond saw blade – Fast, more durable.
  HP water jet – Fast, but advanced mobilization/installation due to bigger team topside. Possibly problems with mixing grit. Additionally, uncertain if cut is successful (achieve full penetration).

This company hires sub-contractors for cutting operations. Mostly same methods as 10 years ago. Challenges related to shallow water, both for vessel and ROV. DeepOcean estimates digging/trenching for cutting 2m below mudline outside-in to 4-5 day´s work.

- **How have the parts been lifted onboard the vessel(s) and transported to the onshore base?**
  Depending on the size of the pieces;
  Heavy – entire structure/platform.
  Medium – Structure cut into a few pieces.
  Small – structure cut into several smaller pieces.
- **Which types of vessels have you been using?**
  Construction vessels (max 600 tones crane weight) and jack-up rigs.
- **Has towing of structure elements been used?**
  Yes, but mostly for whole structures (e.g. loading buoy). For this, usually towing vessel is acquired, as this is often cheaper.
- **Which onshore bases or quay facilities have you been using for the further dismantling and recirculation process?**
  It is typical procedure to keep the elements in the country where the wind park/subsea structure is based. Alas, for floating structures the UK/German coast is not always suitable.
- **Which cutting methods and tools have they been using?**
  This is not within the scope/knowledge of the subsea/decom company.
- **Where has the material been sent for further processing/recirculation?**
  Same as previous.
- **Have you been involved in installation of offshore windmills? Which windmills/parks?**
  No, only for cable grid and export cable for a few projects. For Ørsted and Dong.
- **What has been your Scope of Work in these projects?**
  Cable laying trenching, dredging and connection. Mattress installation.
- **Can the installation process be easily reversed for decommissioning of the windmills?**
  Yes, but what is most cost effective is usually a different method.
- **Will decommissioning projects related to oil and gas be a growing part of your business for the next five years?**
  Yes, they would like to be part of the "decom-wave" hopefully hitting Norway in 5-10 years. In today´s market, the price is too low due to underestimation of cost when planning decom. Companies involved need to lose money before it is possible to earn.

- **Are you planning to expand your international operations related to decommissioning projects or will your main focus be in the Norwegian sector for the next five years?**
  They are involved in decom in UK. UK is already in the "decom-wave"
- **Are you interested in entering the business regarding decommissioning of wind parks? Have you already been involved in such projects? If so, what has been the Scope of Work?**
  Yes, if this can increase revenue.

Appendix B

Minutes of Meeting, Reach Subsea 22nd of February 2019

This document is a summary of minutes of meeting at Reach Subsea on the 22nd of February 2019.

Present:

Morten Roth Stranden, Project Manager, Reach Subsea

Sveinung Dalen, Reach Subsea

Torstein Grutle, Reach Subsea

Jens Christian Lindaas, HVL

Jan Hechler, Master student, HVL

Børre Mæland, Master student, HVL

Martin Urnes, Master student, HVL

Questions related to company visits (subsea operation- /construction companies):

- **Which decommissioning projects (oil and gas) have your company been involved in?**
  Brent, removal of debris on the decom of two of the Brent field fixed platforms.
  Pile removal of Wikinger wind farm (40m depth).
  Removal of trawl protection structure and recovering of concrete subsea structures.
- **What has been your Scope of Work in these projects?**
  Brent SOW – engineering, project management and execution of the scope.
  Wikinger wind farm SOW - Removed 9 piles in the Baltic sea. Mobilized soil plug removal, dredging equipment, abrasive HP water jet.
  Trawl protection removal SOW – engineering, project management, execution and disposal of recovered items.
- **What methods and tools have been used for cutting/dismantling the structures (subsea and topside)?**
  This company has been involved with many methods, depending on the scope of work. Diamond wire, scissor cutting, guillotine and abrasive water jet have all been used.
- **What is your experience using these methods/tools?**
  This company rely on diamond wire cutting, as a standard method. This is always the go-to method if possible. Reliable and simple method, both subsea and top-side. Diamond wire is easy to set up and when doing the mobilization of vessel. Does not

need third party/technical operator! HILTI is expanding and entering the subsea cutting market – with a diamond wire cutting technique that is double the speed as today. Dredging is always a cost driver and is an uncertainty in the plan, it is difficult to estimate time used.

- **How have the parts been lifted onboard the vessel(s) and transported to the onshore base?**
  This company has used subsea basket, due to simple and safe sea fastening of the gathered material.
- **Which types of vessels have you been using?**
  offshore construction vessels, IMR-vessels, PSV.
- **Has towing of structure elements been used?**
  No.
- **Which onshore bases or quay facilities have you been using for the further dismantling and recirculation process?**
  N/A.
- **Which cutting methods and tools have they been using?**
  This is not within the scope/knowledge of the subsea/decom company.
- **Where has the material been sent for further processing/recirculation?**
  Same as previous.
- **Have you been involved in installation of offshore windmills? Which windmills/parks?**
  Not for wind turbines, but for the concrete stabilization mats. And also, the packs of rock, used to lay on cables for protection. Scour protection has also been laid.
- **What has been your Scope of Work in these projects?**
  Mattress installation
- **Can the installation process be easily reversed for decommissioning of the windmills?**
  Yes, but what is most cost effective is usually a different method.
- **Will decommissioning projects related to oil and gas be a growing part of your business for the next five years?**
  Yes, they would like to be part of the "decom-wave" hopefully hitting Norway in 5-10 years.
- **Are you planning to expand your international operations related to decommissioning projects or will your main focus be in the Norwegian sector for the next five years?**
  As long as they can make money, they do anything.
- **Are you interested in entering the business regarding decommissioning of wind parks? Have you already been involved in such projects? If so, what has been the Scope of Work?**
  Yes, if this can increase revenue.

Appendix C

Minutes of Meeting, Kvaerner 15th of March 2019

This document is a summary of minutes of meeting at Kvaerner on the 15th of March 2019.

Present:

Eirill Hatlevik, VP Decommissioning, Kvaerner

Magne Bjelland, Senior Manager Methods and Execution, Kvaerner

Jens Christian Lindaas, HVL

Andres Olivares, HVL

Børre Mæland, Master student, HVL

Martin Urnes, Master, student, HVL

Questions related to company visits (subsea operation- /construction companies):

- **Which decommissioning projects (oil and gas) have your company been involved in?**
  Kvaerner have been involved in decom projects from 1995 and onwards. Reference is made to Attachment 1 Experience List.

- **What has been your Scope of Work in these projects?**
  The projects have been related to engineering and preparation for decommissioning, some projects include removal operation and most include the onshore deconstruction and disposal operations. Reference is made to Attachment 1 Experience List.

- **What methods and tools have been used for cutting /dismantling the structures (subsea and topside)?**
  Main methods used onshore are mechanical cutting by shears (mobile and sationary) and gas cutting. Some automatic cutting and semi-automatic cutting techniques and tools are used. Cold cutting like eg. diamond wire is used for certain operations.

  For offshore and inshore works the techniques for onshore are utilised above waters. Subsea water and water grit cutting technology are used as well as diamond wire, special shears etc. There are various specialised suppliers for subsea cutting tools.

  There was a discussion on the use of explosives, but Kvaerner would rather use other methods if possible. This due to steel quality and uncertain method. Also, it will cause a big problem if it won’t explode correctly.

- **What is your experience using these methods /tools?**
  The most efficient tools as per today are mechanical cutting by shears and gas cutting. Other tools are used tactically for specific tasks. The experience from using the different tools depend on the application and the correct tools and cutting techniques must be selected based on the structure to be cut and working conditions.

  They are working towards more automatically cutting tools.

- **How have the parts been lifted onboard the vessel(s) and transported to the onshore base?**
  Modules and structures have been lifted onboard the vessel/HLV using the vessel crane.

- **Which types of vessels have you been using?**
  Modules and structures have been lifted onboard the vessel/HLV using the vessel crane.

- **Has towing of structure elements been used?**
  Yes, eg. towing of subsea structures using pencil buoy and removing of jacket structure using buoyancy tanks.

- **Which onshore bases or quay facilities have you been using for the further dismantling and recirculation process?**
  Mainly Kvaerner's Disposal site at Eldøyane, Stord and for part of Frigg the Greenhead Base at Lerwick, Shetland.

- **Which cutting methods and tools have they been using?**
  Reference is made to question 3 above.

- **Where has the material been sent for further processing /recirculation?**
  The steel materials are cut in chargeable sizes and shipped to meltery in Europe. Stainless steel, copper, zink etc. is transported to more specialised recycling facilities. Wastes are treated, incinerated or disposed off through approved waste handling contractors.

- **Have you been involved in installation of offshore windmills? Which windmills /parks?**
  No

- **What has been your Scope of Work in these projects?**
  N/A

- **Can the installation process be easily reversed for decommissioning of the windmills?**
  Yes, it can

- **Will decommissioning projects related to oil and gas be a growing part of your business for the next five years?**
  The decom business segment is expected to grow; however the new build and modification activity is still expected to form the major part of our business the next years.

- **Are you planning to expand your international operations related to decommissioning projects or will your main focus be in the Norwegian sector for the next five years?**
  The decom business segment is expected to grow with engagements also outside the Norwegian sector.

- **Are you interested in entering the business regarding decommissioning of wind parks? Have you already been involved in such projects? If so, what has been the Scope of Work?**
  Yes and no. Yes, Offshore Wind will be part of our decommissioning. No, we have not been involved yet

Appendix D

Minutes of Meeting, AF Decom 24th of April 2019

This document is a summary of minutes of meeting at AF Decom on the 24th of April 2019.

Present:

Jeroen Wiskerke, Project Manager, AF Decom

Audhild Rygg, AF Decom

Jens Christian Lindaas, HVL

Børre Mæland, Master student, HVL

Martin Urnes, Master student, HVL

Questions related to company visits:

Introduction

- **Which decommissioning projects (oil and gas) have your company been involved in?**
  AF Decom has been involved in many projects concerning removal, dismantling and recycling; Ekofisk-tank, Ekofisk Cession 1 and 2, Murchison, Janice, B11 and H7, Inde Field.
- **What has been your Scope of Work in these projects?**
  Typical SoW for these projects and AF Decom in general is the removal and/or dismantling/recycling. AF Decom has both been main contractor, but also sub-contractor with Heerema.

Cutting offshore

- **What methods and tools have been used for cutting/dismantling the structures (subsea and topside)?**
  Heerema and subcontractors have mainly been responsible for this part.
- **What is your experience using these methods/tools?**
  N/A

Logistics

- **How have the parts been lifted onboard the vessel(s) and transported to the onshore base?**
  Main principle is reverse-installation, where a heavy lift vessel lifts it onto deck and transport it to Vats. The deep quay facilities are the main advantage for AF Decom. Old platforms are built module based, and new ones are also built to be removed as a few big pieces/modules.
- **Which types of vessels have you been using?**
  Heavy lift vessels like Heerema´s Thialf and similar deepwater construction vessels. These can lift entire jackets and platform decks. Jack-up vessels have also been used, similar to Pacific Osprey.
- **Has towing of structure elements been used?**
  Yes, only for floating loading buoys. Other than that – no.

Cleaning

- **Do you consider cleaning the parts of the rig/structure before and during decommissioning?**
  Yes, cleaning is an important part of the decommissioning process. This relates both to removal of marine growth and removal of hydrocarbons and other deposits inside pipes. High pressure water jet is being used for this purpose.

Onshore dismantling /recycling /waste disposal

- **Which onshore bases or quay facilities have you been using for the further dismantling and recirculation process?**
  They have been using their own facilities at Vats in Rogaland, Norway. This is a facility specially designed for this purpose with large quay areas, deepwater quays that can accommodate heavy lift vessels, and purpose made cleaning/filtering system to handle water spills and chemicals.
- **Which cutting methods and tools have they been using?**
  Oxy-propane due to its fast nature of cutting and low cost. Shear cutter hanging from a crane, but also shear cutter mounted on excavators.
  AF Decom has a stationary shear cutter for 2500 tones – the worlds biggest!
  They were looking into the possibilities of wire-cutting onshore. Automation is something they want to get into. They will additionally look into the use of explosives in one of the future dismantling projects.

- **Where has the material been sent for further processing/recirculation?**
  Stena Recycling, Eco-fiber, HIM, SIM, Celsa (for pure steel). They have an extensive NORM-check on everything leaving the site. (NORM –naturally occurring radioactive material.)

Wind farms

- **Have you been involved in installation of offshore windmills? Which windmills/parks?**
  Not involved in wind turbines so far.
- **What has been your Scope of Work in these projects?**
  N/A
- **Can the installation process be easily reversed for decommissioning of the windmills?**
  Yes, but what is most cost effective is most likely a different method.

Business /marketing

- **Will decommissioning projects related to oil and gas be a growing part of your business for the next five years?**
  If they can earn money.
- **Are you planning to expand your international operations related to decommissioning projects or will your main focus be in the Norwegian sector for the next five years?**
  Reference is made to a later question.
- **Are you interested in entering the business regarding decommissioning of wind parks? Have you already been involved in such projects? If so, what has been the Scope of Work?**
  Yes, if this can be done as serial decommission of many wind turbines. For AF Decom it is about getting big volume into the facilities in a short amount of time.
- **What needs do you identify in terms of labor market and infrastructure today and if entering this new business?**
  No special needs compared to what they have already in relation to facilities and personnel.
- **How important is international cooperation in general and for you particularly?**
  International cooperation and customers are already very important for them so this will not be something new.
- **Do you consider this "DECOM Tools"-project to be relevant and helpful? What do you expect from the project?**
  Yes, it will be interesting to join the "Expert Committee" to follow the project.

Appendix E

Minutes of Meeting, CEDIMA 18th of October 2019

This document is a summary of minutes of meeting at CEDIMA on the 18th of October 2019.

<u>Present:</u>

Frank Siemsen, CEO, CEDIMA

Rolf Tiedtke, Project engineer, CEDIMA

Jan Hechler, Master student, HVL

Questions related to company visits:

- **Which decommissioning projects (in general) have your company been involved in?**
  CEDIMA has been involved in a variety of decom projects. From deconstruction of buildings (walls), nuclear power plants, ship wrecks to the sectioning process of wind turbine blades.

- **What has been your Scope of Work in these projects?**
  The projects have been related to providing proper equipment to realize the cutting/sectioning process as well as support during the designing stage of different mobile cutting units (e.g. mobile blade sectioning unit)
  What methods and tools have been used for cutting /dismantling the structures?

  Within this meeting we mainly discussed the application of the diamond wire saw. Other cutting/sectioning methods haven't been considered.

- **What is your experience using these methods /tools?**
  It can be stated that the diamond wire saw is; with proper maintenance and operation, a very reliable cutting tool. The big advantage of this technology is the great flexibility of possible structures to be cut. The diamond wire could theoretically be infinity long, which generates great possibilities regarding the variety of objects to be cut. Nevertheless, the operation of the diamond wire saw also harbours certain dangerous. A broken diamond wire will turn into an uncontrollable whip, which caused already serious injuries.

- **How was your experience with sectioning wind turbine blades?**
  The results with respect to cutting were very positive. After some small adjustment we were able to cut one blade at its root with a diameter of approximately 2m and a material thickness of roughly 330mm in less than 15min.

- **What is important of applying a diamond wire saw?**
    - Collection of the dust
    - Collection of the waste water
    - Sufficient water cooling in cutting area and at the diamond wire
    - Controlled feeding (high risk if wire tension too high)
    - Low bending radius of the diamond wire
    - Maintain sufficient angle of attack >15°
- **What are typical wire velocities for different materials?**
    - Solid rock ca. 20 m/s
    - Reinforced concrete ca. 25 m/s
    - Abrasive materials ca. 30 m/s
    - Composite materials ca. 30 m/s

Which diameter of the diamond cutting segment has been used for sectioning the wind turbine blades?
Approximately 10-11mm

- **How much water has been provided for cooling the diamond wire as well as the cutting area within the blade sectioning process?**
  Around 0.8m³/h
- **What power rating is needed to cut a wind turbine blade with a diameter of 2m and a material thickness of approximately 300mm in vicinity of the root?**
  For the stationary sectioning unit different power ratings for the hydraulic motor have been tried, but a power output of 15 to 20kW realizes sufficient cutting rates.
- **Are you interested in entering the business regarding decommissioning of wind parks? Have you already been involved in such projects? If so, what has been the Scope of Work?**
  Haven't been involved yet, but it seems like a very interesting sector with high potential for the next decades.

Appendix F

Data sheet HYTORC AVANTI

Data sheet can be found on next page. Reference: [136]

HYDRAULIC

AVANTI® Hydraulic Torque Wrench

The AVANTI Hydraulic Torque Wrench offers the widest range of torque output with a maximum output of more than 130,000 ft-lbs in the largest model. With tens of thousands in use around the world, the AVANTI is the industry's trusted solution for next-generation bolting.

REACTION DRIVE

The AVANTI features a patented industry-first reaction drive (also found on the ICE series) that eliminates the destructive twisting force that occurs in other torque wrenches that have a back-end reaction arm.

TORQUE & ANGLE DIAL

With a simple add-on, the AVANTI system is capable of providing a clear angle reading for bolting methods that incorporate turn of the nut.

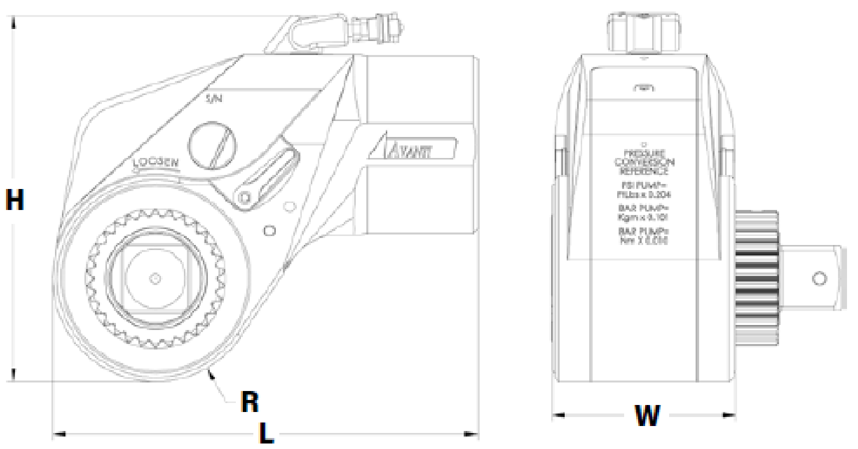
MULTI-USE SYSTEM

1

2

The AVANTI works with all HYTORC bolting systems including fastening with the HYTORC Nut (1) and the revolutionary new HYTORC Washer (2) for added safety, speed, and accuracy on any job.

HYDRAULIC



LEGEND: **H** = HEIGHT **W** = WIDTH **L** = LENGTH **R** = RADIUS

MODEL NUMBER	H	W	L	R	SQUARE DRIVE	WEIGHT	TORQUE	
IMPERIAL	in.					lbs.	ft-lbs (Min)	ft-lbs (Max)
AVANTI - .7	4.19	1.79	4.14	0.99	3/4	3.10	115	767
AVANTI - 1	4.76	2.18	4.71	1.13	3/4	4.50	196	1,284
AVANTI - 3	6.20	2.90	6.15	1.52	1	9.45	460	3,084
AVANTI - 5	7.14	3.38	7.36	1.80	1-1/2	15.60	804	5,360
AVANTI - 8	7.90	3.86	8.24	1.94	1-1/2	20.75	1,150	7,760
AVANTI - 10	8.85	4.35	9.20	2.25	1-1/2	29.20	1,800	11,743
AVANTI - 20	10.22	5.07	10.94	2.60	2-1/2	47.70	2,760	17,890
AVANTI - 35	12.22	6.23	13.45	3.19	2-1/2	82.75	4,905	31,830
AVANTI - 50	13.90	7.04	15.54	3.95	2-1/2	127.70	7,202	46,126
AVANTI - 80	16.84	7.49	19.52	4.69	3-1/2	280.50	11,965	85,695
AVANTI - 130	19.40	8.50	22.73	5.31	3-1/2	585.00	19,395	138,510
METRIC	mm				in.	kg	Nm (Min)	Nm (Max)
AVANTI - .7	106	45	105	25	3/4	1.41	156	1039
AVANTI - 1	121	55	120	29	3/4	2.05	266	1740
AVANTI - 3	157	74	156	39	1	4.30	623	4179
AVANTI - 5	181	86	187	46	1-1/2	7.09	1089	7263
AVANTI - 8	201	98	209	49	1-1/2	9.43	1558	10515
AVANTI - 10	225	110	234	57	1-1/2	13.27	2439	15912
AVANTI - 20	260	129	278	66	2-1/2	21.68	3740	24241
AVANTI - 35	310	158	342	81	2-1/2	37.61	6646	43130
AVANTI - 50	353	179	395	100	2-1/2	58.05	9759	62501
AVANTI - 80	428	190	496	119	3-1/2	127.50	16213	116118
AVANTI - 130	493	216	577	135	3-1/2	265.91	26280	187683

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05142019-P11-CS-AVANTI

Appendix G

Additional CAD drawings of the conceptual blade cutting tool

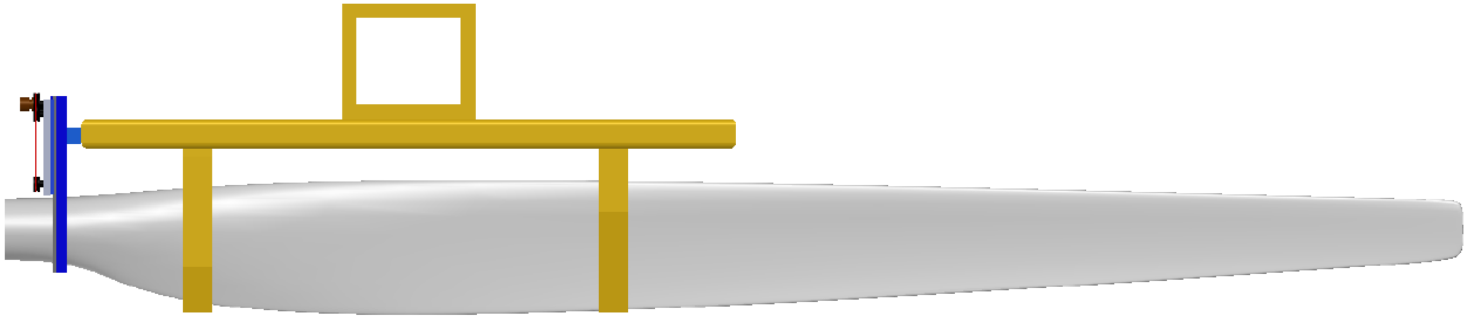
CAD drawings can be found on the next page(s).

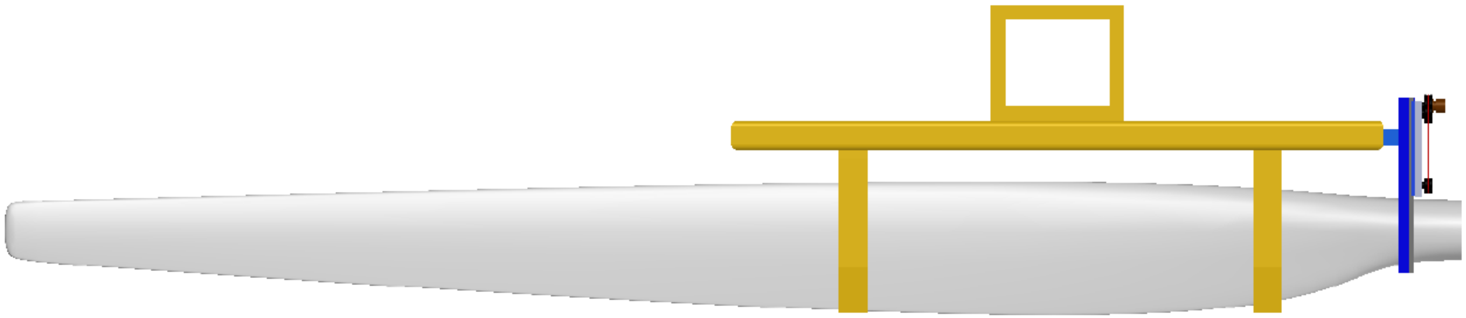
1. Right side view

2. Left side view

3. Top view

4. Bottom view





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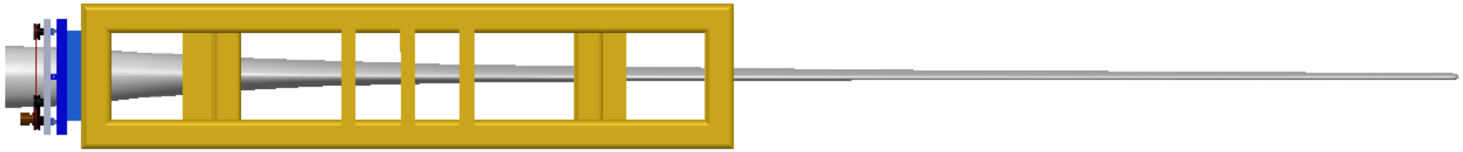

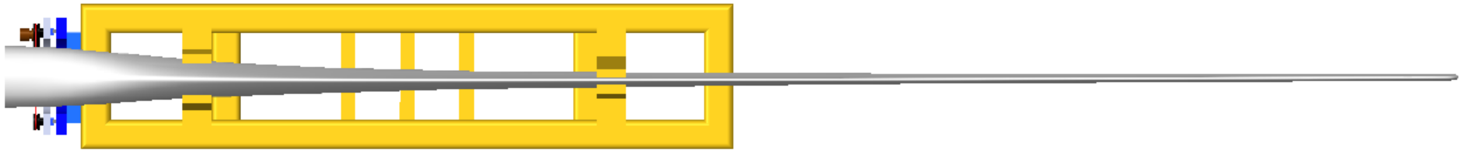

Appendix H

Data sheet aluminum alloy 7075

Data sheet can be found on next page. Reference: [137]

7075 Aluminium

Technical Datasheet

Commercial Aluminium Alloy Service. Quality. Value.

Applications

- Aircraft structures
- Gears & shafts
- Automotive

Product Description

7075 aluminium alloy is a very high strength aerospace aluminium and is commonly used in applications where the strength of the material is critical and where the need for good corrosion resistance is not important. Offering superior stress corrosion resistance, 7075 provides very high yield and tensile strengths which is dictated by the particular chosen temper.

Key features:

- Very high strength aerospace aluminium
- Used where high strength is critical and where good corrosion resistance is not important
- Up to 465 MPa yield strength and 540 MPa tensile strength depending on temper
- Superior stress corrosion

Machinability

Fair

Availability

Bar, sheet, plate

Chemical Composition (weight %)

	Si	Fe	Cu	Mn	Cr	Mg	Zn	Ti	Al	Others
min.			1.20		0.18	2.10	5.10		Bal	
max.	0.40	0.50	2.00	0.30	0.28	2.90	6.10	0.20	Bal	0.15

Mechanical Properties

Tensile Strength	40-78 ksi,	275 - 540 MPa
Yield Strength	24-68 ksi,	455 - 465 MPa

Physical Properties

Density	2.81 g/cm³
Melting Point	635 °C
Modulus of Elasticity	72 GPa
Thermal Conductivity	134-160 W/m.K
Electrical Resistivity	40% IACS

Properties dependent on chosen temper.

Technical Assistance

Our knowledgeable staff backed up by our resident team of qualified metallurgists and engineers, will be pleased to assist further on any technical topic.

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01767 604604	0121 7284940	0117 9712800	01245 466664	0191 4695428	01403 261981	0113 3075167
London	Manchester	Nottingham	Norwich	Redruth	Verwood	General
020 72412430	0161 7948650	0115 9254801	01603 789878	01209 315512	01202 824347	0845 5273331

Appendix I

Calculation of required water pump rating

To be able to cool down the cutting area as well as the diamond wire, a sufficient amount of water has to be supplied. The challenge within the application of a blade cutting tool is a working height of 80m or even more. Available literature suggests a water pressure of 1 to 6bar. The application of a mobile sectioning unit for wind turbine blades has shown that a water amount of approximately 0.8m³/h is enough to ensure efficient cutting operations [98]. For the upcoming exemplary calculation it is assumed that the cutting tool is attached to the blade and the water pump is located on deck of the working unit.

Figure 60 demonstrates an already attached cutting tool at a height of 85m above mean sea level (MSL). The water pump (rotary pump) with an efficiency factor of 0.2 will provide sea water (ρ=1029kg/m³) which has been sucked in right below the water surface. This leads to a geodetic altitude of 85m for the pump. The cooling water will be provided with an atmospheric pressure of 3.5bar.

Figure 60: Geodetic altitude [144]

The formula for the required power on the water pump shaft (P_S) is given by (1) [138].

$$P_S = \frac{\rho * g * Q * H_D}{\eta} \quad (1)$$

P_S: Shaft power [W]
ρ: Density of pumping medium [kg/m³]
g: Gravitational acceleration [m/s²]
Q: Flowrate [m³/s]
H_D: Discharge head [m]
η: Efficiency factor of pump

To be able to calculate the required shaft power (P_S), it is necessary to determine the discharge head (H_D) which has to be provided by the pump. The discharge head (H_D) can be determined by formula (2) [138].

$$H_D = H_{geo} + \frac{(p_o - p_i)}{\rho * g} + \frac{(v^2{}_o - v^2{}_i)}{2 * g} + \sum H_L \quad (2)$$

H_D: Discharge head [m]
H_{geo}: Geodetic altitude [m]
p_i: Inlet pressure [Pa]
P_o: Outlet pressure [Pa]
v_i: Inlet velocity [m/s]
v_o: Outlet velocity [m/s]
ρ: Density of pumping medium [kg/m³]
g: Gravitational acceleration [m/s²]
H_V: Pressure drop due piping etc. [bar]

Due to the intention of a first exemplary calculation with the goal to get a feeling for the required shaft power of the water pump, formula (2) will be simplified to:

$$H_D = H_{geo} + \frac{(p_o - p_i)}{\rho * g}$$

With the following parameters:

H_{geo}: 85m

p_o: 3.5bar

p_i: 0bar (atmospheric pressure)

ρ: 1029kg/m³

g: 9.81m/s²

Q: 0.8 m³/h

η: 0.2

The required discharge head (H_D) is:

$$H_D = H_{geo} + \frac{(p_o - p_i)}{\rho * g} = 85m + \frac{3.5 * 10^5 Pa - 0 * 10^5 Pa}{1029 \frac{kg}{m^3} * 9.81 \frac{m}{s^2}}$$

$$\boldsymbol{H_D = 119.67m}$$

After the discharge head (H_D) has been determined, the required shaft power (P_S) can finally be calculated:

$$P_S = \frac{\rho * g * Q * H_D}{\eta} = \frac{1029 \frac{kg}{m^3} * 9.81 \frac{m}{s^2} * \frac{1}{4500} \frac{m^3}{s} * 119.67m}{0.2}$$

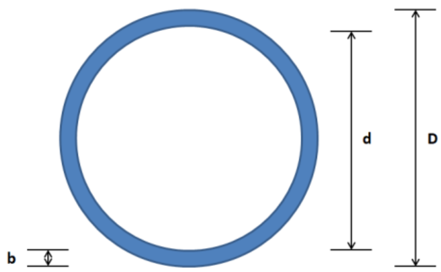
$$\boldsymbol{P_S \approx 1342W = 1.3kW}$$

The calculation has shown that an approximate shaft power of **1.3kW** is required to achieve the desired parameters for the cooling process.

Appendix J

Calculation of the amount of waste generated by cutting operation

For this example a blade geometry shall be used that corresponds roughly with the blade attached to the Siemens SWT-3.6-107 (Sheringham Shoal). The root diameter can be estimated to 2m with a material thickness of 200mm. To determine the amount of waste created during the cutting operation, the required parameters are the area (A) of the circular ring where the blade is supposed to be cut as well as the diameter of the diamond segments. Due to this parameters it is possible to calculate the volume (V) of the generated waste and therefore its mass (M). The formula to determine the area of the circular ring is given by formula (1) [139].



$$A = (D - b) * b * \pi \qquad (1)$$

The following parameters are given:

- Root diameter (D): 2000mm
- Material thickness (b): 200mm
- Cutting segment diameter (C): 12mm
- Spec. density (ρ): 7.8 N/dm^3 (for glass fibre/epoxy bond), [32]
- Gravitational acceleration (g): 9.81 m/s^2

The area to be cut regarding (1):

$$A = (D - b) * b * \pi = (20dm - 2dm) * 2 * \pi$$

$$A = 113dm^2$$

The volume to be cut is given by:

$$V = A * C = 113dm^3 * 0.12$$

$$\mathbf{V = 13.6dm^3}$$

By consideration of the volume that has to be cut, the mass (M) of the generated waste can be estimated by the following:

$$M = \frac{V * \rho}{g} = \frac{13.6\text{dm}^3 * 7.8\text{N/dm}^3}{9.81\ m/s^2}$$

$$\boldsymbol{M \approx 11kg}$$

By considering Sheringham Shoal (88 OWT, 3 blades each) as an example, a total volume of plastic-based waste of approximately **3.600dm³** with a mass of roughly **2.9t** would be generated by the application of a blade cutting tool with a diamond diameter of 12mm.

Appendix K

Estimation of expected feeding force

The following calculation can be seen as a very simplified procedure to get a first idea of the feeding force which can be expected during the cutting operation. This can be useful for a first consideration of the force which is applied to the guiding as well as the driving pulley. Due to a lack of available literature and calculations regarding cutting forces within diamond wire saw applications, the approach of reverse engineering shall be followed. As mentioned in Appendix E, an appropriate power rating for blade sectioning is somewhere between 15 to 20kW (use of a hydraulic motor) with a velocity of the diamond wire of 30m/s (v_w) for composite materials. With those parameters the feeding force to be expected shall be extrapolated backwards. As already mentioned, this is a highly simplified calculation which ignores a variety of different parameters (e.g. aqua-planning caused by cooling water). But it helps to get a first impression if the feeding force will be in a two-digit or five-digit area.

Within this estimation it is assumed that the diamond segments move just straightforward with a constant velocity. This gives the possibility to estimate the force that acts on the wire by formula (1) [141]. Unfortunately no particular coefficient of friction could be found for the material pairing of diamond and composite materials. Therefore, available literature revealed a coefficient of friction (μ) for synthetic diamonds in a range of 0.35 to 0.75 [140]. For this simplification the friction assumptions given by formula (2) shall be used [142]. The net mass of the diamond segment can be neglected.

$$P_r = F_w * v_w \quad (1)$$

$$F_f = \mu * F_n \quad (2)$$

P_r: Reduced power [W]
F_w: Wire force [N]
v_w: Wire speed [m/s]
F_f: Friction force [N]
μ: Coefficient of friction [-]
F_n: Normal force [N]

For this example, a shaft power of 20kW at the hydraulic motor is assumed. Even though the shaft power of the hydraulic motor is around 20kW, the driving power for the wire will decrease due to due to the efficiency of hydraulic motors (75 to 85%) [143]. The appearance of slip between the diamond wire and the driving pulley can be neglected for now. With respect to the efficiency of hydraulic motors, in this example the parameter "Reduced power" (P_r) will be used for the following calculations. With an efficiency of 80% P_r will be 16kW.

With the rearrangement of formula (1), the wire force (F_w) is approximately:

$$F_w = \frac{P_r}{v_w} = \frac{16{,}000W}{30\frac{m}{s}}$$

$$\boldsymbol{F_w \approx 533N}$$

With the wire force (F_w) and the assumptions of friction it is possible to estimate the feeding force (F_{fe}) to be expected during the cutting operation. Figure 61 demonstrates the assumption of friction while the diamond segment is in contact with the blade root.

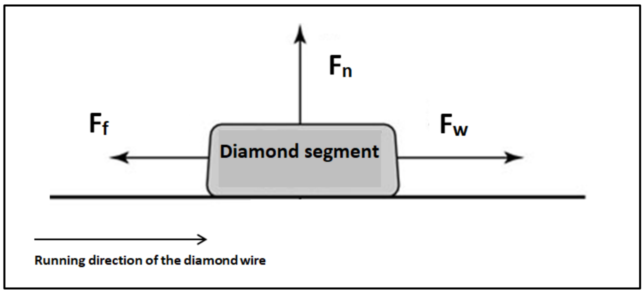


Figure 61: Assumption of friction [145]

With the simplified assumption that $F_w = F_f$ and $F_n = F_{fe}$ (due to same magnitude) and $\mu = 0.6$, the feeding force can be estimated by the rearrangement of formula (2):

$$F_{fe} = \mu * F_w = 0.6 * 533N$$

$$\boldsymbol{F_{fe} \approx 320N}$$

A very simplified estimation of the feeding force (F_{fe}) has shown that a force of approximately **320N** can be expected during the cutting operation.