Buoyancy Lifting of Offshore Platform Jackets

Modelling the economic viability of early stage concept designs

by

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TU Delft

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Abstract

In this thesis a model is set up to assess the economic viability of early stage buoyancy design concepts. The main research question is to find out if a versatile design approach to the buoyancy lifting concept, i.e. being able to take on multiple projects, can result in an economical viable solution for decommissioning offshore platform jackets in the North Sea. The economical viability is tested against the benchmark figure set by the current heavy lifting removal costs.

From a market assessment it becomes clear that 8,190 MT is the most promising size for a buoyancy device with an unknown versatility range. The minimum versatility range that the buoyancy concept of 8,190 MT should achieve, is 940 MT. A removal cost of 3,500 €/MT is used as a benchmark, in accordance with the Oil & Gas Authorities' estimate and cost reduction milestone of 35%. Three buoyancy lifting concepts are set up using design requirements distilled from the market assessment. These are the single structure DeltaLifter concept, the double external buoyancy caissons (EBC) and a configuration of external buoyancy tanks (EBT). All three concepts are tested on their technical feasibility and the operational practicability.

The methodology used in this research to assess the economic viability is to calculate the removal cost per metric tonne for every concept and compare it to the benchmark. To find the removal cost per metric tonne the initial investment costs, the job related voyage costs and the time dependent operating costs are estimated in the model.

The investment costs consist of three parts; the building costs, capital costs and scrapping income. The building costs are constructed with a model of Carreyette and optimized for pontoons. Later ballast control system costs and clamping and skidding costs are added. The capital costs are omitted from this model as it is unlikely it will be financed with any form of debt. The scrapping income is modelled as the steel weight times the scrap rate per metric tonne. The DeltaLifter turns out to be the most expensive structure to build, at roughly 17 million euros. The other two concepts will costs between 10 and 12 million euros.

The voyage costs are build up by multiplying the day rates of the assets required to operate a buoyancy lifted removal by the number of days offshore and adding the lump sum costs for an operation. The voyage costs lay between nine and eleven million euros per job, for the DeltaLifter and the EBT concept respectively. The fixed voyage costs are what could be expected for a buoyancy lifted removal. The running costs are higher than expected, due to the large amount of assets modelled to run an operation.

The operating costs for buoyancy lifting concepts consist of two parts, i.e. the storage costs and the maintenance costs. The storage costs are modelled as quayside storage using quotes from different ports around Europe. The maintenance costs are modelled as a percentage of the investment costs. The yearly operating costs of the three concepts lie close together around 250,000 €.

Finally the removal cost per metric tonne is calculated for the three buoyancy lifting concepts. It can be concluded that a versatile design approach to the buoyancy lifting concept, i.e. being able to take on multiple projects, does result in an economical viable solution. All three concepts presented in this research break even under the benchmark for multiple jacket removals. From the three concepts presented in this report, the EBC concept turns out to be the most promising concept. It is the cheapest structure to build and operationally the best concept.

TU Delft
6 June 2018

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Preface

This report is the result of a nine month research into the buoyancy removal options of fixed steel jackets. It is written as a master thesis to obtain the degree of Master of Science at the Delft University of Technology. The research was conducted at the Ardent Global office in IJmuiden, the Netherlands. The subject of this thesis was set up in accordance with Ardent. In 2012 they conducted a front end engineering study on the buoyancy removal of the BP Miller platform jacket. It was concluded that it was not economically interesting to purpose build external buoyancy caissons for this decommissioning job. With the belief that a different approach to the buoyancy lifted removal could result in an economic viable design, this thesis subject was formed. There were many bumps along the road to a feasible design. The clamping mechanism was not yet thought through, the offloading procedure had been left untouched and the storage options were only discussed very briefly. What struck me the most was that there was no clear view on which market segment to address, how versatile the buoyancy concept needed to be and good understanding of how to quantify the economic potential of early stage design concepts. With the support of the TU Delft the subject of this thesis came to be.

R.Q. Schothorst
Delft, May 2018

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1

Introduction

Many oil and gas rigs scatter the North Sea nowadays and the majority of them are near the end of their design life. Conventional decommissioning methods are overpriced and scarce. Increasing pressure from the public opinion and legislation, forces oil majors to seek out alternative methods for decommissioning. With a legacy of wreck removal operations, Ardent wants to step into the decommissioning market applying their salvage experience. To break the firm grip heavy lift vessel operators have on the decommissioning market, oil majors are very interested in the jacket removal options with limited use of these heavy lift vessels. Many ideas have been generated for the non-heavy lift removal of jackets, but without an economical backbone they are worthless. This thesis attempts to quantify the economical potential of buoyancy lifting decommissioning solutions.

In the following sections an introduction of the problem is given. The company at which the research is conducted is presented. The problem background is sketched, including a previously performed front end engineering design (FEED) study for the BP Miller platform jacket. Furthermore, the objective of the research is stated and backed up by the scope. The full structure of this thesis report is given at the end of this chapter, on page 5.

1.1. Company profile

Marine salvage can be defined as the process of recovering a ship and its cargo after a shipwreck or other maritime casualty. Salvage may encompass towing, re-floating a vessel, or effecting repairs to a ship. A salvage company is specialized in these operations. Ardent Global, or Ardent in short, is such a salvage company operating globally.

Ardent originated in 2015 from the merge between Svitzer Salvage, a salvage company which is part of the Danish Maersk group, and TITAN, an American salvage company (Chan, 2016). Before that, in 2001, Svitzer bought the Dutch tugboat shipping company, called Bureau Wijsmuller, who were also involved in salvage (Voorburg, 2017). They decided to keep the building in IJmuiden as a head office. Following the merge in 2015 Ardent now has two main offices, one in IJmuiden, the Netherlands and one in Houston, Texas, USA.

Figure 1.1: The core activities of Ardent Global; Emergency response, wreck removals and offshore decommissioning (*pictures from ardentglobal.com*).

As a salvage company Ardent specializes in emergency management and wreck removal projects, see figure 1.1. Ardent now starts to venture into the offshore decommissioning market. The emergency management branch reacts globally with quick emergency response, and with a preparedness program. Similar to emergencies onshore, they try to save life, vessels and cargo from loss at sea. The projects that Ardent undertakes are wreck removals and offshore decommissioning projects. Their most known accomplishments are the removal of the West Atlas rig (Sea Trucks Group, 2016) the raising of the Costa Concordia (Chan, 2015) and the largest wreck removal of 2016, the Troll Solution (Schuler, 2016). Ardent now continuous to grow as one of the leading salvage operators on the world.

1.2. Problem background

In the North Sea, there are approximately 650 offshore installations which have a remaining life expectancy of less than 20 years.[1] These structures range from 100 tons up to 80,000 tons and are scattered over oil fields in the Northern, Central and Southern North Sea and the Irish Sea, as illustrated in figure 1.2.

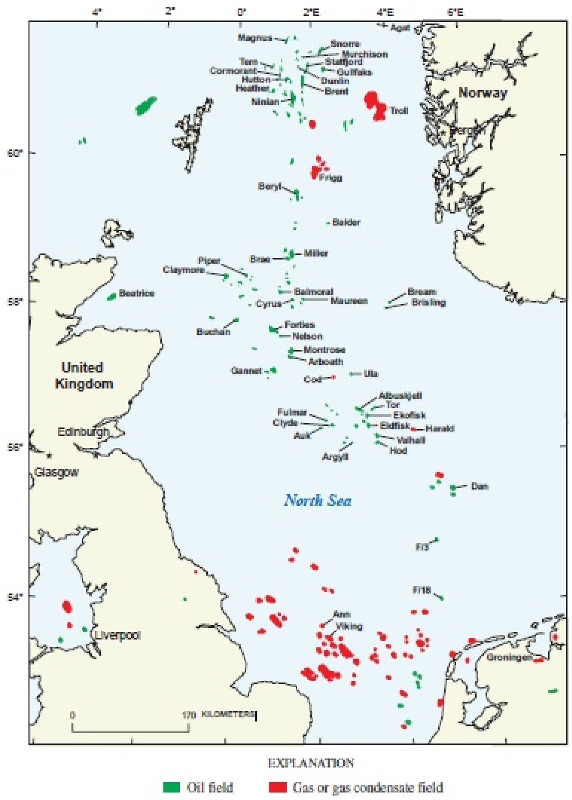


Figure 1.2: Distribution of oil and gas fields in the North Sea (*picure from US Dept. of Interior USGS Bulletin 2204-C (Guatier, 2005)*).

Over the next 20 years these platform cease operations, and will be abandoned. While there are many creative initiatives to leave the platforms in the North Sea, e.g. rigs to reef, carbon capture and storage (CCS) or electrification, according to legislation most of them will have to be removed. The International Maritime Organization (IMO) states that all structures must be removed to at least -55 meter LAT, for the safety of navigation and fishing. In fact, the international OSPAR convention dictates the complete removal of offshore installations in the North Sea except derogation from the general rule (OSPAR, 1998). All North Sea decommissioning is regulated by this convention, and internal regulations from the participating countries refer to OSPAR 98/3 (Decom North Sea, nd), e.g. the Norwegian Petroleum Act 1996 (Norwegian Petroleum Directorate, 1996), the British Petroleum Act 1998 (British Government, 1998) and the Dutch Mining Act 2002 (Nederlandse Rijksoverheid, 2002).

In 2015 more than £2.6 billion was spent on offshore decommissioning worldwide, another £3.1 billion in 2016 (Offshore Energy Today, 2017a). The UK spend £1.1 billion on offshore decommissioning in 2016,

[1] Extracted from OSPAR database (OSPAR, 2015)

and the Oil&Gas Authority UK (OGA) estimates another £17.6 billion for the removal of offshore installations from 2016 to 2025 on the United Kingdom Continental Shelf (UKCS) (OGA, 2016). In 2016, the P50 probability estimate of offshore decommissioning expenditure is prospected at £59.7 billion by the OGA (50% of the Monte Carlo estimations will exceed this number). These numbers only concern the oil and gas platforms on the UKCS, but can be extrapolated to the entire North Sea area to give an insight in the size of the offshore decommissioning market.

Currently three different methods are applied in offshore decommissioning. Either piece small decommission, a single lift technique or by means of heavy lifting. Differences between the three techniques are discussed shortly. Piece small operations mean that the structures are decommissioned in small pieces offshore and shipped into shore via supply vessels for further processing segregation and waste management (Shetland Decommissioning, nd). This method involves a lot of personnel working on the platforms, making it a risky method and time consuming, especially considering the environmental conditions on the North Sea. The single lifting method lifts off the topside structure and the jackets in one lift. The only known application of this method for very large platforms (> 15,000 MT) is the Pioneering Spirit, seen in figure 1.3. With heavy lifting the structure is cut in pieces offshore and lifted of the seabed in large pieces to be brought onshore, before being further processed. This process is relatively quick, but requires large cranes and vessels. The last two methods, single lift and heavy lift, quickly become costly operations, especially for the larger platforms, i.e. > 3,000 MT. A rough estimate to work with nowadays would be 4000 €/MT/day (Offshore Energy Today, 2017b). This is significantly more expensive than piece small decommissioning, but a quicker operation and with less employment on the platforms.

Figure 1.3: The Pioneering Spirit is the only known application of the single lift decommissioning method for very large platforms *(picture from allseas.com)*.

Ardent is exploring the possibilities of offering a new decommissioning solution. The company is looking into the possibility of developing a method to lift platform jackets from the seabed using buoyancy lifting instead of heavy lifting with cranes. Recently the company conducted a study on the removal of the BP Miller platform. For this assignment a front end engineering design (FEED) study was made, suggesting the possibility of a buoyancy lifted removal of the platform jackets (Ardent, 2016). The idea is illustrated in figure 1.4. The report suggests a method where external caissons are attached to the jacket structure and lift it us-

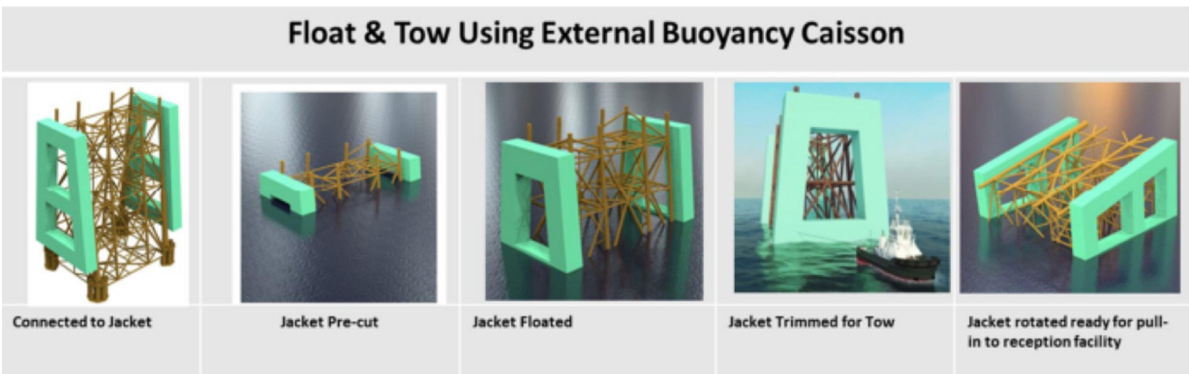


Figure 1.4: The buoyancy lifting idea presented in the BP Miller Decom FEED Study Report (Ardent, 2016).

ing natural buoyancy instead of heavy lifting. The process is comparable to what was done to get the Costa Concordia upright in 2013, see figure 1.5. After the jacket is lifted from the seabed, it can be towed away using tugboats. In order to enter most shallow harbours and onshore demolition sites, the structure can be rotated by ballasting the caissons properly. The buoyancy lifting concept is not new in oil and gas decommissioning,

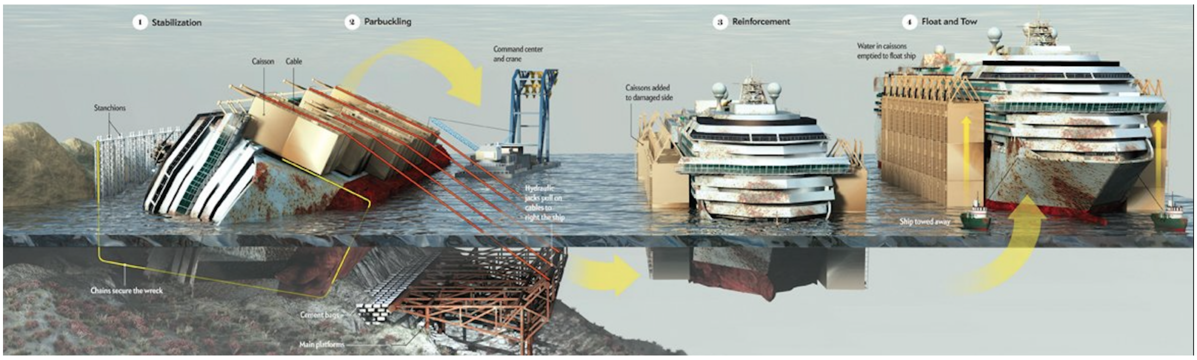


Figure 1.5: The raising of the Costa Concordia in 2013 using external buoyancy caissons (*picture from blogs.scientificamerican.com*).

it was executed once before with the removal of the Frigg DP2 jacket in 2008 (Terdre, 2009). With the aid of buoyancy tanks Aker Solutions successfully floated the jacket clear of the seabed and towed ashore, see figure 1.6. The floating structure still had a draft of more than 80 metres, which did not pose a problem in the deep fjords around Norway. After towage the jacket was set at the seabed at 90 metres waterdepth close to the decommissioning site. There it was subsequently piece small decommissioned. This example illustrates one of the most difficult challenges of the buoyancy lifting concept. The structure should be able to float with a draft less than 15 metres in order to enter ports and decommissioning yards. The buoyancy lifting concept presented by Ardent in the BP Miller FEED study was capable of this feature.

Figure 1.6: Frigg DP2 jacket towed to shore via re-float method *(picture from offshore-mag.com).*

The BP Miller buoyancy lifting concept was designed specifically for a 12,000 MT lift though, not being able to cope with a variety of jackets and therefore not versatile enough to be economically attractive. The design itself was also way too heavy, resulting in even more buoyancy needed to keep the structure afloat as it was required to carry its own weight. This made the structure too big to handle, and too big to store. At this stage the design did not include thorough examination on the clamping methods, ballasting, the storage facilities of the buoyancy caissons and the associated costs, maintenance and employability. Quick estimations made clear that the project would not be economically viable if the caissons were purpose build. Moreover, the timing was not ideal. The study was still in its infancy, when BP started the process of issuing an invitation to tender for the removal. With no proven technology and prices brought down by competitive bidding by Allseas, Heerema and Saipem, the project was finally not assigned to Ardent, leaving the buoyancy lifting study stranded. The BP Miller decommissioning was eventually assigned to Saipem in 2016 and will be decommissioned by heavy lifting (Offshore Energy Today, 2016a).

In a market where increasingly more and larger offshore structures have to be decommissioned, public awareness of environmental issues is raising and governments are trying to cut costs on decommissioning projects, new opportunities for buoyancy lifting emerge. It is worth to mention that the taxpayer pays 50% of decommissioning costs in the UK, 73% in the Netherlands (Offshore Energy Today, 2017b). At the Offshore and Energy Exhibition and Conference in Amsterdam 2017, the UK's Oil and Gas Authority stated (Offshore Energy Today, 2017a): "The UK sector is looking to deliver 35% in cost savings and for this to be achieved, the industry will have to step away from the 'business as usual' mode of operating." To add momentum to this statement, the Oil and Gas Technology Centre (OGTC) in Aberdeen issues a funding for innovative decommissioning ideas. Ardent applied to this fund, and is expected to gain resources for the buoyancy lifting concept. Moreover, end of October 2017 Ardent obtained a research order from Royal Dutch Shell to investigate the buoyancy lifting concept further.

The main obstacle is still to convince the oil majors of this new method. Their concerns rest mainly in the financial viability, technical knowledge, and health, safety and environmental issues (HSE) before even technical feasibility.

1.3. Objective

The objective of this research is to create a model to validate the economic viability of different versatile buoyancy lifting concepts in an early design stage and find out if a **versatile** design approach to the **buoyancy lifting concept**, i.e. being able to take on multiple projects, can result in an **economically viable** solution for decommissioning offshore platform jackets in the North Sea, tested against the benchmark figure set by the current heavy lifting removal costs.

1.4. Scope

The aim of this research is to verify that buoyancy lifting concepts have practical potential. This will be accomplished by proving the economic viability of technical feasible concepts. This means that the technical feasibility of the buoyancy lifting concepts tested in this research is assumed already to be assessed. The concepts will be developed sufficiently to provide the basic parameters required for cost calculations as presented in this thesis. The model will test and compare the economical potential of different concepts and compare them to the benchmark set by heavy lift vessel removal costs. If not found directly, indirect sources will be used to provide a benchmark figure. The generated concepts will only consider buoyancy lifting solutions, and not include heavy lifting, piece small decommissioning or other salvage approached methods. This research will also not include the detachment of the topside. This research will also not look into cutting process to detach the jackets from the seabed. Both operations are assumed to be similar to other methods applied in offshore decommissioning. The concepts, however, will have to be able to cope with multiple projects in order to become economically interesting. That is either a modular or versatile design that can handle a range of different jackets or a design that is also capable of doing other offshore projects, e.g. installation, transportation.

The model constructed in this research will check the economic viability. It will calculate the net present value of the buoyancy concepts to come up with an investment decision. The costs used in this calculation will consist of the costs for a full life cycle, i.e. design, manufacturing, operational, maintenance, storage, and the scrapping costs. For the calculation of these costs as much as possible real numbers will be used by requesting quotes from the appropriate parties. In the absence of quotes or real-life data, estimations will be made using validated methods. The current method of offshore decommissioning using heavy lifting will be used as the benchmark to test the economic viability of the buoyancy lifting concepts.

Geographically the research will mainly but not exclusively focus on structures in the North Seas, confining the Northern, Central and Southern North Sea and the Irish Sea. Relying on a Porter analysis (Porter, 1979, pages 137-145) performed by Ardent, this area could be seen as “the center of excellence” in decommissioning and therefore their prime focus. Furthermore, there is a large database available with details of offshore structures in the OSPAR region, while for other geographical regions this data may be hard to obtain. Besides that the company possesses a lot of valuable information on assets available in the North Sea region and close-out reports from former decommissioning projects.

1.5. Structure of the report

After the introduction to the problem in this chapter, sketching the background and defining the objective and scope of this research, chapter 2 will deal with an overall market assessment. The scope is further narrowed down and a starting point for the design of a buoyancy lifting device is set. Some example jackets are detailed and the benchmark figures for the removal costs in the decommissioning sector are defined. Chapter 2 sets the boundaries of this research. In chapter 3 the buoyancy lifting concepts are introduced. The results of a brainstorm session held at Ardent are presented and categorized. Next, the technical feasibility is clarified. An operational assessment is added and finally the three buoyancy lifting concepts studied in this research are presented. They will be used as a case study to test the model throughout the report. In chapter 4 the methodology behind the economic model is described. The basic calculations used in this model are formulated and the structure of the economic model is laid out. Thereafter, chapters 5, 6 and 7 explain how the costs used in the net present value calculation are found. First the initial investment costs are detailed in chapter 5, next the job related voyage costs are defined in chapter 6 and thirdly the time dependent operating costs are calculated in chapter 7. After all the costs required for the net present value calculation are found, the calculation itself is detailed. In chapter 8 assumptions for the removal cost calculation are explained first, and then the formulae used in the removal cost calculation are presented. At the end of chapter 8 an example run is added. Finally, in chapter 9, the buoyancy lifting concepts are compared to each other and to the benchmark figures defined earlier. A conclusion is made about which buoyancy lifting concept shows most promise in chapter 10. The report is finalized with recommendations at the end of chapter 10.

2
Market assessment

For the design of a buoyancy concept for lifting offshore platform jackets it is important to know which market segment to address. The choice of a market segment has an immense impact on the commercial viability of the concept. Moreover, it defines the initial dimension of the buoyancy lifting device. Therefore a thorough examination of the market should be made. This chapter elaborates on the market analysis performed for this research. Since all decommissioning in the North Sea is strictly regulated, this chapter starts with an insight in the legislation concerned with the decommissioning activities in the North Sea. Some rules that apply to the decommissioning, such as derogation for large jackets, has an influence on the market assessment. Then the market is further explored by segmenting the market by installed weight. The weight of jackets dictates the assets needed to remove the structure to shore. The market segment sizes are estimated using available data on North Sea platforms, their weight and age distribution, and expected decommissioning. The market segments are then quantified to give a first insight in market entry opportunities. After the market size is analyzed, the competition is exposed and measured. Market trends in heavy lift capacity are discussed thereafter and the relation between the number of jackets and the heavy lift capacity is analyzed. A market segment is targeted combining the information from both the market size analysis and the competitive landscape analysis. From here this market segment is analyzed more in depth to find optimal design starting points for the buoyancy device. Once the dimensions of the buoyancy device are distilled, the jackets considered in the market opportunities are analyzed. Two case jackets used throughout this report are presented. Lastly a benchmark is defined for the found opportunities.

2.1. Legislation

Copied from "Prospects for North Sea decommissioning".[1] *For the original document and more information please refer to atlanticmo.com.*

The decommissioning of offshore installations is subject to several types of legislative frameworks, international, regional and national. The requirements for removal originate from legislation regarding safety of navigation, and for the disposal of installations in pollution prevention legislation.

2.1.1. International treaties

The International Maritime Organization (IMO) is the UN-body setting standards for international shipping. It developed guidelines for the removal of offshore installations worldwide in 1989 (IMO, 1989). The guidelines establish removal criteria, requiring that all structures in waters less 100 m and substructures weighing less than 4,000 t must be removed completely, and installations in deeper waters may be removed partially if provided for a 55-m water column for safety of navigation. In addition, it states that all structures installed after 1 January 1998 must be designed so as to be suitable for complete removal. However, bear in mind that the IMO guidelines remain non-binding.

[1] Prospects for North Sea decommissioning (Vollaard, 2017), pages 45-48

2.1.2. Regional conventions

The regional convention that governs marine disposal in the North Sea area is the Oslo and Paris Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR). It came into force in 1998 replacing the 1972 Oslo Convention and 1974 Paris Convention. OSPAR requires the removal to shore of all topsides and all substructures weighing less than 10,000 t. However, for large steel structures – jackets over 10,000 t – the footings may be left in place if permission is granted on specific grounds, and after consultation with all OSPAR states. On a case-by-case basis, exception from the general rule can be granted for concrete structures to able to remain in situ after acceptance of a comparative assessment and derogation application. The derogation does not apply to any steel installation placed after 9 February 1999, the date the decision came in to force. All topsides (i.e. not part of the substructure) must be removed in any case. The OSPAR provisions do not apply to pipelines.

2.1.3. National law

All North Sea decommissioning is regulated by national laws. The national laws from the participating countries all refer to OSPAR 98/3 (Decom North Sea, nd), e.g. the Norwegian Petroleum Act 1996 (Norwegian Petroleum Directorate, 1996), the British Petroleum Act 1998 (British Government, 1998) and the Dutch Mining Act 2002 (Nederlandse Rijksoverheid, 2002). The national laws all overlook their respective continental shelf.

2.1.4. OSPAR revision

It is important to note that the OSPAR 98/3 Decision is reviewed every five years, and comes up to review in Q1 of 2018. Some institutions, like the Marine Alliance for Science and Technology for Scotland, push for the derogation of all jackets up to -55 meters below sea level. Research conducted with 40 experts on benthic ecology, environmental impact, marine ecosystems and other fields confirms that experts are in consensus that leaving the structures in situ benefits the megafauna, has artificial reef effects, less seabed disturbance and provides shelter to many fish and shellfish (MASTS, 2017). For now, all fixed steel jackets in the North Sea region have to be removed, from three meters beneath seabed to the top. Derogation that applies to structures larger than 10,000 tons might be extended to a wider range of jackets following the OSPAR 98/3 revision. Nonetheless, all structures will have to be removed to at least -55 metres.

Latest developments show that the OSPAR 98/3 Decision will remain in force at it is, dictating the removal of all offshore installations (OIC, 2018). Derogation of the general rule by leaving the footings in place remains only an option for jackets larger than 10,000 MT installed before 9 February 1999.

2.1.5. Derogation in this report

Taking derogation into account, means that it could be more challenging to remove a 9,000 MT jacket than a 11,000 MT jacket. To leave the jacket in place could mean up to a 30% weight reduction (Oil & Gas UK, nd). This is confirmed by the Brent Alpha jacket removal (Shell, 2017a). With this in mind, platforms up to 15,000 MT could be potentially removed with 10,000 MT lift capacity. All fixed steel jackets weighing more than 10,000 MT could be considered to fall under derogation, and get a 30% weight reduction. In this research derogation is not considered for any jacket. This is in line with the latest trend in the OSPAR review, pushing for a complete removal of all structures (OIC, 2018). Furthermore, considering the removal of very large structures including complicated operations to remove the footings is more in line with Ardent salvage mindset. Their expertise is a market advantage for “headache” removals. At last, by not considering derogation, a pessimistic approach is used. As a result all market segments above 7,000 MT could be more promising than presented, considering that larger jackets may leave their footings in place. This should be kept in mind when analyzing the market potential.

2.2. Market size

In chapter 1 the North Sea is chosen as the geographical focus of this thesis. It is seen as the centre of excellence for Ardent, and more data on installed structures is available. This research further focuses on the platforms supported by fixed steel jackets. There are a total of 1364 operational offshore installations in the North Sea (OSPAR, 2015), from which 546 are supported by steel jackets. In this section the decommissioning market size for fixed steel jackets in the North Sea will be further examined. First the offshore platform jackets are divided in relevant segments that dictate the market, then a weight and age distribution will be set up to finally quantify the market segments.

2.2.1. Market segments

For the decommissioning market it makes sense to split the market segments by their installed weight, as this defines the assets required for the removal of the jackets. The availability of assets has a large impact on the market potential for alternative methods, and will be examined in the next section. The weight of these jackets range between 100 and 43,700 metric tons. These are the AWG-1 jacket and the Ninian South jacket respectively, see figure 2.1. No natural distinction exist in the weight distribution of heavy lift assets, nor in

Figure 2.1: The Ameland-Westgat-1 is the smallest steel jacket of about 100 tons, and the Ninian South, 43,700 tons, is the heaviest fixed steel jacket in the North Sea *(Pictures from tekla.com and upstreamonline.com respectively)*

the installed fixed steel jackets. For that reason the division proposed by Wood Mackenzie is taken as the segmentation of the market. Later in this research, segmentation will partially be neglected if calculations concerning the competitiveness are to be made. The segments proposed by Wood Mackenzie are presented in table 2.1.

	Number of fixed steel jackets per age [years]							
Market segments in [MT]	<10	11-20	21-30	31-40	41-50	50+	No data	Total
0 - 1,000	9	45	76	40	48	0	0	218
1,000 - 3,000	16	32	40	36	25	1	0	150
3,000 - 5,000	4	12	8	11	2	0	0	37
5,000 - 10,000	9	23	12	13	6	0	0	63
>10,000	4	6	18	13	7	0	0	48
No data	-	-	-	-	-	-	30	30
Total	42	118	154	113	88	1	30	546

Table 2.1: An overview of the steel jackets located in the North Sea, data subtracted from OSPAR Inventory of Offshore Installations - 2015 (OSPAR, 2015), segments defined by Wood Mackenzie.

2.2.2. Weight and age distribution

As can be seen in the left figure in figure 2.2, most of the North Sea fixed steel jackets are small installations, i.e. <3,000 MT. More than 350 of 546 platform jackets can be found in the smallest two groups. Only 7 % of all fixed steel jackets are present in the medium sized group of 3,000 tot 5,000 MT. Roughly a fifth of the installed

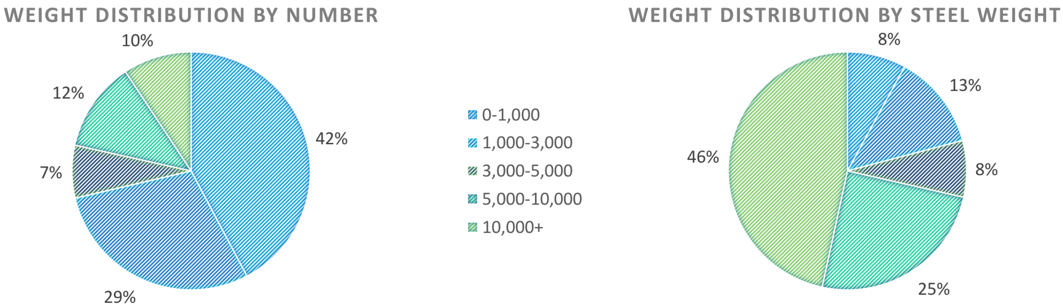


Figure 2.2: The weight distribution by number and by weight of fixed steel jackets in the North Sea

jackets is larger than 5,000 MT. Nonetheless, this group encloses three quarters of the installed steel weight, as can be seen in right figure in figure 2.2. The steel jackets have been designed to the life expectancy of oil

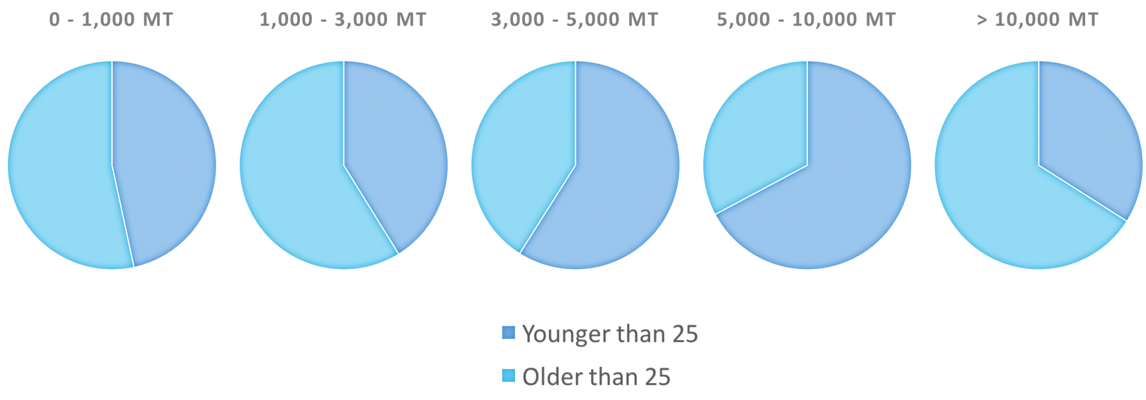


Figure 2.3: The age of the offshore platform jackets for each weight group

fields. This is roughly 25 years (Bureau Veritas, 2010; ABB, 2011; Ghosal, 2016). The average age of the fixed steel jackets is 27 years, with 294 jackets older than 25 years. In figure 2.3 it can be seen that the small jackets and the >10,000 MT weight group have relatively the most older platforms. A more detailed age distribution per jacket weight group can be found in appendix A.

An important remark is that the weight of the fixed steel jackets given in the OSPAR database is the tow-out weight of the jacket. After being put in place the jacket is anchored to the seabed using steel piles, often reinforced by concrete grout. Conductors or risers are added to the steel jacket to facilitate the oil flow. Over the years marine growth collects on the substructure. All these factors can add up to 71% weight increase, as exampled by the Brent Alpha jacket decommissioning (Shell, 2017a, page 21). For the previously conducted FEED study on the Miller jacket, a 25% weight increase can be found (Ardent, 2016, page 13). For the Goldeneye jacket, Shell provided information on the Goldeneye jacket for its decommissioning, stating a 48% weight increase (Shell, 2017b). As conductors normally are taken out prior to jacket removal, the steel pile fixation differs for all jackets, and marine growth rate is subject to many factors, it is hard to estimate the added weight. It is of large impact on the required force to lift a fixed steel jacket, and can therefore not be neglected. For this research a 30% weight increase is assumed and used throughout the report. It is advised to investigate the actual weight on a case-by-case basis, before making any further assumptions.

Another important remark is that the age of the fixed steel jackets does not reflect their decommissioning schedule. A quick research on the age of the only few jackets that have been removed to date in the North Sea shows that some jackets as young as five years are already decommissioned, while other jackets installed the in 70’s are still in place (OGA, 2012).

2.2.3. Segment size quantification

The Atlantic Marine and Offshore predicts that roughly half of the fixed steel jackets in the North Sea will be decommissioned in the next decade (Vollaard, 2017). While it is not certain when the jackets are decommissioned exactly, it is safe to assume the decommissioning market is prominently growing. Nonetheless there is no significant time pressure on the decommissioning of platform jackets, since operators are holding off decommissioning as long as possible. That being said, the Oil & Gas Authority UK and the EBN in the Netherlands still believe the decommissioning market will experience a peak in 2024/2025 (Offshore Energy Today, 2017b). Starting the development of an alternative for decommissioning now, responds to that expectation.

Market prospects in offshore decommissioning are yearly published by the Oil & Gas Authority UK in their Decommissioning Insights (OGA, 2016, 2017b). For the entire North Sea market an estimate of £28 billion can be derived from that report. To make an estimation for the market segments, the substructure removal costs per ton steel are used. In table 2.2 the expected decommissioning costs per segment are given, for platforms older than 35 years. This gives an approximation of the current market size per segment. Considering only jackets that are to be decommissioned soon (i.e. older than 35 years), the Oil & Gas Authorities’ estimate would be £1.7 billion (OGA, 2016, page 9). This validates the method used to quantify the market segments.

The combination of a more mature segment and at the same time the heaviest segments results in the largest current market segment. The jackets larger than 10,000 MT account for 54% of the current decom-

Market segments in [MT]	Total number of jackets	Total weight [MT]	Older than 35	Current market size in millions	Market share
0-1,000	218	141,519	27.9%	£138.2	8.1%
1,000-3,000	150	228,754	26.8%	£214.6	12.6%
3,000-5,000	37	136,397	23.1%	£110.3	6.5%
5,000-10,000	63	440,681	20.3%	£313.1	18.4%
10,000+	48	826,350	32.0%	£925.5	54.4%
Total	516			£1,701.7	100.0%

Table 2.2: Market segment size quantification using the Oil & Gas Authority's substructure removal costs estimate. (Values of 2016)

missioning market. Second largest segment is between 5,000 and 10,000 MT. This segment is the newest of all, with only 20% of the jackets older than 35 years (and thus assumed up for decommissioning now). This also implies that this segment has the most potential to grow. Most jackets are smaller than 1,000 MT, this is the largest group of jackets, but the second smallest in terms of expected decommissioning. With many competitors and only 8% of the expected decommissioning this hints to be a though market segment to entry.

The largest group of jackets, i.e. up to 3,000 MT, only covers 20% of the market share. It is therefore more interesting to focus on the smaller market segments that collectively cover 80% of the market share. As stated before, the choice of market segments has an influence on the interpretation of the market sizes. Nonetheless, it is clear that the focus should lay on jacket larger than approximately 3,000 MT.

2.3. Competitive landscape

Now that the fixed steel jackets installed in the North Sea are inspected more closely, the competitive landscape can be examined. In this section first the main service providers are listed, both of heavy lift solution as alternative removal techniques. Next, the heavy lift assets are quantified to give an insight in the competitiveness of the different market segments. Trends in the competition are distilled from recent press releases. Finally a market segment is targeted combining the information from both the market size analysis and the competitive landscape analysis.

2.3.1. Main service providers

As stated before in chapter 1, there are three different techniques for jacket removal, i.e. piece small, heavy lifting or single lift. The buoyancy lifting concept is a single lift technique, and therefore it will be compared to other single lift techniques using heavy lifting vessels. In this sector owners and/or operators of heavy lift assets are the main competitors. A selection of these competitors are given in table 2.3. Novel single lift ideas are not taken into account as competitors, since no proof of concept is provided for any other technique than using heavy lift assets.

Single lift solution		(Other techniques)	
Allseas	NL	AF Decom	NO
Heerema	NL	Scanmet	SE
Subsea 7	UK	Veolia	UK
Boskalis	NL	Aker	NO
Saipem	IT		
Scaldis	BE		

Table 2.3: A sample of some companies that offer decommissioning solutions in the North Sea.

2.3.2. Quantification of heavy lift assets

To quantify the competition a heavy lifting vessel database is set up. The inputs for this database are the yearly Offshore magazine its worldwide survey of heavy lift vessels (Moon, 2016), the "Prospects for North Sea decommissioning" report (Vollaard, 2017) and previous constructed databases from Ardent on jack-up barges and shear leg cranes. This database gives a non-exhaustive list of the available heavy lifting tools around the world. Even though this is not a complete list, especially for the range of lower lifting capacity, it includes at least all the major heavy lift vessels. From this database a pivot table can be subtracted to give an idea of how many vessels are available in the North Sea and for the different jackets weights. In total 106 heavy lift assets were found. An overview can be seen in figure 2.4, in comparison with the number of fixed steel jackets in that market segment. From this graph it becomes clear that there barely exist heavy lift vessels

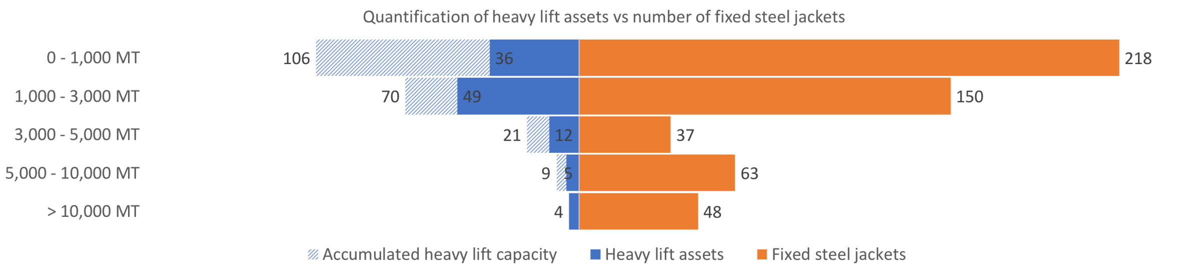


Figure 2.4: A quantification of the single lift competition in the North Sea area.

for a single lift removal of the largest fixed steel jackets. Furthermore, taking into consideration that the larger cranes are also possible of lifting smaller jackets, the smaller fixed steel jackets have significantly more lifting options. This suggests that the decommissioning of the smaller jackets can be seen as a saturated market, whereas the larger segments look more promising to enter the decommissioning market.

2.3.3. Accumulating heavy lift capacity

Comparing the fixed steel jackets to the absolute number of heavy lift vessels would not make sense since larger cranes are also able to lift beneath their maximum capacity. However, it is very unlikely that a crane with a 10,000 MT capacity will consider lifting a 1,000 MT jacket. To what extend a heavy lift vessel will lift beneath its capacity is related to many factors. The most conservative approach is to accumulate the heavy lifting capacity all the way down. Large cranes are then also taking into consideration for the removal of the smallest jackets. As this will disadvantage the market segment with the smaller jackets, a different conclusion might be drawn from the data if a different assumption is made about the accumulation of the heavy lift capacity. A sensitivity check is added varying the percentage of capacity to which a heavy lift vessel will consider a tender. The results become more promising for less conservative markets, i.e. where assets lift way below their capacity, but the same peaks can be seen in the market. It is therefore concluded that it does not affect the market analysis, but should be closer looked upon when considering direct competitors and related revenues and costs. In this thesis the heavy lift capacity will be accumulated completely down, as presented in figure 2.4.

2.3.4. Trends in heavy lift capacity

One important trend to observe is that the fleet of heavy lifting vessels is growing, as already indicated by a 2014 article in Offshore Magazine (Moon, 2014). In table 2.4 a list of expected crane vessels with a crane capacity >3,000 MT is given. New competitors are mainly seen in the very large heavy lifters, >20,000 MT, such as the Sleipnir from Heerema and the SSCV Zeelandia from OOS International. This can be explained by the fact that are minimal single lift solutions in that weight range. Besides that the current assets with a lift capacity >5,000 MT are all older than 25 years, and expected to retire. Most recently Heerema's 8,000 MT crane Hermod was taken out of operation (Foxwell, 2017). The other expected competition is for the capacity beneath 5,000 MT. This can be explained by the large amount of smaller platform jackets.

The strong expected growth adds pressure to the market segments up to 5,000 MT, with an increase of at least more than 40% in heavy lift assets for the middle segment of 3,000 to 5,000 MT. The advent of the very large heavy lifters is less threatening, as they replace the current very old vessels. In the North Sea, the only heavy lifters capable of removing a jacket weighing more than 5,000 MT are Heerema's Balder, Heerema's Thialf and Saipem's Saipem 7000, see figure 2.9. Their age is 40, 33 and 32 years respectively. Furthermore, the twin marine concept is not likely to be expected soon and the Amazing Grace will not future the jacket lifting system (Teunisse, 2017, personal conversation). The new orders for very large heavy lift assets show however that the competition is well aware of the eminently growing decommissioning market. The old fleet is being renewed, and the new vessels are significantly larger than their predecessors. The recent character of most press releases suggest that potentially even more very large heavy lifters are to be expected.

All confirmed new heavy lift vessels will be taken into account for further market segment potential calculations. A newbuild heavy lift vessel is assumed to be confirmed when a keel-laying ceremony has been

Company	Name	Lift capacity [MT]	Expected	source
Allseas	Amazing Grace	72,000	2020	(Allseas, 2013)
Shandong Twin Marine	twin heavy lift	34,000	-	(Offshore Energy Today, 2016b)
OOS International	SSCV Zeelandia	24,000	2022	(O.O.S. International, 2017b)
Heerema	Sleipnir	20,000	2019	(Heerema, 2017)
GeoSea	Orion	5,000	2020	(Decom News, 2017)
OOS International	SSCV Serooskerke	4,400	2019	(O.O.S. International, 2017a)
OOS International	SSCV Walcheren	4,400	2019	(O.O.S. International, 2017a)
Scaldis	Gulliver	4,000	2018	(Martin, 2018)
Boskalis	Bokalift 1	3,000	2018	(Boskalis, 2017)
Boskalis	Bokalift 2	3,000	-	(Boskalis, 2017)

Table 2.4: A selection of the new heavy lift capacity to be expected in the near future.

given. This is because of the dubious nature of the press releases.

2.3.5. Targeted market segments

From analysis of the competitive landscape it becomes clear that the market segment with the smaller jackets, i.e. up to 3,000 MT, is a saturated market. Many single lift options are present for these jackets, and even more are expected to enter the market soon. Moreover, it was found previously that this market segment only covers 20% of the market share. It is therefore concluded to focus on market segments with jackets larger than 3,000 MT. In this segment relatively little heavy lift assets are present and the expected new fleet barely replaces the outdated current heavy lifters. This sector comprises 80% of the market share.

2.4. Defining initial dimension of the buoyancy lifting device

It is established that the buoyancy lifting concepts will focus on market segments with jackets >3,000 MT. In this section the market is further analyzed to define the initial dimensions of the buoyancy lifting device. Some assumptions are made throughout this chapter that influence this market analysis, they are shortly repeated. Then the versatility range is defined and calculated. This versatility range has a large influence on the market segments that are considered interesting, but is unknown at this design stage. The market analysis is therefore repeated for a variety of versatility ranges. For every versatility range the optimal market entry point is calculated. The main dimensions are finally distilled from the buoyancy capacity which returns an optimum for most versatility ranges.

2.4.1. Assumptions

The assumptions concern the possibility for derogation, the actual weight to be lifted, considering piles, grout, marine growth and the accumulation of the heavy lift vessel capacity. To reiterate, derogation is not applied in this research. This means that market segments above 7,000 MT could be more interesting than presented. The tow-out weight of jackets is corrected for marine growth and added weight by 30% as explained before. Lastly, the heavy lift capacity is accumulated completely downwards for any further calculations.

2.4.2. Defining the versatility range

The buoyancy lifting concept will compete against the heavy lift assets that dominate this market nowadays. In contrast to heavy lift assets, which are extremely adaptable to varying jacket weights, it will be a challenge for the buoyancy lifting concepts to cope with a high variety of jackets. The range of weights over which the buoyancy device is able to lift different sized jackets is defined as the versatility range in this thesis. The versatility range of the buoyancy device is unknown at the moment, as no design is yet put on paper. This range, over which the jackets are grouped, is therefore build up as follows.

Ardent has a key performance index where one out of four tender applications should be won. Furthermore, for large investment decisions, at least three to four applications should be present. Combined they dictate that at least sixteen jackets should be available for the new buoyancy lifting concept in order to be considered economically viable. For the further analysis of the market only segments with enough jackets are considered.

The amount of jackets in a market segment that the buoyancy concept will address is dependent on the versatility of the design. It is found that the smallest range for which a market segment with 16 jackets larger than 3,000 MT exists is 390 MT. The buoyancy device will have to be versatile enough to at least cope with a 390 MT weight difference between the jackets it will lift, in order to address a market that meets the investment criteria of Ardent. The maximum versatility range is arbitrarily fixed at 3,000 MT, as this is considered taken well. After all the device should then be able to lift a 3,000 MT jacket as well as a 6,000 MT jacket, or a 8,000 MT and a 11,000 MT for that matter.

2.4.3. Market entry opportunities

With the versatility range defined between 390 and 3,000 MT, the market segments with at least 16 jackets are analyzed for varying versatility ranges. For every versatility range the market segments with at least 16 jackets are identified and divided by the number of current heavy lifting solutions. This score indicates the attractiveness of a market segment. The higher the score, the more jackets per competitor there are present. For a selection of versatility ranges between 500 and 3,000 MT the dots in figure 2.5 show the market segments which contain at least 16 jackets. For every versatility range, the most promising market segments are

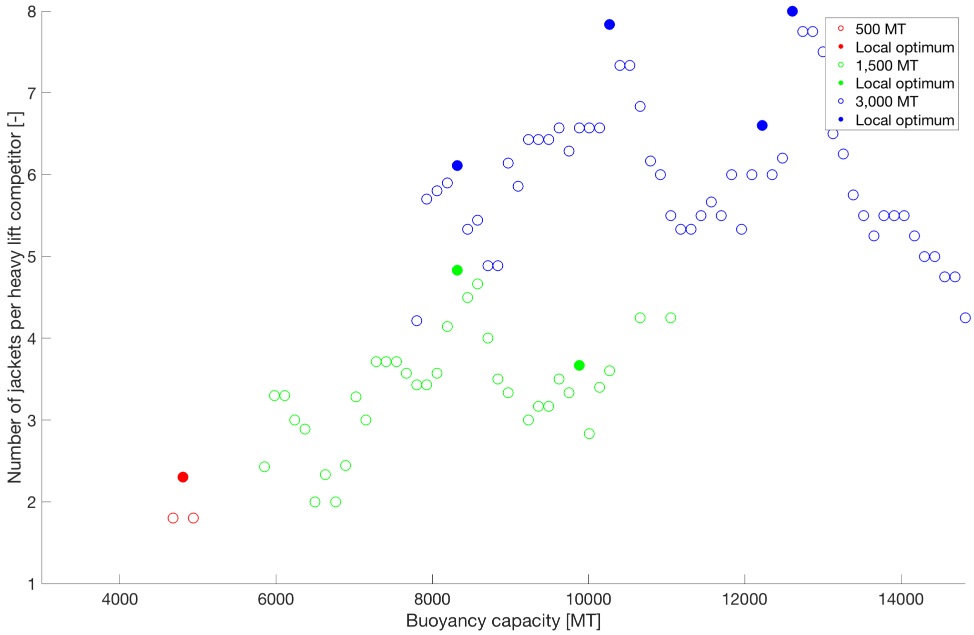


Figure 2.5: The market segments which contain at least 16 jackets are presented here for several versatility ranges. The filled in dots represent the most promising market segments for each versatility range.

highlighted. To find the best market segment for the buoyancy lifting concept, the local maxima of every versatility range are calculated. These are the filled dots in figure 2.5. For a fixed versatility range, the filled dots indicate the best dimension for the buoyancy device. With this buoyancy capacity the most preferred market segments are addressed.

2.4.4. Desired buoyancy lifting capacity

For now the versatility range is unknown. Therefore the point is chosen where most versatility ranges share a local maximum. At this point the buoyancy device addresses a good market segment, regardless of the versatility range. As can be seen in figure 2.6, the safest size for the buoyancy lifting tool is found to be 8,190 MT. If the versatility range turns out to be very large, i.e. 3,000 MT, a device with an 8,190 MT buoyancy capacity returns a removal score of 6.2. This means that every heavy lift assets has on average 6 jackets to remove. If the versatility range turns out to be small, i.e. 1,000 MT, a removal score of 3.5 is found. Note that 8,190 MT

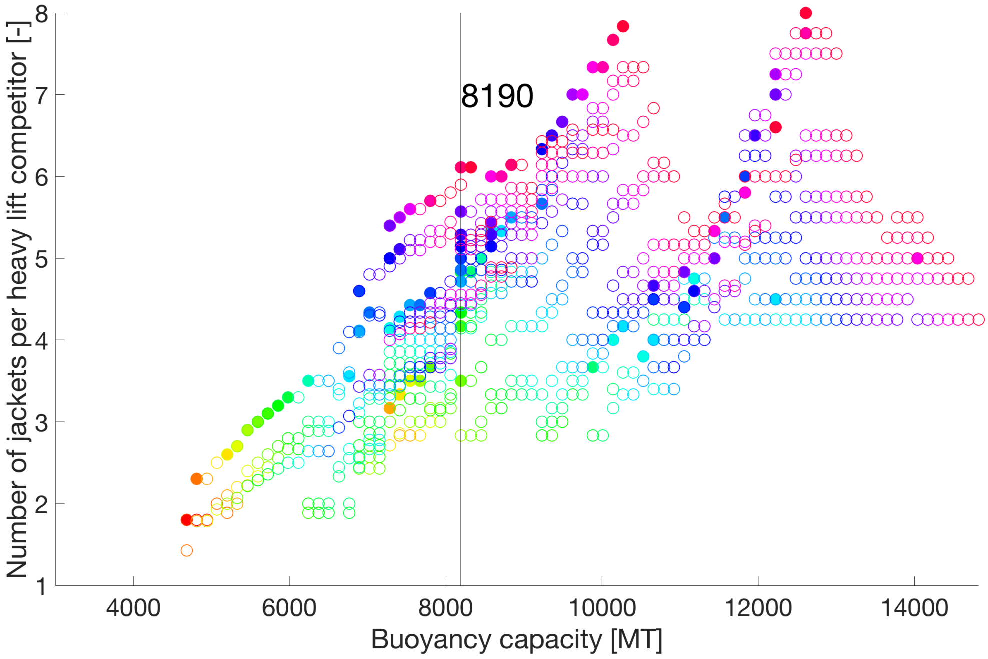


Figure 2.6: For market segments containing at least 16 jackets, a removal score is calculating by diving the amount of jacket by the number of single lift options. This calculation is repeated for versatility ranges between 390 MT (orange) up to 3,000 MT (pink). The optimal size for a buoyancy device with an unknown versatility range is 8,190 MT.

is the ideal buoyancy capacity for a device where the versatility range is unknown. If in a later stadium more knowledge is gathered about the versatility range, a more optimal buoyancy capacity may be found.

Important to note is that a buoyancy device of 8,190 MT is the best option for a unknown versatility range, but not for the minimum versatility range of 390 MT. The minimum versatility range for which a 8,190 MT becomes economically attractive is 940 MT. It should therefore be versatile enough to cope with a weight range of said 940 MT.

2.4.5. Sanity check

A quick estimation of the dimensions a buoyancy device of 8,190 MT can be made if compared to similar barges. This coincides with a 100 by 24 meter barge, having a 4.5 meter draft (Scchambers, 2014; POSH, 2017). Even though these are huge structures, this quick estimation poses no problem compared to the dimensions of a 5,000 to 8,000 MT jacket. It promises for a technical feasible solution.

2.5. Example jackets

Considering the added weight for piles, grout and marine growth, the largest jacket a 8,200 MT buoyancy device can lift is 6,300 MT. For a buoyancy device with a minimum versatility range of 940 MT the jackets that are targeted are shown in table 2.5. They are selected on their main dimensions; number of legs and the water depth at which they are installed. Eleven jackets are found with similar characteristics. Using the figures used to generate market shares, a potential market segment size of £ 250 million can be found for the list presented in table 2.5. Assuming a 25% win rate for tenders, approximately £ 60 million can be derived for a lifting device with the minimum versatility range and a buoyancy capacity of 8,200 MT. To guide the economic assessment made further in this report, two example jackets are chosen, see figure 2.7. They help to visualize the different concepts. Firstly, the Shearwater C PUQ platform jacket is chosen as an example jacket for this research. With a tow-out weight of 5,040 MT it is in the lower range of the 8,200 MT lifting capacity, but for this jacket the Royal Dutch Shell provided drawings and more accurate weight estimates. As information about installed fixed steel jackets is hard to obtain, the availability of data for this jacket makes it preferred. More information on the Shearwater C PUQ jacket is given in appendix D.1. Another drawing was provided by Shell for the Goldeneye jacket. The tow out weight of the Goldeneye jacket is actually 3,000 MT, but it has to

ID	Name	Operator	Weight [MT]	Depth [m]	Age	Legs
NL147	K14-FB-1	ExxonMobil	6250	27	32	4
NO179	OSEBERG D	Statoil	5983	109	17	4
UK0682	Armada Platform	ADNEC	6120	88	20	4
UK0686	Beryl Riser tower	Apache	5600	119	41	4
UK0696	Captain WPPA	Chevron	5500	106	20	4
UK0721	Kittiwake A	EnQuest	5370	87	27	4
UK0894	Captain bridge linked platform	Chevron	5500	104	20	4
UK0975	Buzzard Production Platform	CNOOC	5569	97	11	4
UK1157	Golden Eagle PUQ Platform	CNOOC	6200	105	3	4
UK1158	Golden Eagle W Platform	CNOOC	6200	105	3	4
UK1166	Forties Alpha Satellite Platform	Apache	5285	106	5	4

Table 2.5: The selection of 11 North Sea jackets that have similar characteristics, making an interesting opportunity for a business concept.

Figure 2.7: The two examples jacket used throughout this report. Left the Goldeneye platform jacket and right the Shearwater PUQ platform jacket, both operated by Shell. *(Pictures from `images.google.com`)*

Figure 2.8: The Goldeneye platform location at 58°00'0"N 0°23'0"W. The Shearwater platform is located just a few kilometers south. *(Image from `maps.google.com`)*

be removed with its conductors in place, adding significantly to the weight. The example jackets Shearwater C platform jacket and the Goldeneye platform jacket, are both 4-legged fixed steel jackets, weighing 5,040 and 5,200 MT respectively. Their as-built drawings are added in appendix D. Both jackets are situated in the Northern North Sea, see figure 2.8.

2.6. Benchmark for decommissioning

As stated before in chapter 1 the benchmark method for the removal of offshore platform jackets will be the single lift method using heavy lift vessels. In this section a heavy lift vessel will be selected and described, and the decommissioning costs will be estimated using several channels. These costs will be used to benchmark the buoyancy concept against.

2.6.1. Heavy lift vessel selection

The heavy lift vessels that compete with the concepts of 8,200 MT are the Saipem 7000, Heerema's Thialf, the Svanen and Heerema's Hermod. It should be noted that the Zhen Hua 30 is also capable of lifting up to 12,000 MT but is currently operating as a shipyard crane in Asia and not very likely to start decommissioning in the North Sea. Both the Saipem 7000 and the Thialf are capable of a 14,000 MT tandem lift. With an age of 31 and 32 years respectively, they will not last a lot longer. The Svanen has been mainly used as a civil infrastructure constructing vessel and is now employed to install wind farm jackets in the North Sea. It is not certain if this vessel can handle the removal of fixed steel jackets. The Hermod is up for retirement by the end of 2017 (Foxwell, 2017; Heerema Marine Contractors, 2017). Pictures of the current single lift competition can be seen in figure 2.9. Heerema is currently building a new semi-submersible crane vessel the Sleipnir, up for

Figure 2.9: The single lift competition in the North Sea for the buoyancy concept up to 7,500 MT (f.l.t.r.: Svanen, Thialf, Hermod and Saipem 7000, *pictures from* `images.google.com`)

delivery in 2019, and OOS International is developping the Zeelandia, expected in 2022, see table 2.4. This will most likely be the two competitors for the buoyancy lifting concept.

2.6.2. Decommissioning costs

The costs for decommissioning are an important benchmark to test the economic viability of the concept. Data on the removal costs from operators are not widely available, due to the remarkably competitive market. Several indirect sources are addressed in this section, before making a conclusion on the benchmark figure used in this thesis.

Oil & Gas Authorities' estimate

The Oil & Gas Authority made a cost estimate for offshore decommissioning projects in their report "Decommissioning Insight 2016".[2] The cost estimate is made using the Association for the Advancement of Cost Engineering (AACE) classifications. These seek to define the project stage and indicate the degree of uncertainty in the estimates. Using interviews with professionals and close out reports from decommissioning projects the removal costs per tonne are established. For decommissioning activities from 2016 to 2025 a cost estimation per activity and per tonne is made, see table 2.6. Most of the >4,000 MT platform jackets are located in the Northern and Central North Sea, therefore the £4,400 per tonne figure is the most appropriate to work with. The updated figures in their 2017 report "Decommissioning Insight 2017" report a higher uncertainty

	Southern North Sea and Irish Sea	Central and Northern North Sea and West of Shetland
Facilities "making safe"	£1,200 per tonne	£490 per tonne
Topside removal	£2,600 per tonne	£3,000 per tonne
Substructure removal	£2,600 per tonne	£4,400 per tonne

Table 2.6: Average forecasted cost per tonne for decommissioning activities in the North Sea from 2016 to 2025 as provided by Oil and Gas UK

of costs and a slightly higher average (OGA, 2017b, page 38), as can be seen in figure 2.10 and table 2.7. To be conservative, the 2016 figure will be used when referred to the Oil & Gas UK cost estimates. Important to note are the large error bars in for the Oil & Gas Authorities estimate, see figure 2.10. In essence the cost can be as low as 2,000£/MT up to 10,000£/MT. The 2016 average of the OGA findings of 4,400£may be used in this thesis when referred to the OGA estimate, the error bars will be taken into account nonetheless when used in a comparison. The 2017 report states that the current substructure removal cost in the Northern North Sea are less than 8,000£/MT. The lower boundary is not clearly defined and thus taken at 2,000£/MT, distilled from the graph.

Removal Cost per Tonne	2016 Survey Average	2017 Survey Average
Topsides	£3,600	£2,800
Substructures	£4,300	£4,700

Table 2.7: The 2017 figures from the Oil & Gas UK show a slight increase in substructure removal costs. *Data from Decommissioning Insight 2017 (OGA, 2017b), page 38* (Values of 2016)

Atlantic Marine and Offshore's estimate

The Atlantic Marine and Offshore's 2017 report "Prospects for North Sea decommissioning" states their own iteratively found averages for decommissioning (Vollaard, 2017, page 53). Using the Oil & Gas UK Decommissioning Insights reports and the EBN estimations as an input, they found the figures presented in table 2.8. The quality of this data is ambiguous, on top of that it is based on the Oil & Gas Authorities' estimate. It is therefore not used further in this research.

Larger sized platforms >3,000 tonnes	€/ton
Making safe	415
Onshore disposal	370
Substructure removal	4095
Topside removal	3060

Table 2.8: Decommissioning costs estimates as calculated by the Atlantic Marine and Offshore (Values of 2017)

[2]Decommissioning Insight 2016 (OGA, 2016), page 59 - 66

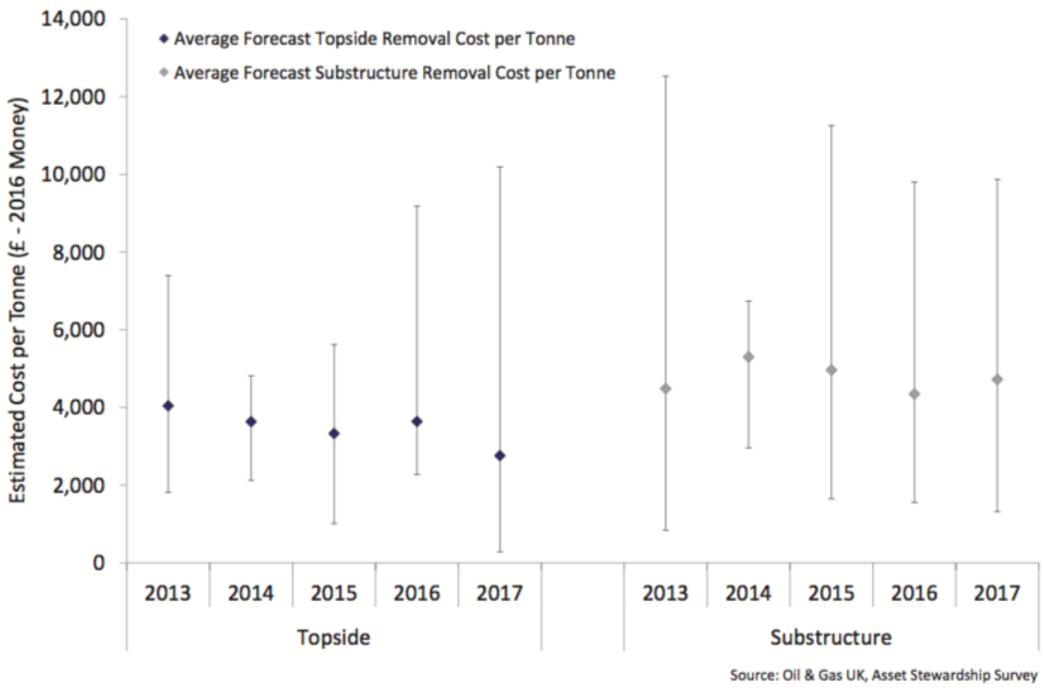


Figure 2.10: The historical variation in the removal costs per tonne for topsides and substructures. Increased uncertainty and a higher average can be seen for the 2017 substructure removal figures. *Graph from Decommissioning Insight 2017 (OGA, 2017b), page 38* (Values of 2017)

Ardent's estimate

At the Offshore and Energy Exhibition and Conference 2017 in Amsterdam, talks with professionals led to the consensus that the costs for heavy lifting operations can be estimated at £3,500 per Tonne. On top of that the Oil & Gas UK stated that they strive for a 35% costs reduction in decommissioning, as plubished in their "Corporate Plan".[3] Ardent stresses to take this into consideration.

2.6.3. Cost estimate used in this report

For the further calculations and benchmarking a decommissioning cost of €3,500 per metric tonne is used. This is more conservative than the AMO estimate and the estimate distilled from professionals. It is in line with the OGA's current £4,700 per metric tonne and 35% cost reduction. An error margin is added in accordance with the Oil & Gas report at -55% and +75% (OGA, 2016).

For the example jackets used in this thesis this cost estimate corresponds with a removal cost of € 17.6 million and € 18.2 million for the Shearwater PUQ platform and the Goldeneye platform respectively. If the buoyancy device proves to be able to remove the platforms for less, an interesting business concept is found.

2.7. Conclusion market assessment

Legislation dictates the complete removal of all man-made structures in the North Sea. Structures larger than 10,000 MT can be reviewed on a case-by-case basis for derogation. The OSPAR Decision 98/3 that dictates this removal is up for review in Q1 of 2018, and a lot of institutions are pushing for the derogation of all substructures. Nonetheless, for this report the current legislation is applied.

There are 546 fixed steel jackets in the North Sea area, most of them <3,000 MT. The age of the installation is on average above their design age, and at roughly half of them is expected to come up for decommissioning in the next 10 years. A total decommissioning cost of £1.7 billion was found for all segments for the next few years. The most promising market segment is for jackets >10,000 MT. The competition considered in this research is the operators of heavy lift vessels able to single lift the jackets. There are 106 heavy lifting assets considered as direct competition, operating either globally or in the North Sea area.

[3]The Oil & Gas Authorities' Corporate Plan 2016-2025 (OGA, 2015), page 17 and their Activity Plan 2017 and 2018 (OGA, 2017a), page 14-15

An increase of the decommissioning market can be expected, with a peak in 2024. New heavy lift assets are coming up in the very large region (>10,000 MT) and the smaller region (up to 5,000 MT). It is believed they replace the current outdated very large heavy lift vessels, address the large jackets with no single lift solution yet, and the large amount of smaller jackets.

For the review of the market gaps some assumptions are made. Jackets weights are increased by 30% for piles, grout, conductors/risers and marine growth. Derogation is not applied in this assessment, market segments from 7,000 MT and up can therefore become more promising than they initially appear. Heavy lift capacity is accumulated all the way down.

From the market assessment it becomes clear that a buoyancy device of 8,190 MT is the most promising concept if the versatility is unknown. For this buoyancy capacity an optimum is found for most versatility ranges. Since the versatility of the concept is unknown, this is the safest best option. The minimum versatility range that the buoyancy concept of 8,190 MT should achieve, is 940 MT. The Shearwater C PUQ platform and the Goldeneye platform will be used as example jackets for the buoyancy concept, as drawings were provided by Shell.

The benchmark for the buoyancy concept will be the single lifting options, which are limited to three vessels. Decommissioning costs of €3,500/MT will be used for further calculations, in accordance with the Oil & Gas Authorities' estimate and cost reduction milestone.

This chapter assessed which market is most interesting to enter for a buoyancy lifting solution to decommissioning. The boundaries found in this chapter will be used as initial design requirements to set up the buoyancy lifting concepts in chapter 3. The benchmark figures found in this chapter will be used to assess the economic viability of the buoyancy lifting concepts in chapter 9.

3
Buoyancy lifting concepts

The focus of this thesis is to model the economic viability of buoyancy lifting concepts. To give some hold on what those buoyancy lifting concepts are, this chapter gives a quick overview of how the concepts originated. First the design requirements arising from the market research are presented. Then the set up of the brainstorm session held at Ardent will be discussed. The results are later categorized and analyzed using a SWOT analysis. The technical feasibility of the different concepts is determined next and finally the operational practicability is assessed. The three most promising concepts are presented at the end of this chapter. They will be tested on their economic viability in this thesis.

3.1. Design requirements

From the market assessment a list of design criteria can be distilled to which the buoyancy lifting concepts will have to fulfill. In this chapter the design specifications are explained. First the technical requirements are detailed, that will define the design of the buoyancy lifting solution. Next the economical requirements are explained that will outline the boundaries of the economical assessment.

3.1.1. Technical requirements

The most prominent design requirement emerging from the market assessment is that the buoyancy lifting device should have a buoyancy capacity of at least 8,190 MT. This is the most optimal market segment when the versatility range is unknown. The versatility range, i.e. the range of fixed steel jacket weights a buoyancy device can handle, should be at least 940 MT. This means that the concept should be able to lift jackets with a tow out weight of 5,400 MT up to 6,300 MT. It is important to note that the buoyancy device will be designed as a salvage tool, avoiding possible class requirements. This might be new to the decommissioning sector, but considered crucial by Ardent. No class means that no strict rules for construction, rigging and towage. For a salvage company, which deals with unusual floating recoveries daily, this is common practice.

Another important design requirement is the draft limitation to ensure the availability and accessibility of dismantling yards. For this purpose a list of dismantling yards is made. Besides operational dismantling yards, also existing yards that have not done any decommissioning projects yet and potential dismantling locations are listed. A selection of this list is given in table 3.1, the full list is available in appendix C. The most important restriction extracted from this list is the water depth at the quayside. The buoyancy lifted concept will have to make sure that it has a limited draft in order to be able to access the dismantling yards. The maximum permissible draft for different countries can be seen in table 3.1. For this research it is assumed that the concept needs a draft smaller than 12 meters in order to find a dismantling yard close by.

Some other important design requirements that were brought up at Ardent were that the buoyancy device should be storable and launchable. The buoyancy lifting device is preferable operable diverless, if necessary with the support of a remote operated underwater vehicle. The tool itself should be as simple as possible, containing minimal moving parts and minimal control. Therefore the control will be external from an offshore support vessel. The tool should minimize offshore work, including the strengthening works on the jacket. It should be able to be towed at 5 knots in 4 metres significant wave height. It should be able to be rigged to the jacket in 1.5 metres significant wave height.

The clamping of the buoyancy device to the jacket is not required to fit perfectly. The clamping can deform

Name	Location	Country	Water depth [m]	Status
AF Environmental Base	Vats	Norway	23	Operational
Lutelandet	Lutelandet	Norway	21	Operational
Able Humber Port	Humber	United Kingdom	17,5	Potential
Dales Voe	Shetland	United Kingdom	12,5	Operational
Eastport	Great Yarmouth	United Kingdom	10	Operational
Teesside Seaton Port	Hartlepool	United Kingdom	9,5	Operational
Damen Verolme	Rotterdam	The Netherlands	12	Existing yard
Hoondert	Vlissingen	The Netherlands	7	Operational

Table 3.1: Selection of some dismantling yards bordering the North Sea. The full list of potential dismantling yards can be found in appendix C.

the jacket to yield. Positive indicators on the clamps are desired, to omit the need for a diving check. The ballast system, controlled from the offshore support vessel, should have a single connecting point.

3.1.2. Economical requirements

The economical design requirements are to compare and evaluate the concepts. The buoyancy lifting device should at least be used more than once. The design should incorporate the re-usability and avoid a purpose build buoyancy tool. Consequently the buoyancy device should be able to adapt to different fixed steel jackets. The total removal costs of a buoyancy lifted decommissioning project should be lower than the 35% cost reduction goal of the Oil & Gas Authority, the benchmark figure used in this report. The buoyancy device will be used as a tool, and thus be written off over a certain amount of projects rather than over its design life.

3.2. Generated ideas

Once the requirements are listed, diverse buoyancy lifting ideas need to be generated. In this section first the methodology used to find as many buoyancy lifting concepts as possible is explained, before detailing all the buoyancy lifting concepts.

3.2.1. Methodology

A brainstorm session was held at Ardent in relation to a case study requested by the Royal Dutch Shell on the non-heavy lift removal of offshore platform jackets. It is a high-level “what is possible” brainstorm, looking into the wildest possibilities of jacket removal. Attending were professionals from Ardent, with a lot of operational experience, a team from SeaLand, an engineering company, and a team from ICE Marine Design, a naval engineering team that bought the patent on the DeltaLifter idea. The full list of attendees can be seen in table 3.2. The broad spectrum of backgrounds ensures that the brainstorm session comprises all aspects involved in the buoyancy lifting decommissioning. For the brainstorm session approved techniques were used provided in the Design Thinking classes (Carree and Hoornstra, 2013). Snapshots of the afternoon can be seen in figure 3.1.

Structural engineering		**Salvage operations**	
Kenneth Nicolson	GBR	Paul van ’t Hof	NLD
Barry Philip	GBR	Coen Landa	NLD
Marcel Negraia	ROU	Jim Robinson	USA
Robert Swan	ROU	Dirk de Jong	NLD
Business management		**Naval architect**	
Richard van der Tuin	NLD	Rob Rutten	NLD
Steve Wight	GBR	Boaz Cochavi	NLD
Steinar Draegebo	ROU	Andrew Barron	USA
Renier van den Bichelaer	NLD	Quinten Schothorst	NLD

Table 3.2: The brainstorm attendees cover all aspects concerned with buoyancy lifting decommissioning operations.

The ideas generated at the brainstorm session are categorized by similar recovery technique. In the following sections the non conventional decommissioning methods that came up are discussed. First the

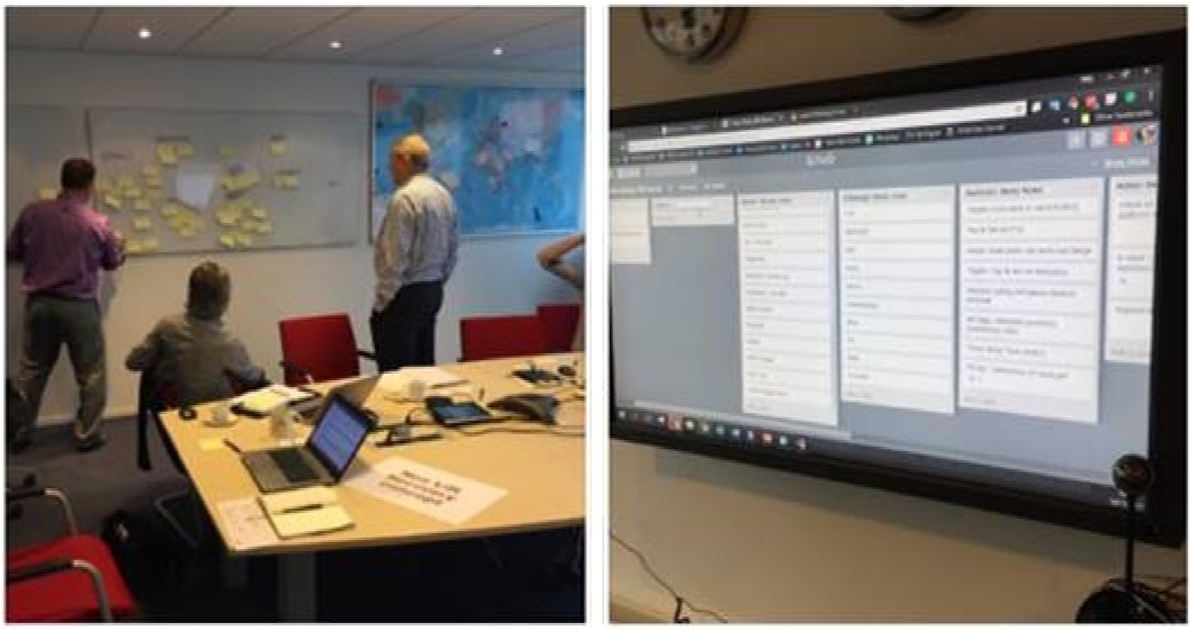


Figure 3.1: Snapshots from the brainstorming session held at Ardent on non-heavy lift removal of offshore platform jackets.

floated recoveries are reviewed, than the non conventional lifts, thirdly some combination of methods and finally the decomposition of jackets.

3.2.2. Floated recovery

External Buoyancy Caisson

The use of external buoyancy caissons (EBC) as designed for the BP Miller jacket (Ardent, 2016) is one of the concepts that came up during this session. This concept will be further examined in this thesis. It is designed as two closed A-frames attached to either side of the jacket, see figure 3.2. This A-frame construction is not only capable of lifting the jacket from the seabed, but also to rotate is on its side by carefully ballasting the caissons. Once lifted and turned on its side, the structure is towed to a dismantling yard.The towed assembly has a limited draft of less than 12 metres.

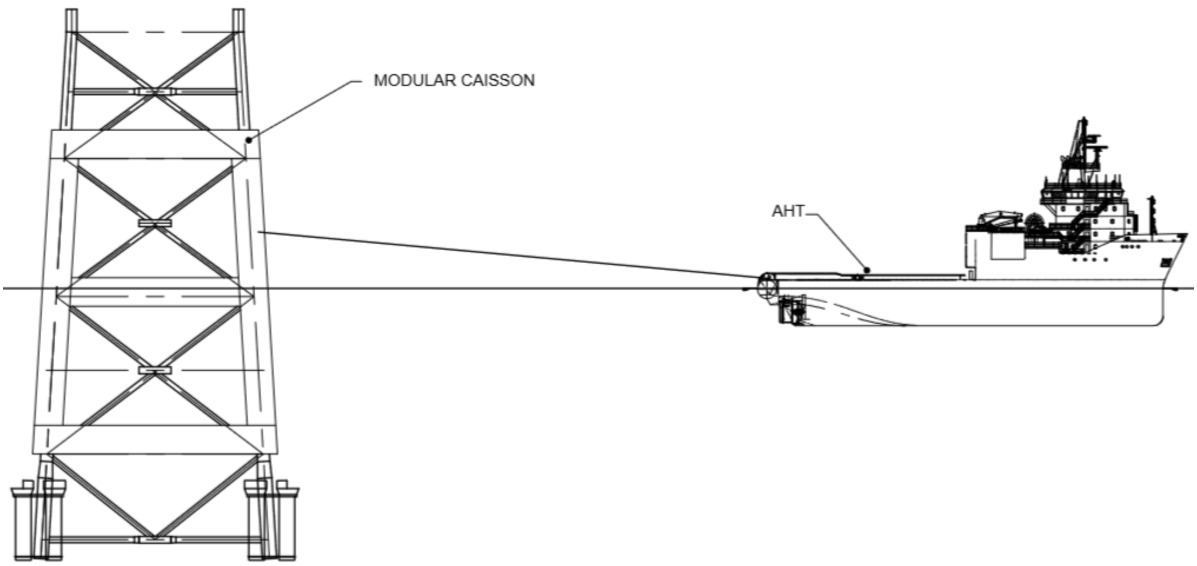


Figure 3.2: The use of external buoyancy caissons (EBC) in the form of a A-frame is one of the concepts.

External Buoyancy Tanks

As exampled by the removal of the Frigg DP2 jacket, the use of buoyancy tanks came up, see figure 3.3. The difference with the EBC is that the EBT do not feature a complex shape and complex ballasting system. The EBT in itself is therefore not able to topple jacket in order to limit the draft. Large ballast controlled tanks are attached in pairs to each leg of the jacket. The jacket legs are then cut and the structure is refloated by deballasting the buoyancy tanks. Once afloat the structure is towed to shore to be dismantled there. This method is used once with the removal of the Frigg DP2 jacket in 2004 (Terdre, 2009). The main disadvantage is the large draft of the structure after the refloating operation. For the Frigg DP2 jacket this was still approximately 90 meters, which posed no problems in the deep fjords around Norway. The structure was towed to sheltered waters and piece small decommissioned there. This is not considered a feasible method, as it does not fulfill the draft requirement of 12 metres. A different configuration of tanks is believed to cope with that problem.

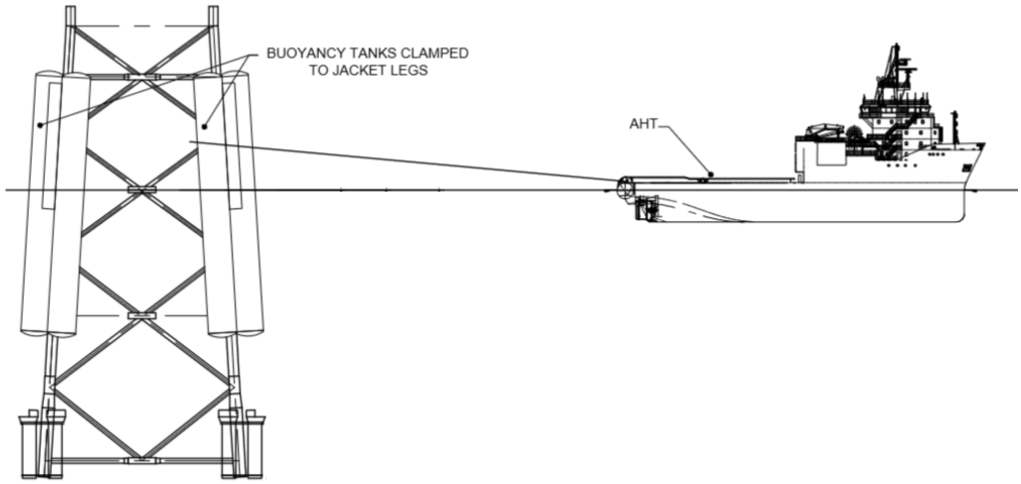


Figure 3.3: External buoyancy tanks as used with the removal of the Frigg DP2 jacket are also considered.

By installing smaller tanks to one side of the structure, the jacket could be toppled and lifted to its side, see figure 3.4. After inflating the stage one buoyancy tanks, the stage two buoyancy tanks then lift the structure to a limited draft of less than 12 metres. Stage 1 buoyancy tanks are smaller, and thus add less weight to be lifted out of the water by the stage two buoyancy tanks. This concept is referred to as External Buoyancy Tanks (EBT) throughout the rest of the report.

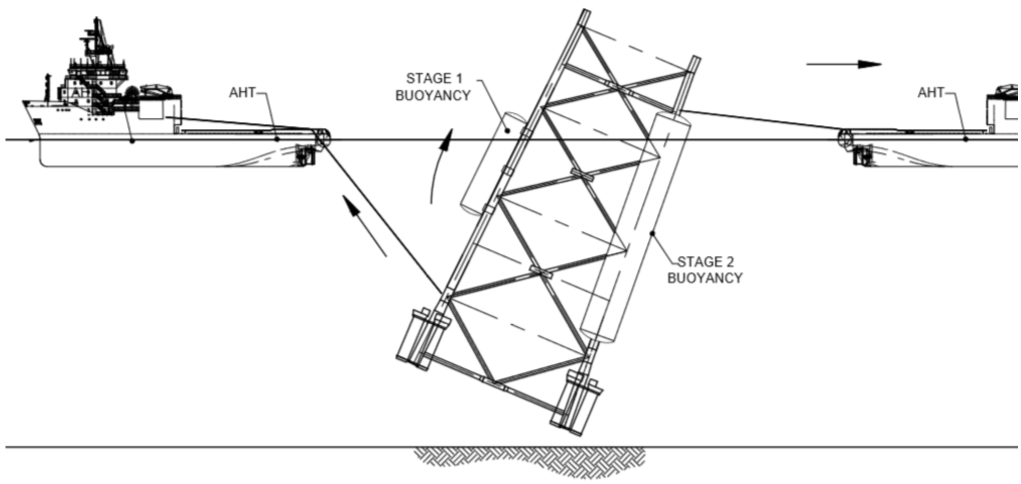


Figure 3.4: A different configuration of tanks may aid to topple the jacket in order to reduce the draft to enter dismantling yards.

Deltalifter

Another buoyancy lifting design was marketed by ICE Marine Design, which bought the DeltaLifter concept a few months ago (ICE Marine Design, 2017). It is a large lambda shaped buoyancy device that "scoops up" the jacket. It is towed into position and deballasted until its pivoting corner rests on the seabed. In some cases the DeltaLifter does not stand on the seabed, but is kept floating next to the jacket, see figure 3.5. It is then pushed against the jacket and attached with clamps. By first deballasting the legs that are attached at the bottom end of the buoyancy device, the structure is pivoted over the round bottom corner of the DeltaLifter. With the jacket tilted the rest of the DeltaLifter is deballasted to refloat the jacket. The large legs at the bottom end also ensure it has enough waterplane area during the last stage of refloating operations. Once afloat the structure can be towed to a dismantling yard. The jacket lays on top of the buoyancy device after refloating. Therefore the jacket can be offloaded using self propelled modular transporters (SPMT) or rails.

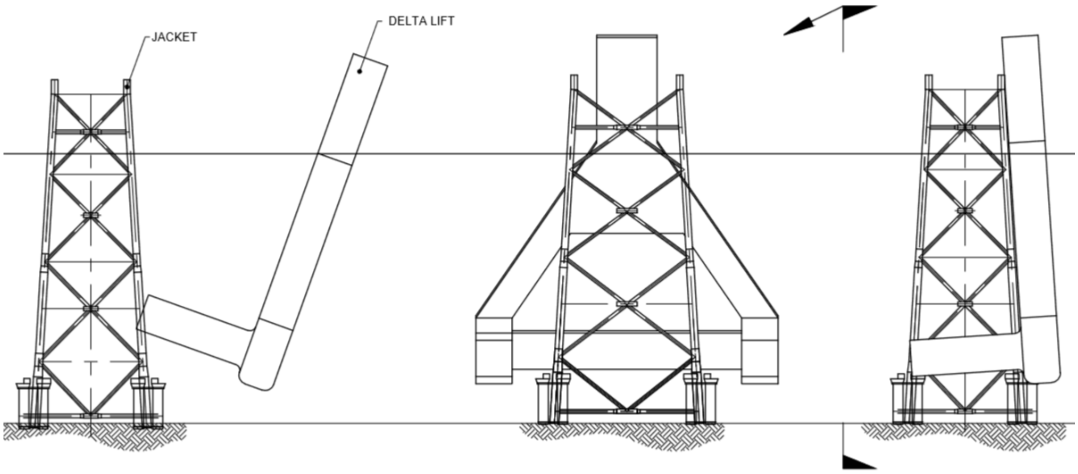


Figure 3.5: The DeltaLifter concept bought by ICE Marine Design a few months ago carries the jacket on top of the structure.

Inflatable Buoyancy

The idea to buoyancy lift the jacket without using a large steel floating structure arose. By attaching inflatable "airbags" to the legs and members of the structure, it can be refloated. Anchor handling tug supply vessels (AHTS) help to topple the jacket into a towing position, see figure 3.6. Yokohama type airbags are attached to the structural members of the jacket. The airbags may potentially be placed in a frame that is attached to the jacket. They are then filled with pressurized air. The structure can be floated up to a limited draft of 12 metres, eliminating the added weight above water, which is a drawback of the EBC. A major drawback, however, is that the inflatable bags are not fit for towing.

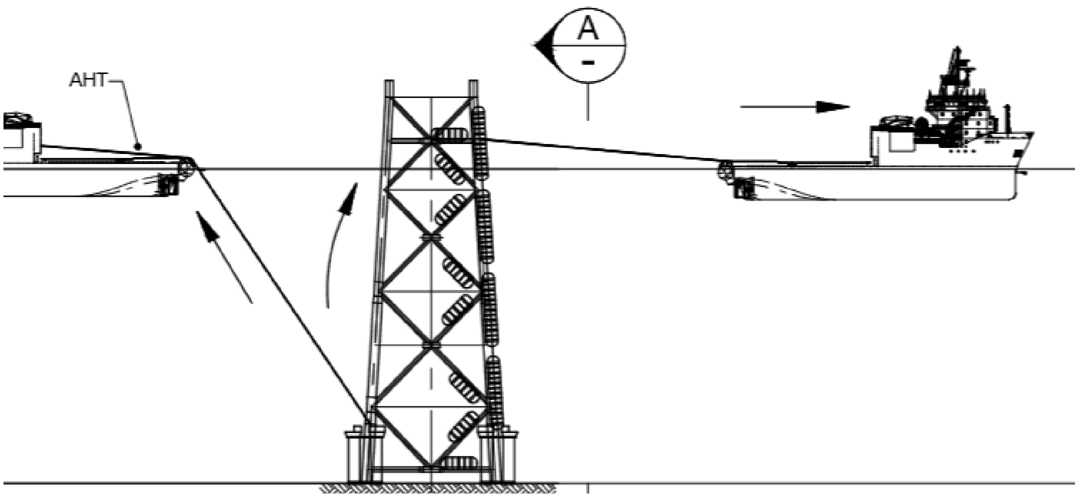


Figure 3.6: Instead of using a large steel floating structure, inflate airbags could be used to refloat the jacket.

Purge/dewater legs

Some jackets are installed as “self floaters”. Larger diameter legs on one side were used as buoyancy device when they were towed out from construction site offshore, see figure 3.7. Once on site, the legs were ballasted to sink the jacket onto the seabed. Often watertight membranes were punctured to sink the jacket and piles are driven through the self-floaters to keep the jacket in place. A possibility to refloat the jacket could be to repair all damages done during installation and dewater the legs and members. With the help of AHTS the jacket could be toppled during the operation.

Figure 3.7: Few jackets are installed as so-called self floaters. The ballasted legs could be repaired and purged with air to refloat the jacket. *Picture from* `shell.co.uk`.

3.2.3. Non conventional lift

To avoid the use of conventional heavy lift vessels, other dedicated vessels could be used for the offshore platform jackets removal. Even though this thesis focuses on the buoyancy removal of platform jackets, this section details some other methods. They will not be implemented further in this thesis, mainly because of the dependency on other large maritime assets. Hiring of these assets is naturally an option, but can not be considered as a distinctive method for Ardent. Nonetheless, some of the non conventional lifting methods would benefit from Ardent’s experience in salvage and are discussed here.

Two barges with chain pullers or strand jacks

Another idea originated from the salvage background from Ardent. The use of chain pullers to recover a wreck from the seabed is a proven method for the salvage company. The technique was used for the recovery of the Fluvius Tamar in 2017. Two barges were used to lift the vessel up in between and transport it to Rotterdam.

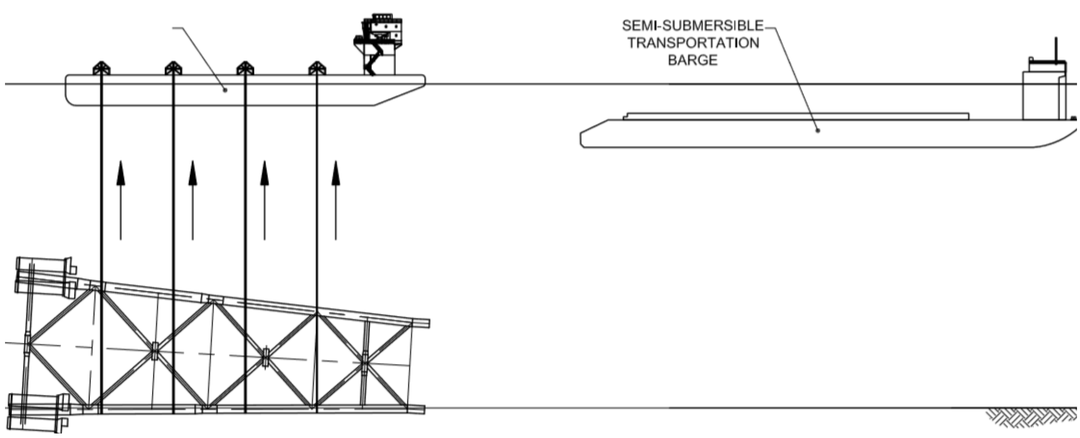


Figure 3.8: Proven method in the salvage industry, the use of strand jacks or chain pullers to lift a wreck from the seabed.

The ship hangs in between the barges in the eight chains that were dug underneath the vessel and pulled up using chain pullers. This method could also be used to recover a (previously) toppled jacket. Instead of towing it in between two barges, it can be manoeuvred over a semi-submersible transportation barge, see figure 3.8.

Single barge with chain pullers or strand jacks

Similar to the operation of lifting a jacket up in between two barges using chain pullers or strand jacks, the jacket can also be hung underneath a single barge. The draft of the entire structure would exceed 15 metres, since the structure now hangs underneath the barge, instead of in between two barges. A fully submersible barge can be rested on the seabed for the barge with jacket underneath to hover over, see figure 3.9. This way the jacket can be refloated to the surface.

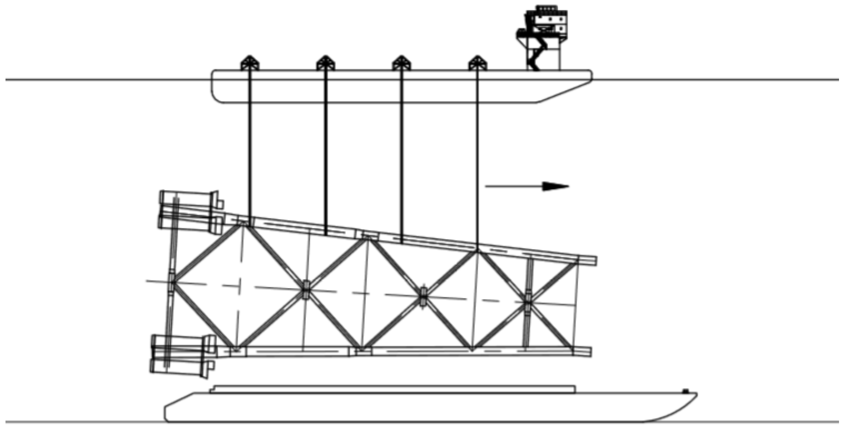


Figure 3.9: The jacket hanging underneath a single barge can be hovered over a fully submersible barge after being toppled and lifted.

Reverse install with pivot barge

Another idea was a literal reverse install, using an especially constructed barge similar to what is used to skid install jackets. With the help of two AHTS vessels and possibly additional buoyancy, a winch is used to pull the jacket on board. This concept is presented in figure 3.10. For this concept the pivot frame would have to be installed on an existing barge, or the vessel would have to be entirely purpose-build.

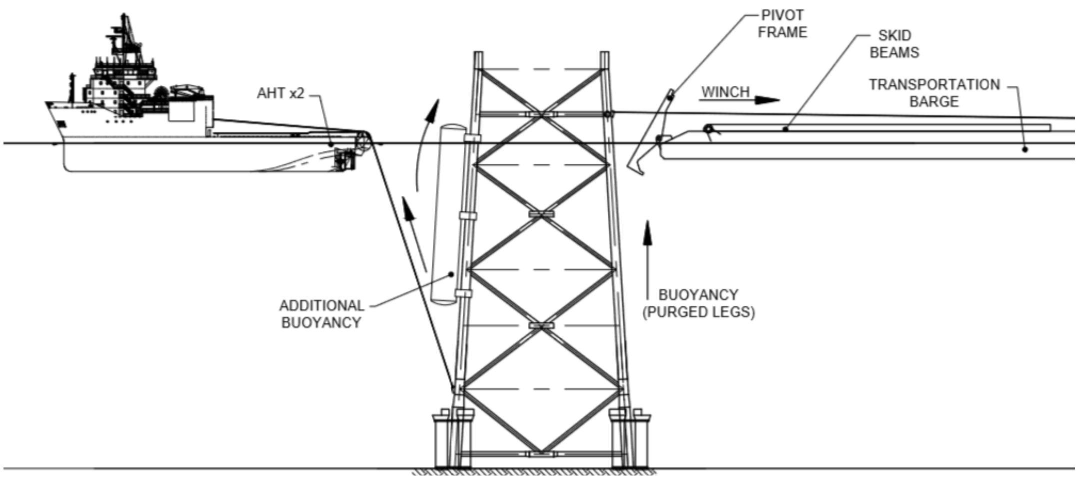


Figure 3.10: Reverse install of jackets using an especially constructed barge with pivoting skid beams.

Versabar

A non conventional heavy lifter now active in the Gulf of Mexico is the Versabar, see figure 3.11. The crane vessel lifts up the jacket from the seabed, rotates the jacket in its hooks and places it on a barge. The barge is then towed to a dismantling yard to offload the jacket. It can lift up to 10,000 MT. It is understood that the Versabar is for sale now and could be moved from the Gulf of Mexico to the North Sea. It is unclear though if the configuration is fit to lift large jackets from the seabed. Moreover, the geometry of the Versabar is not considered ideal for the rough North Sea.

Figure 3.11: The Versabar heavy lifter now active in the Gulf of Mexico is a non conventional heavy lift method which could be used for jacket removals. *(Picture from `versamarine.com`)*

Self propelled jack-up barge

Smaller jack-up barges may be used to assist with the decommissioning of offshore platform jackets. They are now often used for wind park installations, see figure 3.12. Their operational ability is limited to their leg height, and does not often exceeds 40 metres water depth. To decommission an offshore platform jacket, they could assist with other methods presented in this section, or decommission the jacket in smaller pieces.

Figure 3.12: Jack up barges are now often used for wind park installations, but could play a role in jacket decommissioning in shallower waters. *(Picture from `gustomsc.com`)*

3.2.4. Float and lift

A combination of the methods described above can be used as well. Using some, but smaller buoyancy tanks in combination with AHTS vessels to topple and refloat the jacket. Or the hire of a jack-up barge to assist with floated recovery. While this might provide valid decommissioning options, for the sake of simplicity the methods are analyzed separately first.

3.2.5. Decomposition

Corrosion acceleration

Instead of using zinc anodes to protect the jacket structure from corrosion, the idea came up to place cathodes to accelerate the corrosion of iron. This way the jacket dissolves in the sea without a lot of offshore work. Electrical current could be set to the jacket to accelerate the process. This method is not likely to have any practical implication, mainly because of the operational and environmental concerns. Nonetheless, the Oil & Gas Technology Centre is investigating this method recently (OGTC, 2018). It is mentioned here mainly to illustrate the extent of the brainstorming session.

3.3. SWOT analysis

All the concepts described above are assessed using a SWOT analysis. From the SWOT analysis it becomes clear that some concepts have serious weaknesses or are exposed to significant threats. They show less promise than other concepts and are thus eliminated, as can be seen in table 3.3. In this section the elimination of inflatable buoyancy and dewatering jacket legs is explained. Even though some concepts show promise from an initial SWOT analysis, concepts other than the floating options are not considered as part of the scope of this study. As described briefly in section 3.2.3, they are also discontinued in the continuation of this report. The full SWOT analysis can be found in appendix E.

Category	Concept	SWOT	Remarks
Float	External Buoyancy Caisson (EBC)	✓	
	External Buoyancy Tanks (EBT)	✓	
	DeltaLifter	✓	
	Inflatable Buoyancy	!	Discontinued in this thesis
	Purge/dewater legs	!	Discontinued in this thesis
Non conventional lift	Two barge with strand jacks	✓	Out of scope of this thesis
	Single barge with strand jacks	!	Out of scope of this thesis
	Reverse install with pivot barge	✓	Out of scope of this thesis
	Versabar	✓	Out of scope of this thesis
	Self propelled Jack-up rigs	!	Out of scope of this thesis
Float and lift	Combination of buoyancy and tugs	✓	Out of scope of this thesis
Decomposition	Corrosion acceleration	!	Out of scope of this thesis

Table 3.3: A summary of the results from the SWOT analysis. Only the EBC, EBT and DeltaLifter are studied further in this thesis.

3.3.1. Discontinuation purging air in the legs

Purging air into the legs to refloat the jacket is deemed infeasible as an independent solution. It will require at least an additional mechanism to tilt the structure on its side to limit the draft. Often it is found that the legs are perforated by piles and filled with grout or debris. Restoring the watertight compartments could become a problematic operation. Moreover, only eight fixed steel jackets were installed in the North Sea floating on their own legs (OGA, 2012). For all other jackets this method would not be feasible. Also, the piles, grout and debris in combination with the marine growth also add weight to the jacket, that was not supported by the buoyant legs at the tow-out of the structure. Furthermore the poor or even unknown condition of jacket legs could discard this method completely. This method is a good option in combination with other methods, but will not be studied more in depth as an independent solution.

3.3.2. Discontinuation of inflatable buoyancy

Inflatable buoyancy recovery of a fixed steel jacket is also discontinued in this thesis. The main reason is the complicated air control of “airbags”. The refloating operation with inflatable buoyancy was credited least reliable by salvage masters at Ardent. Also the installation time for a lot of small airbags would increase the offshore working time for the ROV support vessel. Furthermore safety aspect arose for the towing operation, potentially imposing high weather limitations and low transit speeds for the journey to a dismantling yard.

3.4. Technical assessment

To find an economical viable buoyancy lifting method, the concepts should be technical feasible. Without a technical feasible solution, the economical implementation does not make sense. To test the technical feasibility of the buoyancy lifting concepts, two approaches are addressed in this thesis. On one side the structural integrity of the buoyancy lifting devices themselves are examined. On the other hand the structural integrity of the jackets during the uplifting operation is examined. If the buoyancy devices endure both test, they are considered technical feasible.

3.4.1. Structural integrity

The structural integrity of the EBT and EBC concept is currently being examined by another thesis student. The first results show promise for both concepts and are presumed technical feasible for the rest of this thesis. The DeltaLifter concept is already technically worked out by ICE Marine design in Romania. More information on the DeltaLifter can be found at `deltalifter.com`.

3.4.2. Jacket integrity

In this section a structural analysis of the stresses on the jackets during refloating operations is given. The objective of the structural analysis for jacket recovery concepts is to provide a mechanism to assess the validity of each concept. If a buoyancy lifting method results in too high stresses on the jacket structure, the option is ruled out. This assessment is intended to provide comparative results for the different methodologies, not a detailed assessment of the specific jackets structural integrity. For this reason, the input weight criteria of each jacket, including effects of marine growth and buoyancy, have not been extensively researched. A simplified approach of 30% weight increase discussed in chapter 2 is used. During the market assessment in chapter 2 two jackets were chosen as example jackets in this research. These are the Shearwater and the Goldeneye jacket, see table 3.4. In accordance with the above, members have also been modelled with full

Name	Tow-out in-air weight	Adjusted weight	# legs	Waterdepth	Drawings
Shearwater	5000 MT	6500 MT	4	90 m	See appendix D.1
Goldeneye	3200 MT	5200 MT	4	120 m	See appendix D.2

Table 3.4: Details of the two example jackets used in this thesis.

wall thickness per the supplied as-built drawings (appendix D), no corrosion allowance and corrosion loss due to years of service have been accounted for at this stage in the analysis. In addition, to simplify the analysis an assumption has been made that all members can be purged with air. This may not be the case in reality, however assuming the opposite is too pessimistic an approach. Also, the impact of hydrodynamic forces from wave induced motion and recovery speeds through the water column or air water interface, have not been included.

The analysis methodology adopted for the recovery methods use Strand7 finite element software with both linear static and non-linear transient dynamic solvers. The models start from an in-situ condition with compression only supports representing the seabed. Artificial buoyancy is turned off 6 metres below the water level to simulate the size of buoyancy units. The effect of artificial buoyancy on the structure is modelled by non-structural point masses added at strategic points.

The post-processing analysis of each model is limited to Von Mises equivalent stress outputs with commentary based on results above or below yield as a benchmark only. Local checks of connectivity, weld assessment or chord plasticisation and shear yield are out the scope of this review.

EBC/EBT refloat analysis

The EBC and the EBT concepts both rely on the transition of buoyancy to raise and rotate the jacket. From a structural perspective there is little difference between the two methods, hence they have been analyzed as a single model for each jacket type. The jackets have been modelled with buoyancy attached at strong nodes, i.e. where braces connect to the main legs. The buoyancy is applied against a time domain to first rotate the jacket into the horizontal plane, then to raise the jacket to a draft of approximately 12 metres. Tubular stress and strain are monitored through the process to confirm whether global structural integrity is exceeded. If the method is considered viable from a structural, operational and economical aspect, a more detailed assessment of the process would be recommended; including increased time domain analysis; staged buoyancy implementation; and effects of wave motion, water particle drag and inertia.

Shearwater jacket First and second stage buoyancy loads have been applied to the node connection points on each of the jacket legs. The buoyancy load applied to meet a 12 metre draft is 3,000 MT and 5,250 MT evenly distributed over 10 nodes per side, for first and second stages, respectively. The maximum stress recorded for

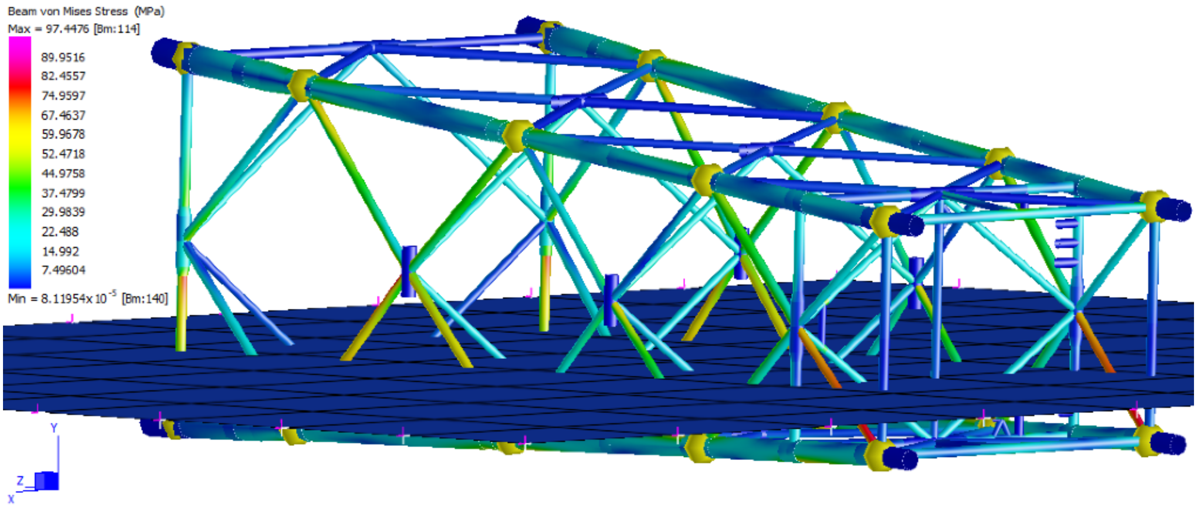


Figure 3.13: Structural analysis for the Shearwater jacket for the EBC and EBT solutions.

raising the jacket is 40MPa, see figure 3.13. The stresses increase to 100MPa during both rotating the jacket and raising it to the 12 metre draft. These stresses are very low, the methodology is very kind to the jacket integrity.

Goldeneye jacket As with the Shearwater jacket, the Goldeneye jacket analysis has been carried out using a first and second stage approach. The buoyancy load required to meet a 12 metre draft is 3,600 MT and 4,320 MT evenly distributed over 12 nodes per side, for first and second stage, respectively. The non-linear

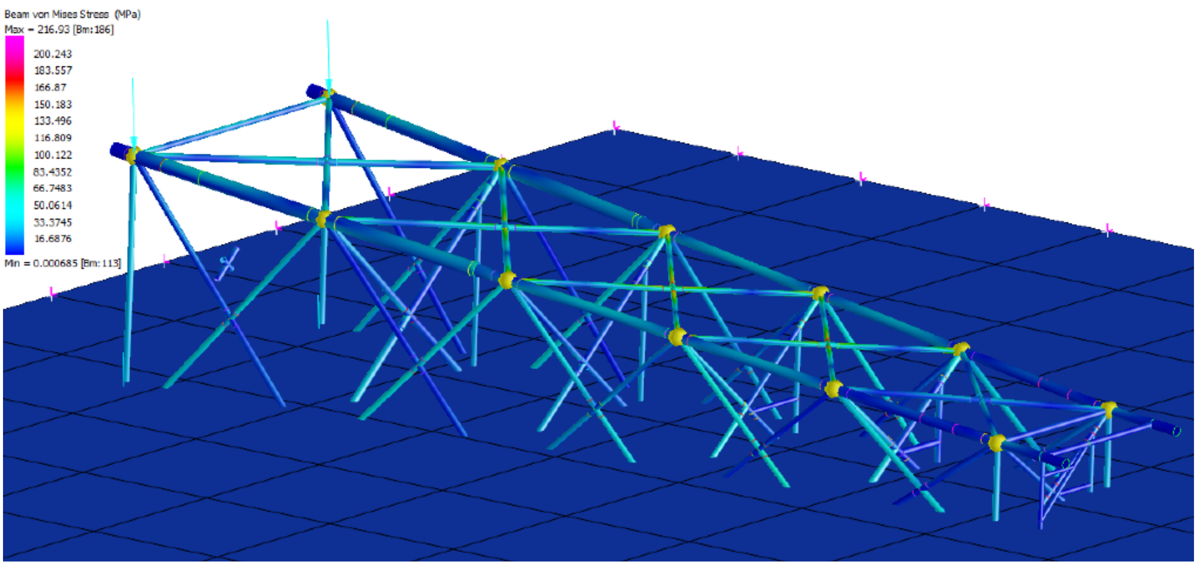


Figure 3.14: Structural analysis for the Goldeneye jacket for the EBC and EBT solutions.

transient dynamic simulation has produced maximum stresses for the initial lift of the jacket of 60MPa, see figure 3.14. They increase to 220MPa during both rotation of the jacket and raising it to the 12 metre draft. The first stage stress ranges are very low, and although the second stage stresses increase significantly, they are still well below maximum allowable stresses required to meet material yield.

DeltaLifter analysis

To simulate the DeltaLifter concept, the barge footprint has been modelled as a solid brick element structure with rigid links connecting the beam element jacket structure at locations where the two footprints coincide. As the two footprints vary, so do link locations, a minimum of four links are employed for any structure. The stress distribution through the jacket is monitored across the time domain simulation.

Shearwater jacket The Shearwater jacket highlights a concern with the DeltaLifter concept, primarily due to its unconventional footprint. As the Shearwater jacket is a 4-leg structure, the available clamping locations on the DeltaLifter deck are limited to those locations where the legs of the jacket and deck coincide, mainly lower down on the barge structure. The alternative is to position clamps higher up on the deck, which coincide with horizontal or diagonal braces, or to add some form of outrigger arrangement to reach the main legs. From preliminary analysis, this results in braces that are significantly over stressed, see figure 3.15. In

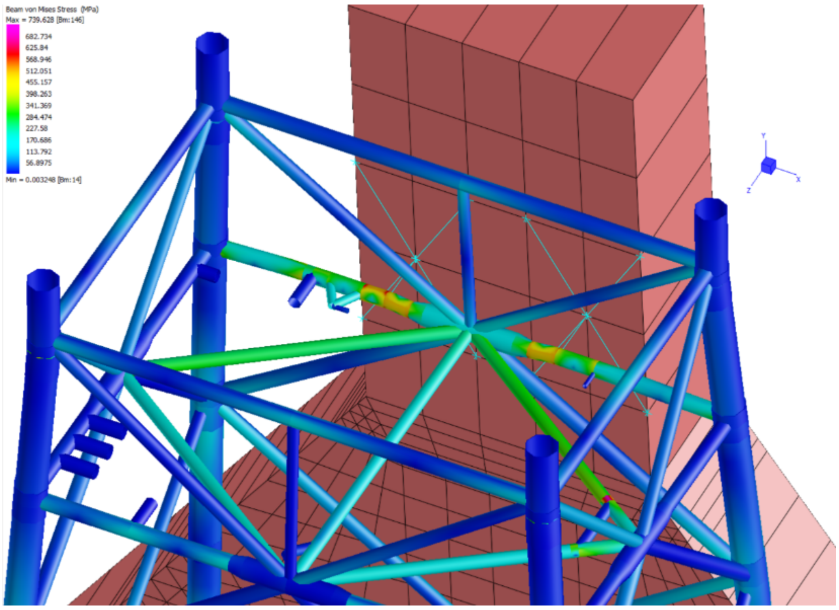


Figure 3.15: High stresses at clamps located on the horizontal braces of the Shearwater jacket at initiation of lifting with the DeltaLifter.

the case of the Shearwater jacket, the consequence of removing the upper clamps has little impact on the jacket structure during the upending process. The resultant stress in the jacket are general smaller without the upper clamps. Maximum Von Mises stresses during the upending process are below yield and hence considered manageable for global stability of the jacket. Refer to figure 3.16 for details of the general stress distribution during the upending process. With the reduction in clamp quantity, the load carried by each clamp will increase and hence will be an important factor in both clamp design and localised analysis of the jacket structure clamp locations.

Goldeneye jacket As the Goldeneye jacket is a tall 4-legged structure, it has a similar problem as the Shearwater jacket for position of clamps on the DeltaLifter vessel. Assuming an option for outriggers on a bespoke basis with the barge, 6-off clamps have been used to secure the jacket structure. Static lift analysis indicates Von Mises stress levels of 330MPa in the based air filled members during initial phases of lift. While the stresses are below yield, they do indicate the importance of the buoyancy created by the air-filled members. An equivalent lift with flooded members would result in stresses exceeding 550MPa, both on the horizontal braces and lower clamp region of the main jacket legs. A model of the lifting procedure can be seen in figure 3.17. The nonlinear transient dynamic analysis shows significantly higher stress levels on the bottom horizontal members during initial pick-up of the jacket structure. The recorded stresses are in the region of 1,000MPa, hence well in excess of yield. Fibre strain levels are around 0.5%, which indicates local yielding

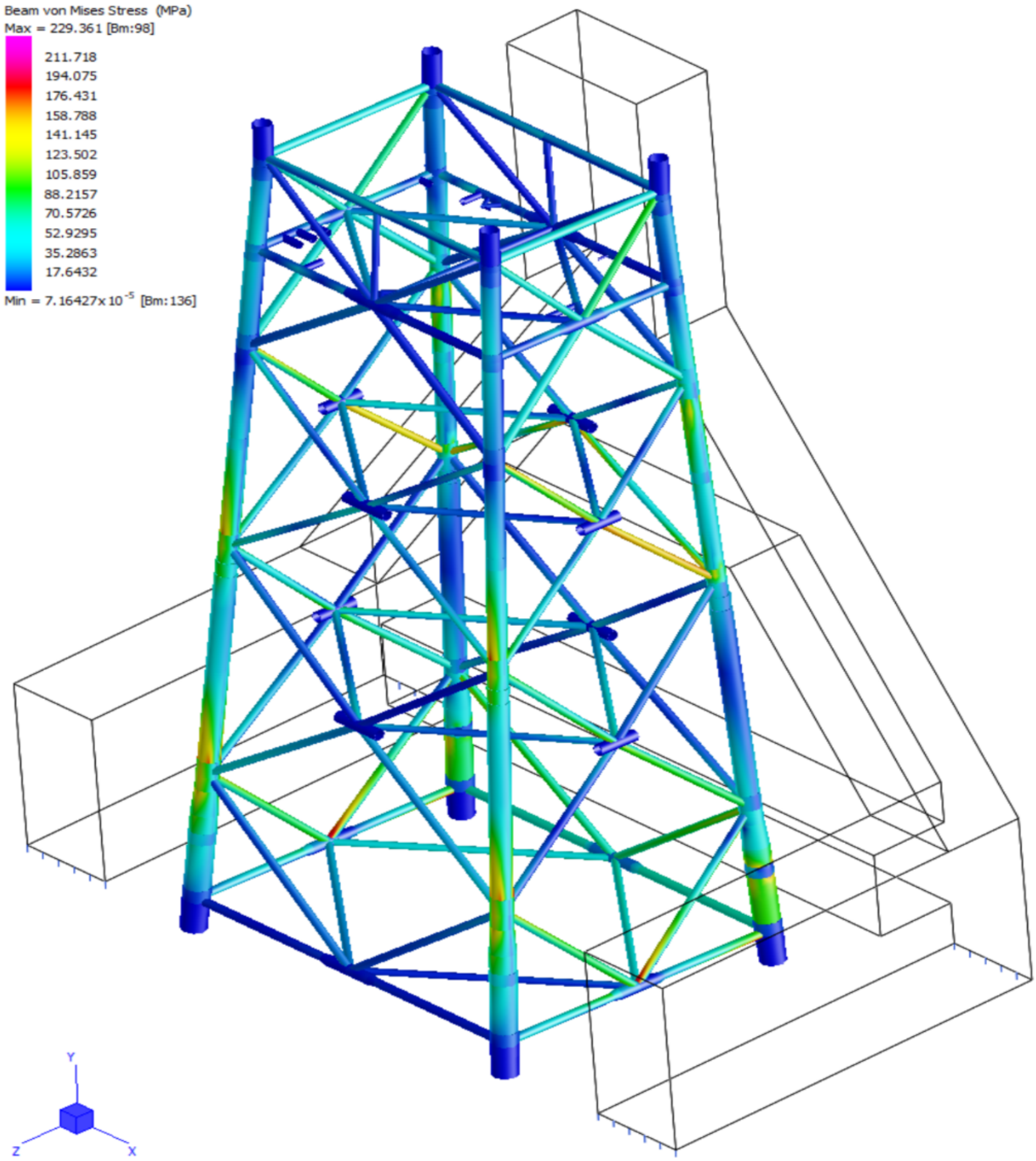


Figure 3.16: Von Mises stress plot at initiation of lifting process of the Shearwater jacket using the DeltaLifter.

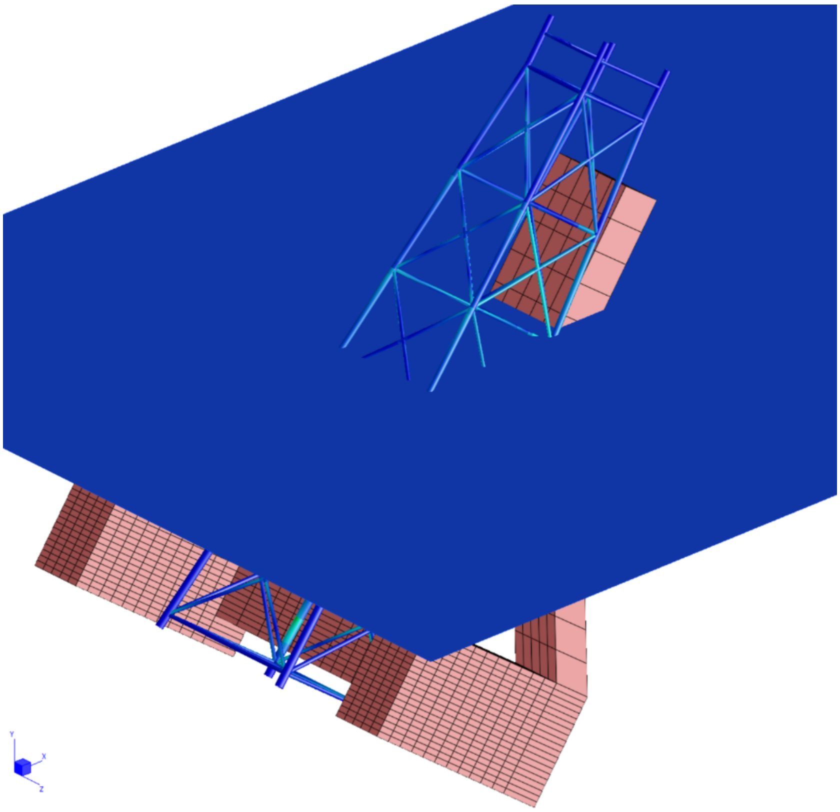


Figure 3.17: DeltaLifter model lifting the Goldeneye jacket.

without local catastrophic failure. Without further detailed analysis it is not possible to determine if local deformation of these members would result in catastrophic failure of the global jacket structure. The analysis does indicate areas of concern with this recovery method for similar jackets types and indicates that a more detailed analysis of jacket structures would be required if the DeltaLifter concept were to be taken further. See to figure 3.18 for details of the high stress locations.

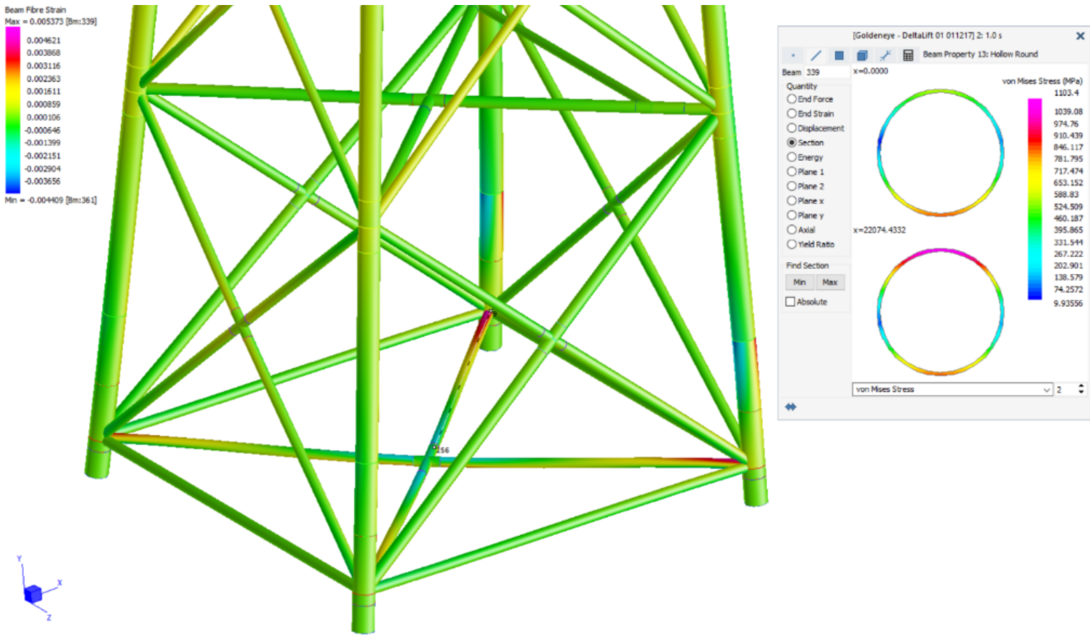


Figure 3.18: High stresses in the lower diagonal braces occur for the lifting of the Goldeneye jacket using the DeltaLifter

3.5. Operational assessment

Finally an operational assessment is made for the three buoyancy lifting concepts. The comparative assessment method described by the Department for Business, Energy & Industrial Strategy (DBEIS) in their decommissioning guidelines enables operators to objectively, transparently and consistently assess a number of different decommissioning options (DBEIS, 2013). The method provided by the DBEIS is commonly used in the sector. The guide to comparative assessments presents a framework to be used, see table 3.5. Each category should be rated qualitatively with a high, medium or low impact, e.g. by using a 1-5 scale. The guidelines state that balancing the impacts of the options is strongly recommended. Each category is therefore weighted to their significance. The sum of the weighted impact gives each decommissioning option a score. At this stage in the research the economical impact is left out, as was similarly done in the Brent Alpha report and quoted by the Department of Business, Energy and Industrial Strategy (Shell, 2017a; DBEIS, 2013). There is too little information on the decommissioning costs of the buoyancy lifting concepts at this point. Moreover, DBEIS states that cost should not be the main driver for an operational assessment.

Assessment criteria		Impact decommissioning option
Safety	Risk to personnel	High - medium - low
	Risk to other users of the sea	High - medium - low
	Risk to those on land	High - medium - low
Environmental	Marine impacts	High - medium - low
	Other environmental compartment	High - medium - low
	Energy/resource consumption	High - medium - low
	Other environmental consequences	High - medium - low
Technical	Risk of major project failure	High - medium - low
Societal	Fisheries impacts	High - medium - low
	Amenities	High - medium - low
	Communities	High - medium - low
Economical	Decommissioning cost	High - medium - low

Table 3.5: The comparative assessment framework for decommissioning options recommended by the Department of Business, Energy and Industrial Strategy (DBEIS, 2013).

Using this method, an operational feasibility score of the concepts is calculated and compared to the current heavy lift solution. The assessment is repeated several times by different stakeholders and departments. The operational assessment was at least done once by naval architects, once by structural engineers and once by the business managers, to avoid biased results. Unfortunately, the results differ for every perspective, see figure 3.19.

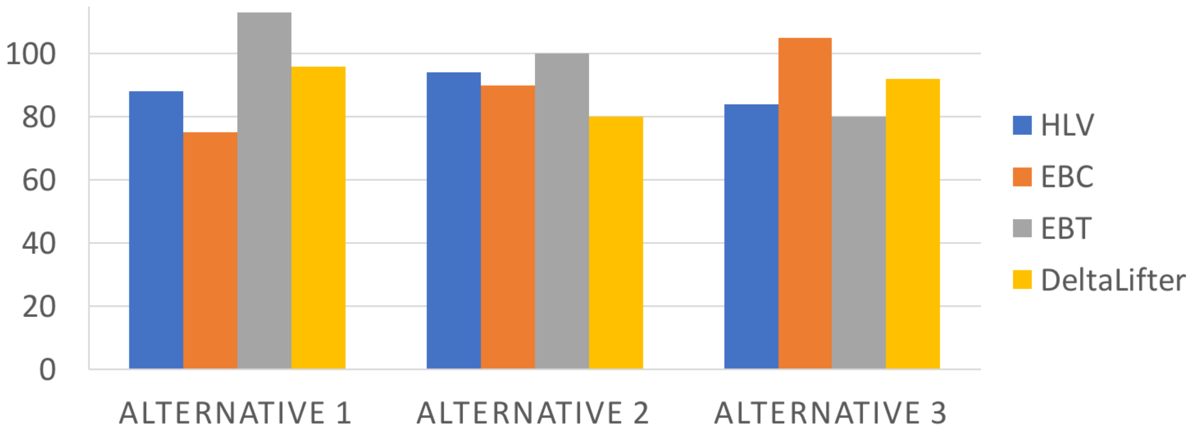


Figure 3.19: Different approaches to the comparative assessment result in no distinct winner. All buoyancy concept are deemed operational feasible nonetheless.

No clear distinction between the different buoyancy lifting concepts can be made from this assessment. Adjusting the weighing of the categories just a little, or the changing of one of the impacts returns a different conclusion about their operational abilities. Small changes in the variables may return any concept as the best option, or discard them all compared to the heavy lift vessel benchmark. This assessment is considered too sensitive and therefore not valid in this stage of design. Nonetheless, all concepts are deemed to be operational feasible.

3.6. Considered buoyancy lifting concepts

The three concepts that will be examined in this thesis are the external buoyancy caisson (EBC), the external buoyancy tanks (EBT) and the DeltaLifter. These are the only three concept using only buoyancy to lift a fixed steel jacket that did not show any major weaknesses or threats in the SWOT-analysis. Concepts using other mechanism than buoyancy fall out of the scope of this thesis. In this section all three concepts are discussed further in depth.

3.6.1. External buoyancy caissons

A concept drawing for the external buoyancy caissons (EBC) was made before for the BP Miller FEED study (Ardent, 2016). The concept is scaled down to fit a 5,000 MT jacket. The scaling is done linearly from the BP Miller jacket to the Goldeneye jacket. The closed A-shape, refer to figure 3.20, is used as the defined shape for the EBC throughout the report. This shape enables a vertical towing of the jackets to sheltered waters, where it can be tilted to a horizontal position. For the steel weight estimation the steel volume is estimated.

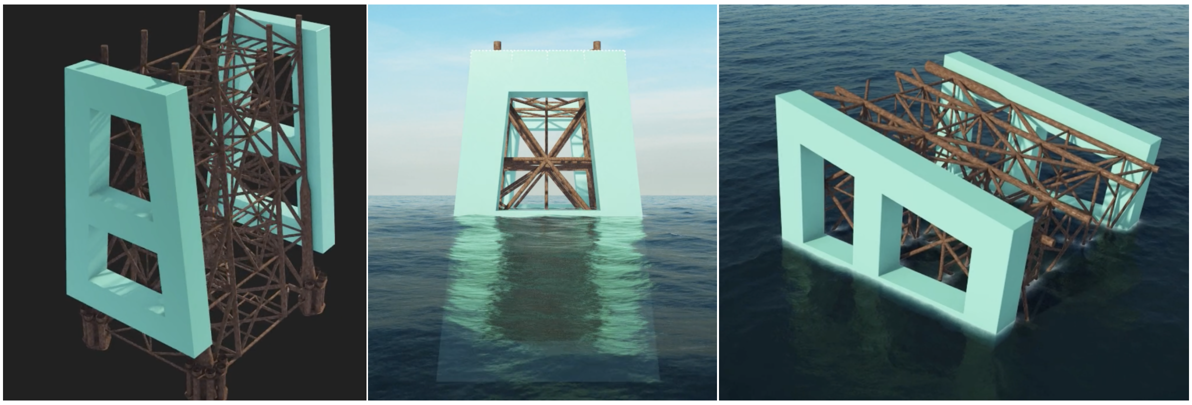


Figure 3.20: The External Buoyancy Caissons as designed for the BP Miller jacket are able to float the structure, tow vertically and rotate horizontally in order to enter the shallow dismantling yards. *Pictures from Ardent*

The dimensions of the EBC are presented in table 3.6. Similarly to the BP Miller concept, a steel thickness of 15 mm is assumed. From comparable builds the additional weight for web frames and stiffeners is assumed at 30% (Bray, 2009; Loon, 2018). Two caissons are used for this concept, each having a steel weight of 1,530 MT. Combined they provide a total displacement of 15,860 MT.

Overall length	70 m
Maximum width	35 m
Draft	5 m
Width A-frame	10 m
Number of caissons	2
Steel weight	1,530 MT
Maximum jacket weight	8,200 MT
Displacement	15,860 MT

Table 3.6: The main dimensions of the EBC, also used to estimate the steel weight.

3.6.2. External buoyancy tanks

The external buyoyancy tanks (EBT) are based on the design of the tanks used to decommission Frigg DP2 platform, see figure 3.21. The main difference with the Frigg DP2 caissons is that this design should be able to rotate the jacket and lift it on top of the buoyancy elements. This is achieved by adding buoyancy in different stages, as explained in section 3.2.2. For the DP2 removal one tank assembly, consisting of two buoyancy

Figure 3.21: The external buoyancy tanks as designed for the decommissioning of the Frigg DP2 jacket. The design used in this thesis uses first stage and second stage buoyancy to rotate the jacket on top of the buoyancy devices. *Pictures from Aker Solutions*

tanks, was attached to each one of the four legs. Each assembly generated 3,600 MT of buoyancy and had a steel weight 1,000 MT (Terdre, 2009). That was just enough to lift the roughly 11,000 MT jacket. In the design used in this thesis the jacket eventually floats on top of the EBT. To entirely lift the jacket out of the water, even more buoyancy should be added. Even though the jackets addressed in this research are smaller, similar sized EBT as the DP2 tanks are used. They are 65 metres in length and have a diameter of 6.5 metres each. They are grouped in pairs and weigh 1,000 MT, as stated before. Five pairs of buoyancy tanks are modelled in this thesis to generate a lifting force of 18,125 MT. More main dimensions of this design are found in table 3.7.

Overall length	65 m
Diameter	6.5 m
Tanks per assembly	2
Number of assemblies	5
Steel weight	1,000 MT
Maximum jacket weight	8,200 MT
Displacement	18,125 MT

Table 3.7: The main dimensions of the EBT. They are modelled similarly sized as the Frigg DP2 tanks.

3.6.3. DeltaLifter

The DeltaLifter concept is a concept developed by a Norway engineering team specialized in decommissioning solutions. The DeltaLifter concept is patented and the patent was bought by a Romanian engineering company, which independently verified the steel weights and structural calculations. They are now trying to commercialize the huge structure. With two towers on deck, refer to figure 3.22 for pictures, it is skillfully designed to always have some waterplane area to ensure hydrostatic stability during the uplifting process.

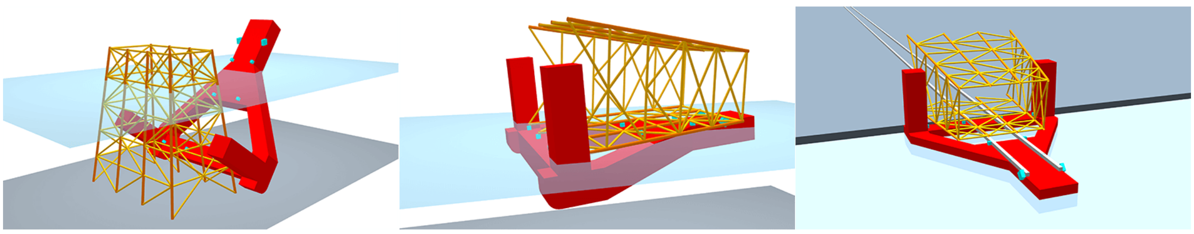


Figure 3.22: The DeltaLifter concept is a patented delta shaped concept. The two towers ensure enough waterplane area during uplifting operations. *Pictures from deltalifter.com*

Once lifted, the jacket is transported on deck and can be skidded off at quayside. The structure is immensely oversized to fit around the larger jackets, and to ensure a waterplane area. The steel weight is estimated at 6,178 MT, and it has a total displacement of 41,189 MT. More principal particulars of the DeltaLifter are given in table 3.8. More information on this concept can be found at `deltalifter.com`.

Overall length	115 m
Maximum width	100 m
Draft	12 m
Height column	37 m
Number of caissons	1
Steel weight	6,178 MT
Maximum jacket weight	8,200 MT
Displacement	41,189 MT

Table 3.8: The principal particulars of the DeltaLifter concept. More information can be found at `deltalifter.com`

3.7. Conclusion buoyancy lifting concepts

In this chapter three buoyancy lifting concepts are set up using design requirements distilled from the market assessment in chapter 2. Three concepts are chosen to be worked out further, based on a SWOT analysis, i.e. the DeltaLifter, the external buoyancy caissons and external buoyancy tanks. All three concepts are tested on their technical feasibility and the operational practicability. These three concepts will be used as a case study for the economic model presented in chapter 4 and further throughout this research.

4
Economic assessment methodology

The main objective of this thesis is to find out if buoyancy lifting of offshore platform jackets can be an economically interesting concept. In chapter 2 an opportunity was found to offer decommissioning solutions for jackets larger than 5,000 MT. In chapter 3 several concepts were generated and discussed. The technical feasibility of the design concepts was established. Three concepts are taken further in this thesis to test if buoyancy lifted removal can be economically viable. In this chapter the method to test the economical viability is explained.

A model is set up to compare the different concepts to each other and to the benchmark figures defined in chapter 2. First the methodology is described. The economic comparison tool is determined using Benford's economic criteria. Once the right tool is found it is adjusted to cope with the difference between vessels and the buoyancy lifting concepts. Secondly, it is explained how this comparison figure is found for the different concepts and which input data is required for the calculation. The model itself is constructed in MS Excel for the sake of usability by Ardent.

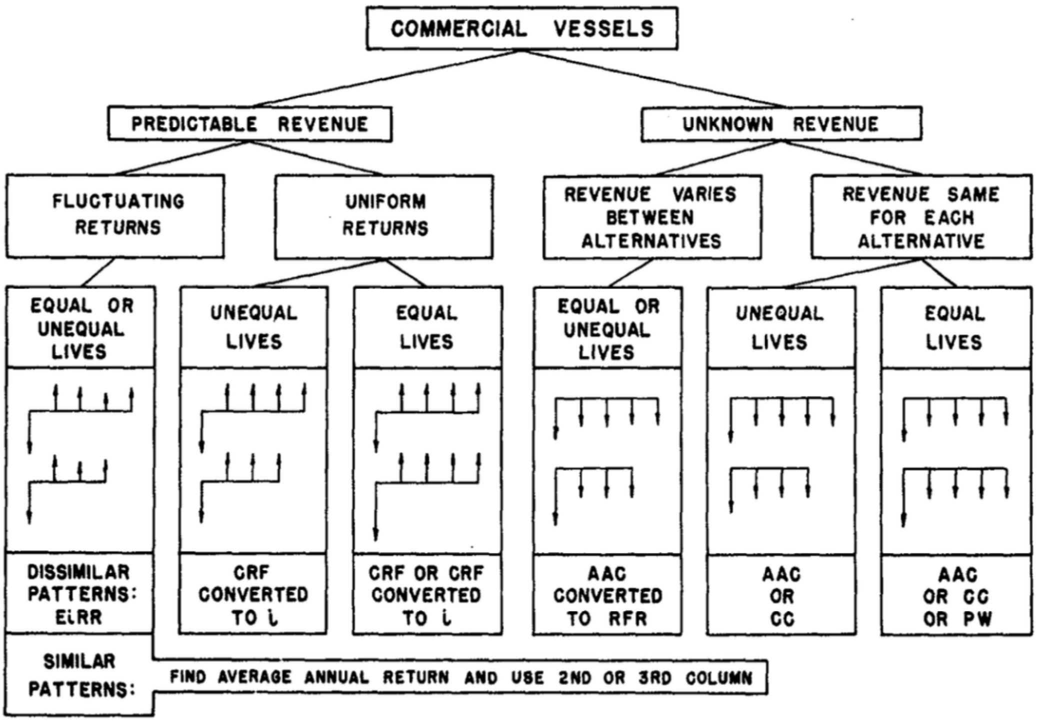


Figure 4.1: Suitable criteria under various economic circumstances *(Graph from Benford (1965))*

4.1. Methodology

Benford identified six different approaches to comparing design options for commercial vessels (Benford, 1965, page 34), see figure 4.1. This method is used in this thesis to establish which economic criteria to use in the economic comparison of concepts. Following the flowchart in figure 4.1, the average annual costs (AAC) is suggested as an economical comparison tool. The revenue generated by the buoyancy lifting concepts is unknown, but the same for each alternative. All three concepts are designed for the same business concept established in chapter 2, namely the removal of jacket larger than 5,000 MT. It can be safely assumed that the buoyancy concepts generate the same revenue and have equal lives.

In this thesis, however, the required freight rate (RFR) will be used as the economic criteria. This criterion is suggested when the revenue is not the same between alternatives. The assumption made about same revenue and equal lives for every buoyancy lifting concept then lapses. The required freight rate is defined as the AAC divided by the cargo carried each year (Benford, 1965, page 36). For decommissioning activities the required freight rate could be translated to the removal costs per tonne. The buoyancy lifting concepts basically transport a 5,000 MT jacket from the field to shore. By dividing all the costs of buoyancy lifted decommissioning by the weight of the decommissioned jacket, the removal costs per tonne are found, similarly as done to calculate the required freight rate. It might seem to be an unnecessary additional step to divide the average annual costs by the yearly transported cargo (or jacket weight in this case), but this way the same figure can be used to compare concepts to the benchmark figures found in chapter 2. Furthermore, the required freight rate is the rate at which an investment in a ship will break even, the break even rate (Watson, 2002). The removal costs per tonne then also reflect the minimum amount of income required per metric tonne of jacket weight for which an investment in a buoyancy lifting device would break even over its design life.

The removal cost per metric tonne is adopted as the economic tool for comparison for three distinct reasons. It is an understandable comparison tool. The concept with the lowest removal costs per metric tonne would be the most competitive one. The removal costs can also easily be compared with the benchmark figures defined by the Oil & Gas Authority UK and the Atlantic Marine Offshore in chapter 2. Finally it also gives Ardent a clear guideline for tendering, defining a lower bound. The upper bound would be defined by the benchmark figures, providing a clear range for bidding.

4.2. Net present value calculation

As stated before, the removal cost per metric tonne is the break even rate for an investment. To find the break even rate, a net present value (NPV) calculation will have to be made, including all cash flows related to the concepts (Watson, 2002, page 497). The costs for maritime operations are defined by Stopford in five parts, i.e. voyage costs, operating costs, periodic maintenance costs, capital costs and cargo handling costs (Stopford, 2009). This division of costs is made for sea-going vessels and can not be taken over literally. Moreover, to generate the NPV the cash flows have to be calculated, not the costs. Costs often result in negative cash flows; voyage costs, periodic maintenance and the operating costs are therefore discussed as presented by Stopford. The voyage costs are job-related costs and will be discussed in chapter 6. The operating and maintenance costs are both time dependent and thus discussed together in chapter 7. Capital costs, however, consider financing options and the depreciation of the vessel. As depreciation is a cost, but does not directly result in a cash flow, it is not taken into account for the cash flow calculation of the model. More importantly for a NPV calculation is the investment cost which has to be earned back. The building costs, scrapping income and cash flows related to capital decisions, e.g. loan payback and interest costs, are discussed in chapter 5. Finally, since no cargo is handled by the buoyancy device, cargo handling costs are not discussed in this thesis. All costs related to the handling of the “cargo” are job-related and accounted for in the voyage costs. The cost breakdown structure for used in this model is presented in table 4.1.

Chapter	Name	Periodicity	Cashflows
5	Investment costs	Non-periodic	Building costs, scrapping income
		Yearly	Interest costs, loan payback
6	Voyage costs	Per job	Material hire costs, labour costs, (de)mobilisation costs, ...
7	Operating costs	Yearly	Survey docking, special docking, repair costs, storage costs, ...

Table 4.1: The cash flow breakdown structure used in this thesis.

When all cash flows are found, the NPV can be calculated. The NPV should be zero for an investment to break even. With no income defined, except the scrapping income, the NPV will be negative. By setting the NPV to zero the required income can be derived, which can be calculated back to the required lump sum per job. This is the required income per decommissioning job to break even. Dividing the required lump sum by the jacket weight will provide the removal costs per metric tonne.

4.3. Conclusion economic assessment methodology

In this chapter the methodology used in this research to assess the economic viability is detailed. The removal costs per metric tonne is used as the comparison figure between buoyancy lifting concepts defined in chapter 3 and the benchmark defined in chapter 2. A net present value calculation will have to be made to find the removal costs per metric tonne. A more detailed explanation of this calculation is presented in chapter 8. An example run is provided at the end of chapter 8. The input needed to calculate the NPV is presented in the following chapters 5, 6 and 7.

5

Investment costs

In order to perform buoyancy lifted removals, the concepts presented in chapter 3 will have to be build. The building costs, capital costs and scrapping income define the initial investment that will have to be earned back. To estimate the investment costs of a buoyancy lifting concept the building costs and financial structure should be known. In this section the calculation and the implementation in the model for all three buoyancy lifting concepts is explained. Furthermore the scrapping income is also calculated in this section. At the end of this chapter an overview of all investment costs for the three concepts is given.

5.1. Building cost estimation

First the building costs of a buoyancy lifting concept need to be estimated. In this section the methodology used to estimate the building costs is derived from a shipbuilding construction costs estimation tool. A work breakdown structure is described to guide the estimation. The shipbuilders' methodology is optimized for pontoons because no database is present for buoyancy lifting concepts. Finally costs for a ballast control system and clamping and skidding systems are added.

5.1.1. Methodology

A lot of research has been conducted on constructing an early stage cost estimation tool for different kind of vessels, but none focus on barge-like floating structures. As a basis for this cost estimation, the method presented by Carreyette (1977) is used. It states that, in shipbuilding, when an object is increased in size a non-proportional increase of costs can be found. Costs in shipbuilding follow thus the equation 5.1. Aalbers (2014) added the factor c for complexity of specific systems.[1] Rather than using the cost estimation formula 5.1 as a whole, it is used to find the parameters of different cost groups. The reason for making the cost estimation for different groups is the error compensation effect. The accuracy of an estimation can be significantly improved when the overall forecasted value is calculated as the sum of its individual parts (Fischer and Holbach, 2011).

$$C_i = c_i * a_i * W_i^{b_i} \tag{5.1}$$

Where,

$$\begin{aligned} C &= cost \\ W &= weight \\ a,b,c &= parameters \\ i &= specific\,system \end{aligned}$$

5.1.2. Work breakdown structure

Parameters a, b and c for different cost groups are calculated by Aalbers (2014) and Frouws (2017) for general cargo vessels. These parameters are fine-tuned to a database of 30 vessels ranging up to 140 meters. The work

[1] Even though a and c are both factors, the splitting of the pair enables to carefully find the cost parameter a and use c for minor adjustments for more or lesser complex systems.

breakdown structure used by Aalbers and Frouws for the division of cost groups is adopted and adapted to the buoyancy lifting concepts, see table 5.1. All subsystems that do not appertain the buoyancy lifting concepts

Nr	System	Main Subsystems
1	General & Engineering	Engineering, Planning, Production information, Transport, Scaffolding, Auxiliary constructions, Launching, Trials
2	Hull & Conservation	Hull, Superstructures, Integrated tanks and foundations, Conservation
3	Ships Equipment	Steering System, Mooring System, Anti-rolling devices, Stores, Lifesaving &Fire fighting Systems, Transport systems, HVAC, Stairs, Railings, Masts
4	Accommodation	Outfitting, Carpentry, Inventory
5	Electrical Systems	Switchboards, Automation, Lighting, Navigation and Communication, Cabling
6	Propulsion & Power Systems	Propeller & Shaft, Reduction gear, Main Engine, Auxiliary Engines, Alternators, Boilers, Thrusters
7	Systems for Propulsion & Power Systems	Fuel oil-, Lub.oil-, Cooling water Pumps, Compressors, Separators, Heaters, Coolers, Piping & Valves
8	Bilge, Ballast & Sanitary Systems	Bilge/Ballast/FiFi pumps, Freshwater generator, Sewage plant, Piping & Valves, *Pressure transmitters, Inclinometers, Cabling*
9	*Clamping & Skidding* Systems	Hatch covers, Deck cranes, Refrigeration plant, Side doors, Towing winch, Cargo pumping system, *Clamps, Skidding rails*

Table 5.1: Work breakdown structure adopted from Aalbers (2014) and adapted for buoyancy lifting concepts. As can be seen system groups 3 to 7 are eliminated in this building cost estimation.

are removed from the work breakdown structure. As can be seen in table 5.1 the system groups for Ships Equipment, Accommodation, Electrical Systems, Propulsion & Power Systems and Systems for Propulsion & Power Systems are discarded completely as none of the subsystems occur in the buoyancy lifting concepts. All concepts will be non-self propelled, floating structures, handled by tugs, eliminating the need for onboard power generation and complementary systems. Power required for ballast pumps will be generated externally, e.g. from a supply vessel nearby. Accommodation is also not integrated in the buoyancy lifting design concepts. Systems groups 8 & 9 will have to be adjusted for a complex ballast system and clamping and skidding mechanism respectively. For the other systems, General & Engineering and Hull & Conservation, the parameters will have to be adjusted for towed, floating structures.

5.1.3. Optimization for pontoons

A database of around 20 specific vessels is required in order to perform a linear regression on the parameters in Carreyette's method to fine-tune equation 5.1 to said specific vessels (Sheteling, 2013). Semi-submersible North Sea barges are the closest approximation to the buoyancy lifting concepts. Unfortunately, no public data exist on the cost structure of existing semi-submersible barges, nor does Ardent have access to the required data. The model will therefore be build up with increasing complexity. With the availability of cost estimation for pontoons provided by Bray (2009), the parameters of systems 1, 2 and 8 (see table 5.1) were optimized to pontoons. The General & Engineering group is believed not to alter too much from regular shipbuilding, and the parameters are therefore left intact. Pontoons, much like the buoyancy lifting concepts, have simple designs compared to cargo vessels. This makes them easier to construct. It makes sense to adjust the complexity parameter of Hull & Conservation man-hours to cover this difference. Lastly the Bilge, Ballast & Sanitary Systems have to be adjusted to pontoons. As can be seen in table 5.1, the amount of systems to be installed is roughly half of that in cargo vessels (costs related to the more complex ballast system found in the buoyancy lifting concepts will be added later). Adjusting the a parameter to approximately half its value proved to cope perfectly with this alteration. The elimination of systems groups 3, 4, 5, 6, 7 and 9 and the two minor alterations from the parameters provided by Aalbers and Frouws led to a coefficient of determination[2] of 0.9928 between the model and the data provided by Bray. As can be seen in figure 5.1, the

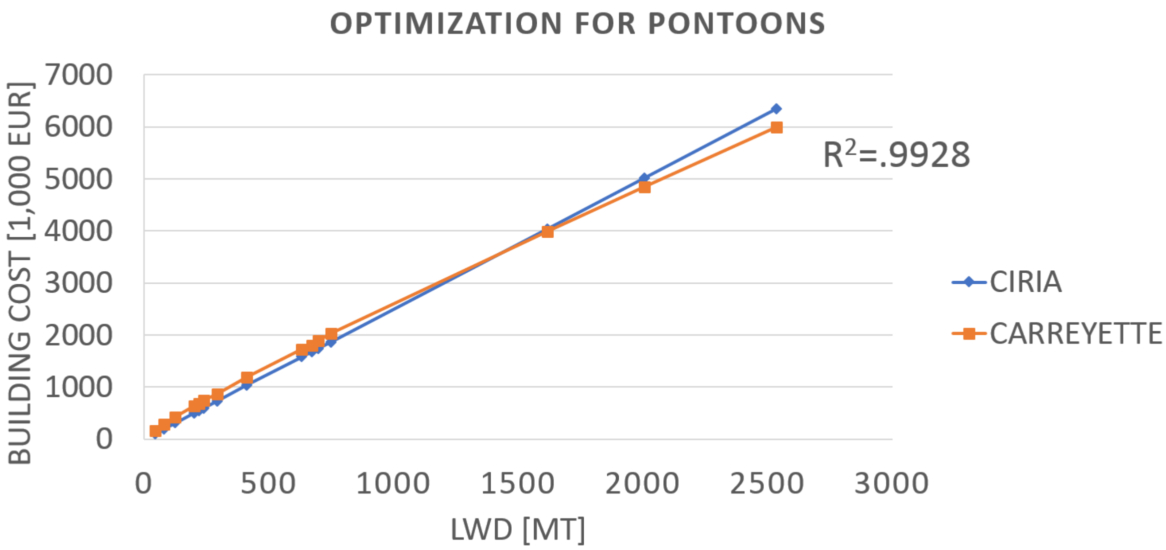


Figure 5.1: Comparison of the CIRIA cost standard to the adjusted method of Carreyette.

method of Carreyette includes economies of scale with the factor b. Unlike the CIRIA standard, which holds a linear relationship between weight and cost, the costs in Carreyette's method go slightly down for increasingly larger structures. Incorporating this effect, the method of Carreyette is believed to be more accurate. The parameters adopted from Aalbers and Frouws and optimized for pontoons can be found in table 5.2. These numbers were checked with in-house collected data from six barges via contacts at F3O. Altering the

Nr	System	Parameters:	a	b	c
1	General & Engineering	Material costs	2500	0,72	1
		Man-hour costs	13,5	0,9	1
2	Hull & Conservation	Material costs	950	1	1
		Man-hour costs	100	0,885	**0,5**
8	Bilge, Ballast & Sanitary Systems	Material costs	**75**	0,93	1
		Man-hour costs	2,75	1	1

Table 5.2: The parameters for Carreyette's formula adopted from Aalbers and Frouws. The figures in bold are optimized for non-self propelled complex floating structures.

man-hour cost from 30€/hr to 20€/hr to differentiate between European and Far East build (Bureau of Labor Statistics, 2012), gave a coefficient of determination of 0.9931. Furthermore a quote from Lerwick Engineering & Fabrication for the bare-hull build of two A-frames (no complex ballast or clamping and skidding systems) was compared to the model optimized for pontoons, giving a difference in building costs of less than 4%.

5.1.4. Ballast control systems cost

From here the complexity is increased by adding the cost of a more complex ballast control system. A highly detailed quote provided by Monitor Systems for a ballast system as described in the BP Miller FEED study (Ardent, 2016) provided enough insight to construct a detailed ballast system cost for different sized concepts.

[2] More information on the coefficient of determination can be found in Sheteling (2013).

The quote is deconstructed in 33 items of which a fully controllable ballast system exist, their unit price and quantity required. Most of the items are dependant on the amount of ballast tanks, which can be estimated with the total ballast volume. This deconstructed quote is used to accurately make a high-level estimate for the ballast control system costs depending on the ballast volume. An overview of the ballast control system cost deconstruction is given in table 5.3.

Item	QTY	Description	Unit Price	Total Price
1, 2, 14, 15	Concept	PLC, software, engineering, FAT	£204,113	£204,113
3, 8-10, 18-19, 33	# Caisson	Power distribution housing, draft hydrostatic pressure transmitters, atmospheric pressure transmitters, inclinometers, profibus, power cable to vessel	£13,425	£60,332
4-7, 11-13, 16-17, 20-32	# Tanks	Remote I/O, low range hydrostatic pressure transmitter, high range hydrostatic pressure transmitter, atmospheric pressure transmitter, level switches, submersible valves, profibus, power cables	£28,697	£999,539
			Total price	£1,263,984

Table 5.3: An overview of the detailed ballast control system cost structure, filled in for the DeltaLifter concept. (Values of 2016)

5.1.5. Clamping & skidding systems

For the clamping and skidding systems, systems group 9 in table 5.1, there are no quotes or other cost data at hand. Clamping can be done in a wide range of complexity, varying the cost remarkably. In the BP Miller FEED study several clamping methods are proposed (Ardent, 2016). These include a hook and pin method, off-the-shelf friction clamps, hydraulic scrapyard-like claws, magnetic grips and chains gripped around the structure. They are all applicable to the different buoyancy lifting concepts, and at this high-level concept design stage too soon to convergence on a particular clamping method. The costs concerning the clamping and skidding will for now be reserved as a percentage of the structure's lightweight, similarly as was done for cargo handling systems by Aalbers. The percentage is chosen to be 15%, so that the cost related to additional systems is close to what seems reasonable in the industry. It is advised to look into this matter soon and optimize the costs concerning the jacket handling systems.

5.1.6. Building cost model

The final building cost estimation model is presented in table 5.4. The system groups 1 & 2 are adopted from Aalbers and Frouws, with a minor alteration for the Hull & Conservations complexity factor. System groups 3 through 7 are omitted from the model, as they do not occur in the buoyancy lifting concepts. System group 8 is substituted with a different approach using a detailed quote. This copes with the more complex ballast system the concepts have in comparison to pontoons. Additional systems, group 9, are approximated with a percentage of the lightweight, similarly as done by Aalbers.

Nr	1		2		8	9	
	GENERAL & ENGINEERING		HULL & CONSERVATION		BILGE & BALLAST SYSTEMS	CLAMPING & SKIDDING SYSTEMS	
	Lightweight	Lightweight	Wsgross	Ws Kcb		Additional systems Lightweight Perc of Wsm	Additional systems Lightweight 0.15
a	2500	13.5	950	100		2500	6
b	0.72	0.9	1	0.885	See table 5.3	1	1
c	1	1	1	0.5		1	1
		30€/hr		30€/hr			30€/hr
	Materials	Man-hour	Materials	Man-hour		Materials	Man-hour
	€ 1,332,936.66	€ 1,037,628.53	€ 6,520,192.00	€ 4,383,406.13	€ 1,661,254.66	€ 2,298,000.00	€ 165,456.00
						Total cost	€ 17,398,873.98

Table 5.4: The final building cost estimation, as exampled here for the DeltaLifter concept. (Values of 2017)

5.2. Capital costs

To build the concepts the initial investment should be paid. To come up with roughly 20 million euros a bank loan could help. This would cause some additional costs that have to be modelled. The yearly interests, loan paybacks and leverage effects are cash flows that have an impact on the net present value calculation. Ardent pursues an asset light strategy and is not likely to invest in a maritime asset. The investment in a buoyancy lifting concept as presented in chapter 3 will most likely be made with equity from a joint-venture between Ardent and an offshore asset holding company. Moreover, a concept like this will only be developed once at least 80% of the required decommissioning jobs are confirmed. It it thus basically financed on a project basis. With the initial investment brought up purely from equity, no financial costs will occur in the net present value estimation. It is confirmed by Ardent that investments are not likely made with a bank loan. Therefore no loans, paybacks or interest payments are added in the NPV. If Ardent wishes to change their view on financing decisions, it could be easily implemented in the model.

5.3. Scrapping income estimation

The scrapping income of the buoyancy lifting concept will add a positive cashflow at the end of design life, by selling the massive steel structure for scrap metal. The scrapping income is calculated as the lightweight times the scrap rate per metric tonne. A scrap rate of €300/MT is used in the model (go-shipping.net, 2018). This scrapping income will be discounted in the net present value calculation and scrapping rates one design life further may vary from what they are today. This model is primarily build for comparing concepts, using the same scrap rate for all concepts. This justifies the arbitrarily chosen scrap rate. However, if forecasted rates are preferred, it can be changed in the model accordingly.

5.4. Total investment costs

The initial investment costs are defined as the building costs in this thesis, since no capital costs are modelled. The building costs for every concept are different, which will naturally have an impact of the concept comparison at the end of this research. The scrapping income is a small positive cash flow at the end of an asset's life recovered from selling the buoyancy devices for scrap metal. To find the building costs, the method of Carreyette with input from Aalbers and Frouws was used and optimized for pontoons using data from Bray. Ballast control costs were added using a quote from monitor. Skidding and clamping system costs were added as a percentage. The scrapping income is defined as a rate per metric tonne of steel. Finally no capital costs were modelled, as Ardent will finance the investment entirely with equity.

	Bare hull	Ballast control system	Skidding and clamping	Total building costs	Scrapping income
DeltaLifter	€ 13,274,163	€ 1,661,254	€ 2,463,456	€ 17,398,873	€ 1,853,400
EBC	€ 7,207,130	€ 954,934	€ 1,447,200	€ 9,609,264	€ 1,080,000
EBT	€ 9,776,152	€ 981,746	€ 2,010,000	€ 12,767,899	€ 1,350,000

Table 5.5: The initial investment costs for the different buoyancy lifting concepts. (Values of 2017)

All in all this results in the total investment costs presented in table 5.5. As can be seen the DeltaLifter is the most expensive structure to build. This is mostly because of its immense size. The DeltaLifter concept is so oversized to accommodate two columns in order to enhance the water plane area. This ensures the stability during the uplifting process. The EBC turns out to be the cheapest to build. It is smaller than the DeltaLifter. That results in cheaper bare hull building costs and a smaller ballast control system to install. Thirdly, the clamping and skidding systems are modelled cheaper than those on the DeltaLifter concept. The EBT concept is a little more expensive to build than the EBC. Instead of two caissons, five tank assemblies have to be build. Moreover, the ballast control system now has to regulate five different tanks, and five tanks will have to be clamped to the steel platform jacket. The scrapping income of all three concepts simply reflects their total steel weight. From this comparison a natural inclination towards the EBC concept arises, but first the voyage costs and operating costs will be examined in the following two chapters.

5.5. Benchmark check

Several inputs are used to check the results of the investment cost calculation. First of all, from interviews with ICE Marine Design it became clear that the building costs of the DeltaLifter would be 1 to 2 % of the building costs of the Pioneering Spirit. The Pioneering Spirit building costs are estimated at 1.3 billion euros (Allseas, 2015), providing us with a building cost estimate for the DeltaLifter between 13 and 20 million euros. This is nearly identical to the 17 million euros found through the building cost estimation model presented in this chapter.

Internally building costs estimations are used often as well. They are mostly based on a fixed price per tonne steel to come up with an estimate. Using five dollars per kilogram steel, the building cost estimations using this approach are slightly higher, but comparable. The model presented in this chapter, based on Carreyette, provides a more detailed cost estimation and is believed to be more accurate.

5.6. Conclusion investment costs

In this chapter the investment costs of the three buoyancy lifting concepts are detailed. They consist of the building costs, capital costs and the scrapping income. The building costs are constructed with a model of Carreyette optimized for pontoons. Later ballast control system and clamping and skidding costs are added. The capital costs are omitted from this model as it is unlikely it will be financed with any form of debt. The scrapping income is modelled as the steel weight times the scrap rate per metric tonne. The DeltaLifter turned out to be the most expensive structure to build, at roughly 17 million euros. This is in line with the estimation provided by ICE Marine Design. The other two concepts will costs between 10 and 12 million euros to build, which is slightly lower than the five dollars per kilogram steel estimation usually applied at Ardent. The model provides a more detailed estimation and is therefore believed to be more accurate.

In chapter 4 the model used to assess the economic viability was presented. The investment costs found in this chapter define the initial investment that will have to be earned back. It is used in chapter 8 to calculate the net present value of each buoyancy lifting concept.

6

Voyage costs

In this section the modelling of the voyage costs for the different buoyancy lifting concepts is explained. These are all the costs related to performing a decommissioning project. If the concept does not execute a job, none of these costs occur. In this section first the project duration for a buoyancy lifted decommission is detailed. Then the asset related costs are calculated, before detailing the additional voyage costs. The running costs are defined at the end of this chapter to give insight in the impact of delay.

6.1. Project duration

The job duration is often the main cost driver for offshore projects. It is therefore important to have a good understanding of the project duration. In this section the project duration is detailed. First the work breakdown structure for a buoyancy lifted jacket removal is detailed. Then the initial duration of the project steps is defined. Weather downtime is added at the end of this section to come up with the total project duration.

The project duration is assumed to be equal for all buoyancy lifting concepts, and only to differ for the different size of fixed steel jackets. This assumption is made on the bases that the operational steps for all three concepts is identical. The difference in voyage costs for different buoyancy concepts will be defined by three things. Firstly, a different set of assets is assigned for each task for every buoyancy lifting concept. Secondly, the rigging duration is in function of the amount of caissons. Thirdly, the offloading costs are different for the three buoyancy lifting concepts. If this approach turns out to be insufficient, a more detailed project duration can be set up varying for both jacket size and removal method. Even though this thesis focuses on the removal of jackets larger than 5,000 MT, all jacket weight categories defined in chapter 2 are modelled. The smaller weight categories offer a hold for Ardent to compare the output with their previous decommissioning experiences. In addition it extents the possibility of the tool to test different market strategies if desired.

6.1.1. Work breakdown structure

To produce a good estimation on the duration of an offshore jacket decommissioning, a work breakdown structure (WBS) is needed as a hold. A WBS helps to get a focused estimation on duration by dividing the projects in tasks. This results in a more accurate estimation of both initial duration and the potential weather downtime. Even though the buoyancy lifting concepts are different, they follow a similar sequence of tasks. It is thus assumed that the same WBS applies to all concepts. This makes it more accessible to compare between alternatives. The most comprehensive work breakdown structure found in literature is presented by

Substructure removal	Removal preparation, removal, vessels, sea-fastening, transportation and load-in.

Figure 6.1: The most detailed work breakdown structure found in literature is published by the Oil & Gas Authority (OGA, 2013).

the Oil and Gas Authority UK (OGA, 2013), see figure 6.1. This is a brief description that not suffices for this research. Other sources can be the close-out reports from previous decommissioning projects or tenders for future projects. As companies see their knowledge on decommissioning as a market advantage, these WBS are not more detailed then or literally refer to the OGA publication in figure 6.1. It can be concluded that the OGA WBS is reliable as it is commonly used in the sector, but needs elaboration. A more detailed WBS is set up as follows. Tasks are defined as process steps that either require different assets or different weather conditions, and are set up to be consecutive. Dividing the tasks for various asset configurations enables a smooth calculation further down the road. By splitting up the tasks for different weather conditions a more accurate weather downtime can be calculated. The consecutive structure implies that all tasks begin after the previous task ended. This enables an easy calculation of the entire duration by adding up all the individual times. The resulting work breakdown structure is presented in figure 6.2 and table 6.1.

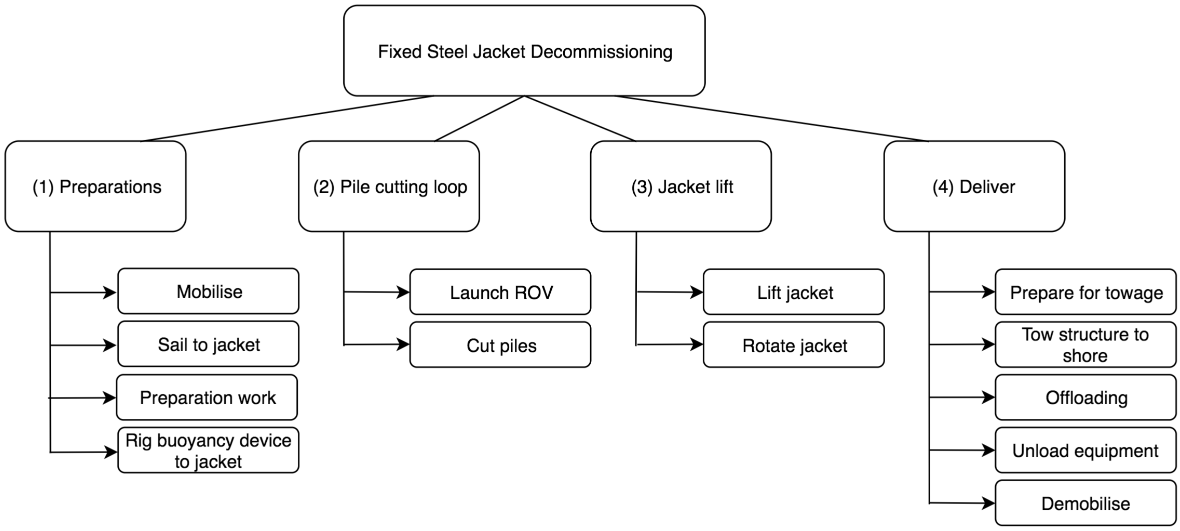


Figure 6.2: The work breakdown structure for offshore jacket removal operations using a buoyancy lifting device.

Nr	Task	Description
1.1	Mobilise	Mobilisation of vessels and personnel and the load of equipment
1.2	Sail to jacket	Transfer from mobilisation port to site
1.3	Preparation work	Removing temporary power supply, removing navigational lightning, inspecting jacket integrity, scaffolding, strengthening works
1.4	Rig buoyancy device to jacket	Positioning the buoyancy device, rigging the buoyancy device to the jacket
2.1	Launch ROV	Launching of the remote operated vehicle to initiate the pile cutting loop
2.2	Cut piles	A repetition of dredging, installing cutting tool, cutting piles and de-installing cutting tool
3.1	Lift jacket	The actual lifting of the jacket
3.2	Rotate jacket	The manoeuvre of getting the floating structure into towing position
4.1	Prepare for towage	Securing jacket for transit to dismantling yard
4.2	Tow structure to shore	Towage from site to dismantling yard
4.3	Offloading	Load-in of the jacket
4.4	Unload equipment	Unloading of the equipment
4.5	Demobilise	Demobilisation of vessels and personnel

Table 6.1: The work breakdown structure for offshore jacket removal operations using a buoyancy lifting device.

6.1.2. Initial project duration

The duration is set up according to the tendering guidelines at Ardent and in cooperation with the tender managers. The resulting duration for the buoyancy lifted removal for different sizes of fixed steel jackets can be found in table 6.2. The focus of this thesis is on the 5,000-10,000 MT jackets, so that one will be used to explain the duration. Mobilising is fixed at approximately five working days. The sailing distance is unknown, but assumed to by within two full days of sailing. The preparation works are linearly interpolated between the 1,000 MT and 10,000 MT jacket. As the jacket size increases, the preparation works take longer. For both

	Jacket weight [MT]	0-1,000	1,000-3,000	3,000-5,000	5,000-10,000	>10,000
1.1	Mobilise vessels	100 hrs	100 hrs	100 hrs	100 hrs	100 hrs
1.2	Sail to jackets	50 hrs	50 hrs	50 hrs	50 hrs	50 hrs
1.3	Jacket preparation work	60 hrs	100 hrs	140 hrs	180 hrs	220 hrs
1.4	Rig buoyancy device to jacket	22 hrs	29 hrs	36 hrs	43 hrs	50 hrs
2.1	Launch ROV	4 hrs	4 hrs	4 hrs	4 hrs	4 hrs
2.2	Pile cutting loop	132 hrs	132 hrs	132 hrs	132 hrs	44 hrs
3.1	Lift jackets	24 hrs	30 hrs	36 hrs	42 hrs	48 hrs
3.2	Rotate jacket	12 hrs	12 hrs	12 hrs	12 hrs	12 hrs
3.3	Prepare for towage	22 hrs	39 hrs	56 hrs	73 hrs	90 hrs
4.1	Tow structure to shore	70 hrs	70 hrs	70 hrs	70 hrs	70 hrs
4.2	Offloading					
4.3	Unload equipment	20 hrs	25 hrs	30 hrs	35 hrs	40 hrs
4.4	Demobilise vessels	24 hrs	24 hrs	24 hrs	24 hrs	24 hrs
	Total initial project duration	23.8 days	27.2 days	30.6 days	34.0 days	33.1 days

Table 6.2: The duration for different sizes of fixed steel jacket as constructed with the tender managers at Ardent.

ends the duration is estimated by tendering managers at Ardent. A similar process is used to estimate the lifting procedure, sea-fastening and unloading of equipment. The rigging of the buoyancy devices is linearly interpolated as well, but also dependent on the number of caissons to be installed. The launch of the ROV has a fixed time, regardless of the jacket size. It is modelled as a one hour operation per leg. Pile cutting is calculated depending on the number of legs or piles that have to cut. As stated in table 6.1, this includes dredging, installing of the cutting tool, the actual cutting and de-install of the cutting tool. One loop of pile cutting is assumed to take 11 hours. In table 6.2 the Goldeneye jacket is modelled with four legs, and three pile at every leg. In total 12 piles have to be cut, each taking 11 hours of ROV work time. Only four ROV launches are needed, one at each leg. The launch of the ROV therefore takes four hours and the pile cutting loop another 132 hours. In the case derogation is assumed, i.e. a jacket >10,000 MT, the legs can be cut above the pile skirts. This requires only four cuts instead of twelve, as the legs are cut and piles are left in situ. That is why the duration of the pile cutting loop for the largest weight group is shorter than for smaller sized jackets. The rotation of the jacket, towage to shore and demobilisation are assumed independent of jacket size and estimated as presented in table 6.2. As stated before, all task are consecutive. The total duration of the offshore task can thus be calculated by adding up all the individual duration. Note that the initial project duration shown in table 6.2 are hard entries constructed with colleagues at Ardent, all the times presented here can be reiterated later if found to be inconsistent or incorrect.

Important to mention is that the offloading step is not taken into account in the project duration. From a salvage perspective the job ends when the wreck is delivered to quayside. How it is further processed is often outside of their workscope. Often a third party takes the work from there. Furthermore, the offloading remains a unknown procedure for some buoyancy lifting concepts and is ought to be worked out at a later stage. In this report it is not taken into consideration as a variable voyage costs, but is dealed with as a fixed cost later in this chapter.

6.1.3. Weather downtime

The duration of offshore operations is highly dependent on the weather conditions. Certain operations can only be done in calm weather and ask for a sufficient weather window to be executed. This can cause significant delays, that will add to the project duration and costs. For a fair comparison with the current removal methods it is of key importance to include the weather unknown into the model.

To determine weather downtime two approaches can be used; the prediction of downtime on basis of wave scatter diagrams or the determination of the job duration on basis of scenario simulations (van der Wal and de Boer, 2004). The first method is widely used in the industry. The downtime is expressed as a percentage of the time that a certain operation can not be carried out. This method can also be used for a combination of operations however using this approach does not take into account critical events. This can lead to a significant underprediction of the downtime. For the determination of the downtime on basis of scenario simulations long term seastate time records are used. By checking for each subsequent time step which operational mode is applicable and if this mode can be carried out the workability is determined.

Preferably every scenario is run through simulation software to obtain the most accurate weather downtime. It is, however, not feasible to run every scenario through a seastate weather downtime calculating software every time a new input is given, as the program works with e-mailed in- and output. Therefore the downtime will be expressed as a percentage of the initial project step duration in this thesis. The percentage of weather downtime is then added to the critical project steps as a weather delay. To identify the critical steps, and come up with weather downtime percentages, the scenario simulation method is used. Several scenarios are run through the software, and critical tasks are identified. The critical tasks then are assigned an average percentage weather delay to add to their initial duration in order to incorporate the weather downtime. The software usually worked with at Ardent is ABPMer. The input it requires are set of activities, their location and limiting weather conditions. For the removal of a fixed steel jacket the work breakdown structure defined previously is used, at the location of the model jacket Goldeneye. This is considered a representative location, since all jackets focused on in this thesis are located in the Northern North Sea, see chapter 2. A sensitivity check for the location can easily be conducted by running the scenarios elsewhere. The limiting weather conditions are given in table 6.3. As a result ABPMer produces an elaborate Excel sheet. To minimize the risk of delay, operations will preferably be executed from May to July, as can be seen in figure 6.3.

Tasks	Longitude	Latitude	Task duration [hrs]	Weather window [hrs]	Max wave height [m]	Max wave period [s]	Max wind speed [m/s]
Mobilise	4,1453	51,9496	100				
Sail to jackets	-0,363663	58,001502	50		4		20
Jacket preparation work	-0,363663	58,001502	180	4	2,5	8	18
Rig buoyancy device to jacket	-0,363663	58,001502	43	18	1,5		
Launch ROV	-0,363663	58,001502	4	4	2,5	8	18
Pile cutting	-0,363663	58,001502	140	11	4		
Lift jackets	-0,363663	58,001502	43	24	2	8	
Load jacket	-0,363663	58,001502	12	12	2,5		
Sea-fasten jacket	-0,363663	58,001502	73	22	3		
Tow structure to shore	-0,363663	58,001502	70		3	9	20
Offloading	3,573611	51,442499					
Unload equipment	3,573611	51,442499	35				15
Demobilise	3,573611	51,442499	24				16

Table 6.3: The input for ABPMer consists of a list of activities, their location and limiting sea states.

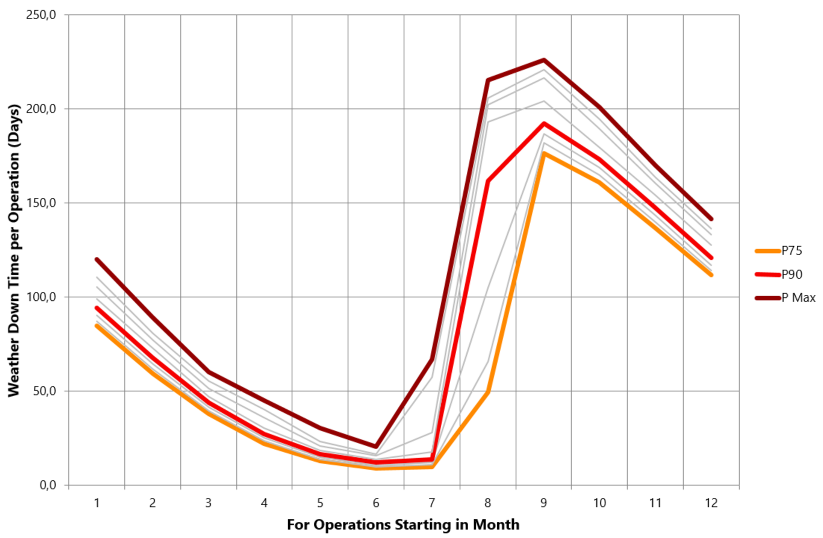


Figure 6.3: To minimize the risk of weather delays, offshore operations are commonly started between May and July. *(Output from ABPMer)*

Commonly used in the sector is the use of P85 for tendering purposes. Using a P85 the weather downtime is limited to roughly 40%. The critical activities are the preparation works, rigging, launching of the ROV, lifting and towing operations, see figure 6.4. The delay of the critical steps grows up to double of their initial duration. To incorporate this downtime effect the delay of the critical events is added as a percentage of the initial duration to the activities, see table 6.4. The percentages are for the removal of 5,000 MT to 10,000 MT sized jackets at the Goldeneye platform location in the Northern North Sea. The overall project delay adds up to approximately 40%, in agreement with the P85 estimation from ABPMer. For the other weight categories, different locations are modelled according to their example jackets. Note that a change of activities, location, limiting weather conditions or start date would require to reiterate the percentages used in the model.

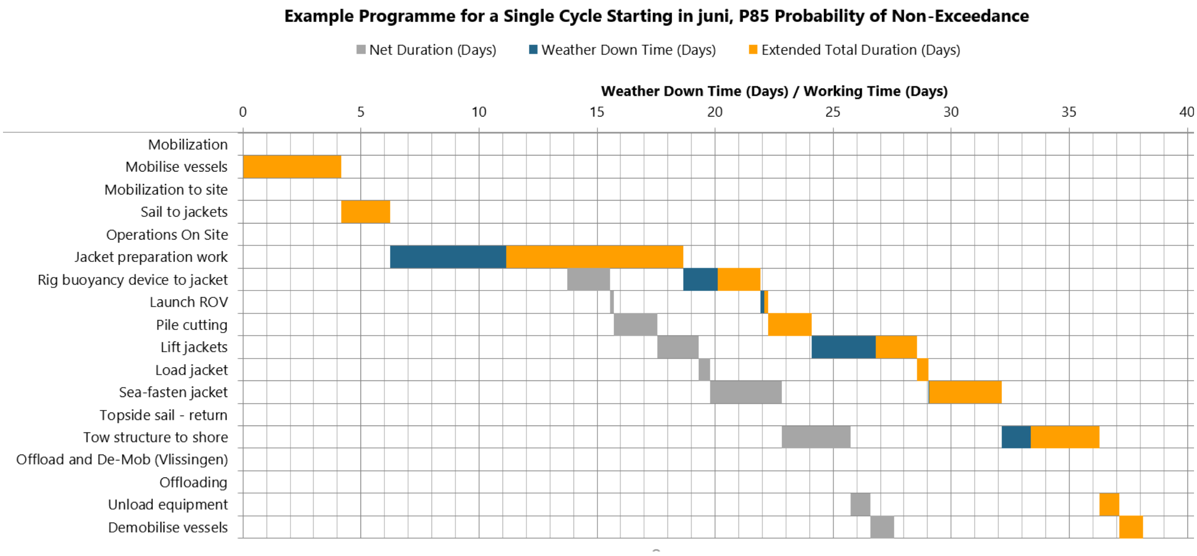


Figure 6.4: An example run for the removal of the Goldeneye platform. The most critical activities are the preparation work, rigging, launching of the ROV and the actual lifting. *(Output from ABPMer)*

		Initial duration [hrs]	ABPMer weather downtime factor	Extended duration [hrs]
1.1	Mobilise vessels	100	0%	100
1.2	Sail to jackets	50	40%	70
1.3	Jacket preparation work	180	70%	306
1.4	Rig buoyancy device to jacket	43	80%	77.4
2.1	Launch ROV	4	80%	7.2
2.2	Pile cutting loop	132	8%	142.6
3.1	Lift jackets	42	100%	84
3.2	Load jacket	12	10%	13.2
3.3	Sea-fasten jacket	73	10%	80.3
4.1	Tow structure to shore	70	40%	98
4.2	Offloading			
4.3	Unload equipment	35	0%	35
4.4	Demobilise vessels	24	0%	24
	Total project duration	34.0 days	35%	47.6 days

Table 6.4: The weather downtime factors distilled from ABPMer used in this research to incorporate the weather unknown in the voyage costs. Exampled here for the 5,000 MT to 10,000 MT jacket removal.

A weather delay of 35% is considered usual in the offshore industry. For high level concept design the Royal Dutch Shell uses a fixed percentage over the total project duration of 40% (Veen, 2018). The total project duration of 48 days is in line with other offshore work of similar size.

6.2. Vessel, equipment and labour costs

The next step is to determine the project costs. In this section first the assets used in a buoyancy lifted removal are presented. This goes for hired vessels, equipment and personnel. Then their day rates and lump sum costs are defined to price the assets. Following, the hire duration is defined for every asset. The total asset costs can then be calculated.

6.2.1. Asset selection

The assets required for an offshore decommissioning using buoyancy lifting devices are split in three parts, i.e. vessels, equipment and crew. The buoyancy lifting device itself it left out of the equation for now. The investment costs of the buoyancy lifting tool are already defined in chapter 5. This is the investment that will have to be earned back. The buoyancy device is assumed to not cause additional voyage costs. Voyage costs made by the buoyancy lifting device, e.g. mobilisation or small repairs on the job, are modelled by other assets.

Vessels

Ocean going tugs are needed to tow and manoeuvre the buoyancy devices to the jacket, assist with the lifting process and tow the structure back to shore. Anchor handling tug supply vessels (AHTS) are therefore added in three different sizes, i.e. 50MT bollard pull, 100MT bollard pull and 200MT bollard pull. A configuration of the three sizes AHTS is sufficient for all buoyancy lifting offshore operations. Otherwise, smaller capacity tugs can probably be hired at a lower rate than one of the three defined AHTS, e.g. a 150 MT bollard pull AHTS will be cheaper than a 200 MT bollard pull AHTS and can thus be modelled as one. Secondly, a remotely operated underwater vehicle (ROV) is added to the list. This ROV is used to inspect the underwater members and legs for marine growth and structural integrity, install the cutting tool and assist with the underwater rigging of the buoyancy device. Lastly, an offshore supply vessel (OSV) is added to the assets. This vessel will accommodate all offshore personnel, handle the ROV and control the ballasting system of the buoyancy devices. Examples of all vessels are given in figure 6.5.

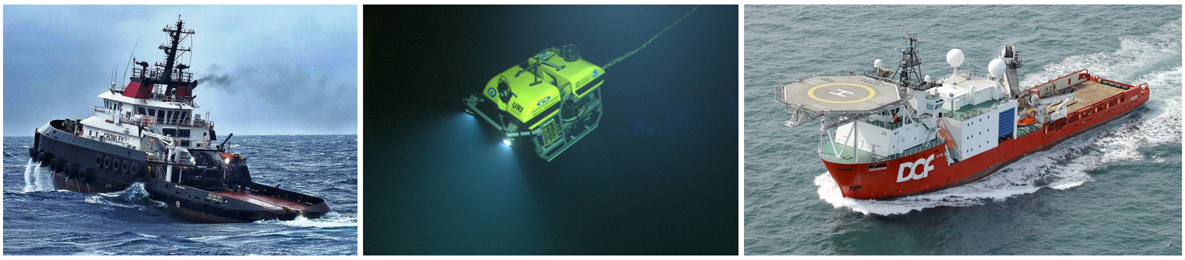


Figure 6.5: Some examples of vessels fit for buoyancy lifted removal of offshore platform jackets. From left to right, a 150 MT bollard pull ocean going tug, a remotely operated underwater vehicle and an offshore support vessel. *(Pictures from images.google.com)*

Equipment

Some equipment is needed for offshore operations as well. Most obvious cutting equipment is needed to cut through the legs, piles and grout in order to detach the jacket from the seabed. This will be one of the following three tools; a diamond wire cutter, an abrasive water jet cutter or a hydraulic shear cutter (OGA, 2012). The exact cutting method is not detailed in this thesis, as it is considered out of scope. The cutting of the legs is assumed to be a similar process regardless of the removal method. It is therefore of no importance which cutting mechanism is used, as long as it is consistent throughout the comparison. The diamond wire cutter is chosen in this research to generate costing estimates. Besides cutting equipment, general salvage equipment will be needed for the offshore operations. Generators and compressors are needed for the ballast system to work, and welding equipment for the seafastening procedure. All equipment for the ballast control module is modelled in the building costs, see chapter 5. An example of the cutting equipment is given in figure 6.6.

Personnel

Next the personnel needed is listed. For every salvage operation Ardent has at least a team of five colleagues they sent out. This team exist of a project manager, salvage master, assistant salvage master, naval architect and a logistics coordinator. At the office in IJmuiden or Houston a team will support the operation among other projects. To model the overhead costs dedicated to this project one full time equivalent person is added

Figure 6.6: A diamond wire cutter is used as the cutting tool in this thesis to generate cutting equipment cost estimates. *(Picture from ias-group.com)*

called the "office team & logistical support". To operate the ROV a specialised crew is needed. It takes two people to operate the ROV itself, two to operate the diamond wire cutter, a project leader and a field engineer. In order to work 24 hours a day, two full crews are needed. This adds up to a total of twelve people as the ROV crew. Furthermore welders and rope-access people are needed to assist with the preparation work and seafastening. A crew of at least seven people is recommended, accordingly fourteen people are added to accommodate the 24 hour working days. Finally, a lifting supervisor was recommended by Ardent to coordinate the complex lifting procedure. For a list of the modelled personnel, refer to table 6.7. Examples of some personnel are added in figure 6.7.

Figure 6.7: Examples of rope-access personnel and welders. *(Pictures from arabianoilandgas.com and cecventura.com)*

6.2.2. Day rates and lump sum

The cost per asset are required to calculate the project costs. This information is not readily available in literature, and only to a limited extent on the internet. The cost presented in this section are found through interviews and discussions at Ardent. The costs are mostly divided in two categories; lump sum and day rates. Lump sum is a single payment made for an asset, it is not depending on time. Prime examples of lump sum are delivery fees, mobilisation fees or procurement. Day rates, as the name says, are the rates payed per day. Vessel hire, equipment hire or salaries are examples of day rate costs.

Vessels

As discussed previously, five different assets have been chosen in this thesis, i.e. anchor handling tug supply vessels (AHTS) in different sizes, a remote operated vehicle (ROV) and an offshore support vessel (OSV). Their rates are presented in table 6.5. The delivery fee and vessel or equipment day rates have been drawn up with professionals at Ardent. These include the port charges and pilotage fees. Canal dues are not likely to be encountered. The mobilisation/demobilisation fee is modelled as a one day hire, i.e. the sum of the vessel day rate and one day of transit fuel consumption. The fuel rates are estimated using two approaches. The first approach is an estimation based on the installed power of typical AHTS or OSV. It is assumed that a

	Lump sum		Dayrates		Fuel rates		
Asset	Delivery	Mob/Demob	Vessel	Equipment	Towing	Transit	Operational
AHTS50BP	€ 20,000	€ 13,000	€ 6,000	0	€ 9,300	€7,000	€ 2,500
AHTS100BP	€ 60,000	€ 21,000	€ 11,000	0	€ 13,300	€ 10,000	€ 3,500
AHTS200BP	€ 70,000	€ 32,500	€ 20,000	0	€ 16,600	€ 12,500	€ 7,500
ROV	€ 15,000	0	0	€ 2,500	n.a.	n.a.	n.a.
OSV	€ 50,000	€ 47,500	€ 40,000	0	n.a.	€ 7,500	€ 2,500

Table 6.5: The rates used in this research for hiring different floating assets. (Value of 2017)

vessel uses all of its power during towing, 75 per cent of the total power while sailing, during operations the vessel uses 20 per cent of the total installed power (Woodyard, 2009). Ardent has access to fuel specifications of two vessels. From this specification a consumption of three metric tons per day per megawatt can be found. The second approach is through estimates of fuel consumption per day. One estimate comes from a paper published in the ABB internal review journal, which specifies the fuel consumption of a 200MT bollard pull tug (Myklebust, 2010). The other estimates come from Ardent. A price of 450 €/MT for MGO is used for the different approaches.[1] The fuel day rates can be found in table 6.5 in the right three most columns.

Equipment

The cost of equipment is presented in table 6.6. The cost of cutting equipment consists mainly of consumables and smaller portion for the hire of the machine itself. General equipment is mostly from Ardent itself, and does not need to be hired. There are costs, modelled as a lump sum, for bringing the equipment back to its original condition, buying additional material and consumables. An equal sized portion is for the hire of extra general equipment.

Equipment	Lump sum	Day rate
Cutting equipment	€ 97,000	€ 8,000
General equipment	€ 4,000	€ 5,000

Table 6.6: Costs of general and cutting equipment used in this research. (Value of 2017)

Wages

The labour costs are defined as a day rate between 650 and 900 euros a day, refer to table 6.7. The full time equivalent “office team & logistical support” modelled to cover the project related overhead costs is credited at 1,250 €. On top of that every person is allocated a lump sum of 2,200 € for travelling expenses. Labour costs for pilotage and other harbour costs are included in the delivery fee. Accommodation for all the offshore personnel on board the offshore support vessel is credited at 70 € per person per day.

Personnel	Lump sum	Dayrate
Office team & logistical support		€ 1,250
Salvage master	€ 2,200	€ 900
Assistant salvage master	€ 2,200	€ 750
Project manager	€ 2,200	€ 750
Naval architect	€ 2,200	€ 750
Logistics coordinator	€ 2,200	€ 750
Lifting supervisor	€ 2,200	€ 1,000
ROV crew	€ 2,200	€ 900
Welders/rope-access	€ 2,200	€ 650
Accommodation		€70 p.p.p.d.

Table 6.7: Personnel day rates and travelling expenses used in this research. (Value of 2017)

[1] Price of MGO in Rotterdam from March 2018, found online at shipandbunker.com.

6.2.3. Duration of asset hire

To come up with the total costs of an asset, the amount of days on hire for every asset is calculated in this section. All vessels, equipment and personnel need to be mobilised and sailed to the jacket. The OSV will guide the entire project from beginning till end, unlike the AHTS with the buoyancy caissons which can wait until the preparation work is done before moving to the site. Since the ROV, all equipment and the entire crew is housed on the OSV, they are bound to its schedule. The lifting supervisor can be flown in later to assist with the lifting operation. Taking this in consideration the duration for every asset can be found, see table 6.8.

	Mob	Preparation	Rigging	Lifting	Tow to shore	Demob	
OSV, ROV, equipment, personnel	✓	✓	✓	✓	✓	✓	43.6 days
AHTS, buoyancy device	✓		✓	✓	✓	✓	30.8 days
Lifting supervisor	✓			✓	✓		12.9 days

Table 6.8: Example of asset hire duration for the Goldeneye platform removal. The project duration of many assets is dependable on the offshore supply vessel.

6.3. Additional voyage costs

In addition to the costs for vessel, equipment and personnel hire, there are some other voyage costs to consider. There are non-asset related costs that are encountered at every project, i.e. job engineering, legal and insurance costs. Secondly, the costs associated with the offloading process are calculated separately as will be explained in this section.

6.3.1. Legal, insurance and engineering costs

There are other project related costs, that do not depend on assets, see table 6.9. They are modelled in three parts, i.e. the legal costs, insurances and engineering cost. They are all budgeted as a lump sum at the beginning of a project.

The insurance of salvage companies, like Ardent, is project based. That means that for every project a fee is payed to the marine insurance company, rather than a fixed price per year. The cost of insurance depends on the job duration and the value of the project. For decommissioning projects of fixed steel jackets of approximately 5,000 MT this fee is estimated at € 45,000. Legal costs are budgeted to cover claims and hiring costs of legal instances. Sometimes an import/export advisor is required, the contract agreements have to be scanned or arguments have to be fought out at the end of a project. For all legal purposes Ardent has two people in service modelled in the office team and logistical support. Additional legal force is hired, and therefore € 25,000 is budgeted for large contracts.

Non-asset	Lump sum
Insurance	€ 45,000
Legal	€ 25,000
Job engineering	€ 150,000

Table 6.9: Rates of non-asset related costs used in this research. (Value of 2017)

Job engineering is the inevitable time spent organizing each project. Total weight and integrity calculations will have to be done for every single jacket, as well as hydrostatic and hydrodynamic stability calculations during the lifting, uprightning and towing of the structure. All these calculation are project related and thus voyage costs. One of the advantages of the salvage approach of the fixed steel jacket removal is that the job engineering costs are way lower than for traditional lifting methods. On one hand because no highly detailed lifting plan is to be calculated, and on the other hand because the salvage mindset does not require extremely detailed engineering.

6.3.2. Offloading

The costs related with the offloading of the structure are kept aside in this assessment. From a salvage perspective the job ends with the delivery of the wreck at the quayside. How it is offloaded, dismantled and processed is not of their concern. It is however of great importance to include the offloading cost in the model in order to compare to the heavy lift vessel benchmark. The offloading of the structure can be done using different techniques and the chosen method depends on the concept as well. Most promising methods discussed at Ardent were to skid the structure from the deck of the buoyancy device on to the quayside, create a rock dump ramp at the quayside and pull the structure onshore, use harbour cranes to lift the jacket onshore, find a dry dock large enough to dock the structure or piece small decommission the jacket along the quayside. The choice of appropriate offloading method is considered out of scope and is not detailed in this thesis. To model the offloading costs, whilst coping with the high variety of methods, the associated costs are kept aside in the voyage cost calculation. This way they can more accurately be improved in the future, when more is known about the offloading procedure.

For now the offloading costs are defined differently for every concept as follows. The DeltaLifter concept has the prime advantage of transporting the jacket on deck and will be able to skid the structure on to the quayside. This will require some additional skidding system to be installed, as already modelled in the investment costs in chapter 5. The offloading costs are still modelled at € 1,000,000. This is the lowest rate of all three concepts, but still considerable since still a lot of uncertainty exist towards the offloading method. The EBC concept carries the jacket in between its caissons and will not be able to skid the structure on to the quayside. Most probably a rock dump will have to made or the jacket has to be piece small decommissioned along quayside. This are the least favourable offloading possibilities and the offloading costs of the EBC are modelled at € 4,000,000 for now. The EBT concept has a slight advantage over the EBC for transporting the jacket on top of the buoyancy elements. Moreover, the smaller EBT can more easily be removed using harbour cranes than the large EBC. For now the offloading costs of the EBT are modelled at € 2,500,000.

6.4. Total voyage costs

The total duration and resulting voyage costs are exampled in this section for the DeltaLifter concept lifting the Goldeneye jacket. In table 6.10 the summary is shown. For every step of the work breakdown structure the costs and duration are given. This is a useful tool to assess and compare the operation. The mobilisation

Nr	Task	Costs	Duration [days]
1.1	Mobilise vessels	€ 1,668,027	4.5
1.2	Sail to jackets	€ 590,982	2.9
1.3	Jacket preparation work	€ 1,224,000	13.9
1.4	Rig buoyancy device to jacket	€ 613,570	3.5
2.1	Pile cutting loop	€ 1,255,680	7.2
3.1	Lift jackets	€ 665,890	3.8
3.2	Load jacket	€ 104,640	0.6
3.3	Sea-fasten jacket	€ 636,560	3.7
4.1	Tow structure to shore	€ 720,791	4.1
4.2	Offloading	€ 1,500,000	-
4.3	Unload equipment	€ 277,454	1.6
4.4	Demobilise vessels	€ 344,754	1.1
	Total	€ 9,602,352	46.9

Table 6.10: The total voyage costs exampled for the DeltaLifter concept lifting the Goldeneye platform. (Value of 2017)

costs are one of the highest in this table. This can be explained due to the fact that all fixed costs are credited to this process step. This is common practice at Ardent, as it shows the committed costs of starting a project. A more detailed examination of those fixed costs is given in the next section. The costs of all following tasks is dependable on the assets that are working on the task. Their day rates and the duration of the task compose the total voyage cost of each process step. The incremental cost of an extra day of work is called the running cost and is explained in more detail in the next section. The offloading of the structure is taken out of the duration of the removal operation, as this falls out of the work scope for a salvage company like Ardent. The costs are budgeted separately as explained above. This results in a total voyage cost of roughly 10 million euros and a project duration of 47 days. The comparison of these numbers to the heavy lifting baseline and to the other buoyancy lifting solutions is added in chapter 9.

6.5. Fixed costs and running costs

To give better insight in the validity of the voyage costs, the fixed costs and running costs are calculated. Fixed costs are costs that are initiated once a project is started, regardless of how long the project lasts. They consist of mobilisation and demobilisation costs, delivery fees, procurement and other lump sum voyage costs. In this example the fixed costs are € 771,600, see table 6.11. This is in line with what could be expected for a buoyancy lifted removal.

Delivery fees	€ 215,000
Mobilisation	€ 114,000
Travel expenses	€ 17,600
Procurement	€ 101,000
Insurance	€ 45,000
Legal	€ 15,000
Job engineering	€ 150,000
Total	€ 771,600

Table 6.11: The fixed costs for starting an offshore operation for the DeltaLifter concept, exampled in this section. (Value of 2017)

Running costs are the incremental costs of every day added to the project duration. The running costs are the summation of day rates during a process step. The running costs can be split up to see how they are build up. This is a useful tool to compare the voyage costs with previously executed projects. For this example the running cost are € 174,400, refer to table 6.12. This is higher than expected, due to the large amount of vessels required to run the operation. To improve the design in a way it requires less tugs to be handled would result in a significant voyage cost reduction.

AHTS	€ 86,400
OSV & ROV	€ 45,000
Equipment	€ 13,000
Personnel	€ 27,550
Accommodation	€ 2,450
Total	€ 174,400

Table 6.12: The running costs for the DeltaLifter solution exampled in this section are rather high, due to the large amount of vessels required to manoeuvre the lifting device. (Value of 2017)

6.6. Conclusion voyage costs

In this chapter the job variable voyage costs are detailed. They are used as input of the net present value calculation of each concept in chapter 8. The voyage costs are build up by multiplying the day rates of the assets required to operate a buoyancy lifted removal by the number of days offshore and adding the lump sum costs for an operation. To check the voyage costs of the different concepts the fixed costs and running costs are set up. From this analysis it becomes clear that the fixed costs are what could be expected for a buoyancy lifted removal. The running costs are higher than expected, due to the large amount of assets modelled to run an operation. It is concluded that the voyage costs can be reduced by improving the design in a way it requires less tugs.

The voyage costs found in this chapter are one of the cash flows needed to calculate the net present value of the different concepts, as explained in chapter 4. It will be used in chapter 8 to find the removal costs per metric tonne of the different buoyancy lifting concepts.

7 Operating costs

The third category of costs that influence the cash flow of the buoyancy lifting concepts are the operating costs. Stopford defined the operating costs using the following categories; crew costs, stores and consumables, repairs and maintenance, insurance and general costs (Stopford, 2009). For the buoyancy lifting concepts, not all of these are applicable. Crew, for instance, is only hired when the device is taken on a job. For the buoyancy lifting concepts it is a variable cost already discussed with the voyage costs in chapter 6. Same goes for the stores and consumables, insurance and general costs. Other than with ships, that have to be operational the entire year, the buoyancy device can be stored when not in use. They are more maritime assets than vessels. The only time dependent operating costs are thus the storage costs for the buoyancy device and the repairs and maintenance to keep the buoyancy device in working condition. Both of these costs result directly in a cash flow and are discussed in this chapter.

7.1. Storage

When not operating offshore to remove fixed steel jackets the buoyancy device will have to be stored until the next project. The size of the buoyancy devices limits its storage possibilities. In this section several options are discussed, and the storage costs are detailed. Eventually, when the device is build, more accurate quotes will have to be gathered to get a more precise storage pricing.

7.1.1. Storage options

Several storage options were discussed at Ardent for the buoyancy devices. Four storage options are discussed in this section, together with their main concerns. The most obvious is a quayside mooring. The buoyancy devices are then moored against a quayside and kept there until the next job is commenced. While the draft and length of the buoyancy device pose no problems, this still might be an infeasible storing option, as the width of the buoyancy device is too large. The buoyancy device would not fit between docks or hinder the passing traffic.

Another option would be onshore storage. To get the buoyancy devices onshore, large cranes would be needed. Besides that, the devices will need to be transported to a suitable open location of reasonable acreage. This might be an option for the smaller modular external buoyancy tanks, but is considered infeasible for the other two options.

A third storing option is offshore storing. Like large tankers ride for anchor off the coast before entering port, the buoyancy devices may be anchored a few miles out of harbour. The legislation or insurance concerning off the coast anchoring is not examined in this research. Redundancy might be required, on board personnel might be mandatory and maybe a maximum duration is imposed by the government.

A fourth storage option was the idea to sink the buoyancy devices and refloat them when needed. The devices are build to cope with such an operation, however, it may impose some conservation problems to the ballast control systems. The maintenance costs of the structures might increase drastically due to the escalated exposure to the elements. Also some legal issues may arise with the seabed storage of buoyancy devices. This method is considered infeasible, but brought up nonetheless to illustrate the extend of storage options.

As becomes clear from this section, the storage method is not clearly defined in this research and considered out of scope. The quayside storage option will be used as a norm as this is considered the most practical solution at the moment. Moreover, most information on the storage costs is available for quayside mooring. A more detailed inquiry will have to be made in the future, however, to consider the width limitations or the potential of alternative storage methods.

7.1.2. Modelled storage costs

The storage costs are commonly modelled as a day rate per metre of quayside. From personal inquiry a quote from the Eemshaven quay rate of € 3.69 per metre per day is found (Zweepe, 2018). This is in line with quotes found for the Port of Rotterdam, rated at € 3.16 per metre per day (Port of Rotterdam, 2018). These rates exlude harbour dues, agency fees, linesmen and pilotage. These costs, often charged as lump sum, are only to be paid once. They are modelled at € 10,000 in this section. Using a quay rate of € 4 per metre per day, this results in yearly storage costs ranging from € 156,000 to € 214,400 for the EBT and the EBC respectively (values of 2017). Note the uncertainty of storage options and the possibility of not finding a suitable storing solution at all. A quayside storage may not be feasible, as discussed previously. It is advised to investigate the storage options in more detail in the concept phase.

7.2. Maintenance

Besides the storage costs, maintenance costs are operating costs the buoyancy device encounters. Maintenance is modelled as a periodic cost that occurs every few years. Small repairs are taken into account on a job to job basis, and thus modelled with the voyage costs, see chapter 6. The operating maintenance costs consist of two parts. The actual large repairs done in a dry dock every five years and the maintenance surveys that take place in between dry dock sessions. Both are discussed in this section.

7.2.1. Dry docking

Dry docking for repairs is done once every five years, as is required by SOLAS regulation for sea-going vessels (Kantharia, 2017). When the buoyancy device is in a dry dock for its survey, it is out of service. This has a smaller impact than for ships, as the structure is mainly used in the summer months, see chapter 6. In the winter months it is free for its periodic survey docking. The costs for survey docking are modelled as a percentage of the investment costs, equal to those modelled for sea-going vessels. Every survey docking the costs are increased to model the device getting older (Frouws, 2017). Older structures tent to require more repairs and thorough survey docking. The percentages used in this thesis are presented in table 7.1.

Number	Age of buoyancy device	Costs
Dry dock 1	5 years	1.4%
Dry dock 2	10 years	1.6%
Dry dock 3	15 years	1.8%
Dry dock 4	20 years	2.0%
Dry dock 5	25 years	2.2%

Table 7.1: The dry docking tariffs adopted in this thesis reflect those presented by Frouws for sea-going vessels (Frouws, 2017).

7.2.2. Maintenance survey

Maintenance surveys are done in between dry docking to check the conditions of the buoyancy lifting device. This can be in the form a dry docking as well, or a wet underwater inspection. Depending on the survey the dry docking may be extended or if necessary advanced. For modelling purposes the maintenance surveys are held exactly three years before a dry docking and have no influence on the dry docking. The costs of maintenance surveys is modelled as a percentage of the investment costs, similarly as done in ship design evaluation models (Frouws, 2017). The percentages can be found in table 7.2.

7.2.3. Total maintenance cost

The periodic maintenance costs as they are modelled now will induce costs every 2 or 3 years. The first dry docking for the DeltaLifter is modelled at € 200,000, the first maintenance survey at € 170,000. This is considered reasonable for the repairs and maintenance of the buoyancy device. Most of the valuable equipment is

Number	Age of buoyancy device	Costs
Survey 1	2 years	1.0%
Survey 2	7 years	1.1%
Survey 3	12 years	1.2%
Survey 4	17 years	1.3%
Survey 5	22 years	1.4%

Table 7.2: The periodicy and costs of the maintenance surveys for the buoyancy lifting devices, adopted from Frouws (Frouws, 2017).

hired from third parties, e.g. compressors, generators, control panels, etc., and does not cause maintenance costs. Furthermore, small repairs on the equipment and the buoyancy device are modelled for every voyage, see chapter 6.

7.3. Total operating costs

The yearly operating costs are found by adding the storage costs and the maintenance costs averaged over five years. As the storage costs are dependent on the quayside length the device occupies and the maintenance costs are related to the investment costs, the operating costs are quite distinct for the different buoyancy concepts. In table 7.3 an overview of the operating costs for the different concepts are given. It is interesting to note that the yearly operating costs for all concept are actually quite similar. As stated before they are expected to differ significantly because of their variation in investment costs and length. It becomes clear, however, that the most expensive concept to store is the EBC, with two caissons of 70 metres, is actually the cheapest to maintain. The storage and maintenance costs seem to level the differences in operating costs between the concepts. The DeltaLifter is the most expensive concept to maintain, resulting in the highest yearly operating costs. The EBT is the cheapest concept to store, resulting in the lowest operating costs. All in all the operating costs are all in the same range and are not assumed to be a differentiator for the concept comparison in chapter 9.

	Length [m]	Storage costs	Survey docking	Dry docking	Yearly operating costs
DeltaLifter	115	€ 177,900	€ 174,796	€ 244,714	€ 261,800
EBC	2x 70	€ 214,400	€ 93,834	€ 131,367	€ 259,440
EBT	100	€ 156,000	€ 128,600	€ 180,040	€ 217,728

Table 7.3: The yearly operating costs for the different buoyancy lifting concepts. (Value of 2017)

7.4. Conclusion operating costs

The operating costs for buoyancy lifting concepts consist of two parts, i.e. the storage costs and the maintenance costs. The storage costs are modelled as quayside storage using quotes from different ports around Europe. The maintenance costs are modelled as a percentage of the investment costs. The yearly operating costs of the three concepts lie close together. The external buoyancy tanks have the cheapest operating costs and the DeltaLifter is the most expensive to run.

The time dependent operating costs are the last input required for the net present value calculation as presented in chapter 4. They will be used to calculate the removal costs per metric tonne in chapter 8, together with the investment costs from chapter 5 and the voyage costs from chapter 6.

8

Removal cost calculation

As explained in chapter 4, the costs found in chapters 5, 6 and 7 can be used to calculate the net present value of an investment in buoyancy lifting concepts. From the NPV calculation the removal costs per metric tonne can be determined. In this chapter this removal cost calculation is detailed. First the assumptions made for the removal cost calculation are explained. Next the transformation from NPV equations to the removal cost per metric tonne is clarified. At the end of the chapter the removal cost calculation is exampled for the DeltaLifter concept decommissioning the Goldeneye jacket. The comparison of all buoyancy lifting concepts will be detailed in chapter 9.

8.1. The present value formula

For investment decisions often the net present value is used as an economic tool. In this research the removal cost per metric tonne is found using a net present value calculation. In a net present value calculation all future cash flows are discounted back to their present value (PV), using formula 8.1. The summation of the present values of all future cash flows is the net present value.

$$PV = \sum \frac{CF}{(1+i)^t} \tag{8.1}$$

Where,

$$\begin{aligned} PV &= Present\ value \\ CF &= Cash\ flow\ (future\ value) \\ i &= Discount\ rate \\ t &= period \end{aligned}$$

8.2. Assumptions

Before diving into the NPV calculation itself some assumptions are detailed in this section. Key figures in a NPV calculation are the cash flows, the period over which the calculation is done and the discount rate, as presented above in formula 8.1. In this section the assumptions concerning each of these elements of the NPV are discussed.

8.2.1. Cash flows

The cash flows in this calculation are the costs for a buoyancy removal defined in chapter 4. How the cash flows are build up is already discussed in chapters 5, 6 and 7. All costs credited to a certain year will always be modelled at the end of that year. Investment costs take place in year 0. The scrap income always at the end of life. The voyage costs, operating costs and the income are assumed constant for different projects.

If only one decommissioning job is appointed for several years, it is assumed to take place at the end of that period. This is the most logical placement, as the buoyancy device is stored until it is assigned to this one job. This is also the least favourable option, as costs far in the future are discounted heavier than costs in the near future. At a discount rate of 10% this means that if a project would break even with an income of 30 million per job if it is executed now, it would break even at 48 million per job if executed in five years from now. [1] To check the sensitivity of this assumption, another set of scenarios can be calculated with the project taking place as much in front of the period as possible. This it the most favourable option, illustrating the best case scenario. All possibilities of project placement in the design life will then occur between the best and the worst case scenario. To confine the risk the worst case scenario is used throughout the report.

8.2.2. Discount rate

The discount rate is defined as the required interest rate minus the expected growth rate. The interest rate and growth rate are fixed at 10% and 3.2% respectively, in consultation with the CFO at Ardent. A discount rate of 6.8% is used for the NPV calculation.[2]

8.2.3. Discount period

The period over which the NPV calculation is done is usually the design life of the maritime asset, assumed 25 years by Ardent. The buoyancy lifting devices, however, are not seen as maritime assets. The mindset is to use them as a tool and scrap the caissons after several jobs. This has several benefits. Firstly, this way the structures do not fall under strict class regulations, allowing for a salvage approach to the decommissioning task. Secondly, it ensures a good understanding with the clients about the pay-off of the huge buoyant structures. The clients like to have an advantage over their competitors pushing for a limited life. Lastly, freeing Ardent from the thought of owning a buoyancy device for 25 years, but instead deploying a salvage tool for several jobs, fits with its asset light strategy. This helps to convince the shareholders and thus the financing of the structures.

The length of the NPV calculation is consequently dependent on the amount of jobs a buoyancy device completes. From former research it became clear that the buoyancy devices are not economically viable if they are purpose build for one jacket (Ardent, 2016). The NPV calculation is therefore done multiple times for one up to ten jackets. Since the decommissioning can only be done between May and June, see chapter 6, a maximum of two jackets a year can be removed. The calculation will thus model up to five years. It is assumed that the buoyancy devices become economically attractive with less than ten jackets. If this is not the case, the calculation can be extended for another ten jackets, or modelling up to ten years. For clarification refer to table 8.1.

		Number of jackets to remove									
		1	2	3	4	5	6	7	8	9	10
Years	1	✓	✓	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.
	2	✓	✓	✓	✓	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.
	3	✓	✓	✓	✓	✓	✓	n.f.	n.f.	n.f.	n.f.
	4	✓	✓	✓	✓	✓	✓	✓	✓	n.f.	n.f.
	5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 8.1: A total of 30 scenarios will be calculated for the different buoyancy lifting scenarios. If the buoyancy devices are not economically viable for 10 jackets, more scenarios can be added.

The depreciation of the buoyancy lifting device is inherently taken into account with the NPV calculation, as the investment is earned back over a certain period. In this period (1 to 5 years) different amounts of jackets can be removed, resulting in a different cost structure. The scenarios could therefore also be interpreted as the amount of jackets the buoyancy lifting concepts are depreciated over, for certain amount of running years.

8.3. Calculation

To credit all future cash flows in their current value, the present value of every cash flow is calculated, using formula 8.1. The present values can be summed to calculate the NPV. The NPV should be zero for an investment to break even. With no income defined, besides the scrapping income, the NPV will generate a negative

[1] 30 million $*(1+0,1)^5$= 48 million

[2] This is the real interest rate considering a inflation of 3.2% and a nominal interest rate of 10%. Even though this is not a common inflation rate nowadays, it is assumed as an average of the past years in consultation with Ardent. The nominal rate of 10% is also quite high, once again set up in consultation with Ardent. A lower real interest rate would result in lower removal costs per metric tonne.

number. The decommissioning income should thus be at least the value of the NPV to break even. To find the removal costs per metric tonne, the present value found for the decommissioning income has to be written in cash flows in the future. This incoming cash flows in the future are defined as the required lump sum. Note that the required lump sum is assumed to be constant for every project, and can therefore be taken out of the equation, see formula 8.2. This can be rewritten to find the constant income cash flows or the required lump sum, see formula 8.3. Dividing the required lump sum by the weight of the fixed steel jacket gives the removal costs per metric tonne. This figure is often used in the sector as a benchmark figure.

$$PV = CF * \sum \frac{1}{(1+i)^t} \tag{8.2}$$

$$CF = \frac{PV}{\sum \frac{1}{(1+i)^t}} \tag{8.3}$$

Where,

$$\begin{aligned} PV &= Present\ value \\ CF &= Cash\ flow\ (future\ value) \\ i &= Discount\ rate \\ t &= period \end{aligned}$$

8.4. Example run

In this section the calculation of the removal cost per metric tonne is exampled for the DeltaLifter concept lifting three Goldeneye platform equivalents over the course of four years. In the next chapter, chapter 9, all scenarios presented above are calculated for all three buoyancy lifting concepts. For the example run refer to table 8.2. As can be seen in table 8.2 the investment costs are already in their present value as the investment

	Year 0	Year 1	Year 2	Year 3	Year 4	Present value
Investment cost	(17,598,544)					(17,598,544)
Voyage cost				(9,620,983)	(19,241,967)	(22,687,665)
Storage cost		(6,000,000)	(6,000,000)	(6,000,000)	(6,000,000)	(20,415,366)
No storage when on job				716,644	1,433,288	1,689,949
Periodic maintenance costs			(175,985)			(154,289)
Scrap income					1,853,400	1,424,571
				NPV		(57,741,343)
				Required income (PV)		57,741,343
				Required lump sum (FV)		24,485,926
				Removal cost per MT		4,709

Table 8.2: An example calculation of the required lump sum for the DeltaLifter concept lifting three Goldeneye jacket equivalents over the course of four years. The 4,700 €/MT is not competitive enough in the current market. (Value of 2017)

cost are assumed to take place in year 0. Since three jobs are done in four years and all jobs are done at the end of a period, no jobs are executed in the first two years. Voyage costs only occur in the last two years, i.e. one job in year 3 and two jobs in year 4. Operating costs on the other hand are time dependent and present in all four years. In the last two years a discount on the storage costs is given when the buoyancy lifting devices are on a job. Periodic maintenance costs only consist of a maintenance survey in year two. The scrap income is received at the end of year four. The present values of all these cash flows can be seen in the right column. The sum of these cash flows gives the NPV, which is negative as expected. The required income needed in the present to break even is equal to the NPV, but positive. For this income the project would break even, i.e. the NPV would be zero. The required lump sum can be calculated from the present value of the required income using formula 8.3, see formula 8.4. The removal costs per metric tonne are finally found by dividing the required lump sum by the weight of the fixed steel jacket.

$$Required\ lumpsum = \frac{57,741,343}{\left(\frac{1}{(1+0.068)^3} + \frac{2}{(1+0.068)^4}\right)} = 24,485,926 \tag{8.4}$$

8.5. Conclusion removal cost calculation

All cash flows required to calculate the net present value were presented in chapters 5 to 7. In this chapter the removal cost per metric tonne calculation is made and exampled for the DeltaLifter. The comparison of the removal costs of the three different concepts is concluded in chapter 9. Their economic viability is also tested in chapter 9 by comparing the removal costs to the benchmark found in chapter 2.

9 Concept comparison

In this chapter the concepts are compared to the benchmark figures set in chapter 2. Using the removal cost per metric tonne calculation presented in chapter 8, the removal cost per metric tonne of every concept is calculated. This figure will indicate if the concepts are economically viable by comparing them to the removal cost figures found in chapter 2. Besides comparing to the benchmark, the concepts will also be compared to each other. This will specify which concept is most competitive from an economical point of view. The goal of this chapter is to identify if any or all concepts are economically viable and if so, which concept is most promising.

9.1. Benchmark comparison

First the concepts will be compared to the current removal method. In chapter 2 it was concluded that the heavy lift removal of offshore jackets is the accepted benchmark method. Cost estimates for this method were not found directly, but through calculation from historical data and interviews on offshore jacket removals done by the Oil & Gas Authority UK, the Atlantic Marine Offshore and Ardent. As stated before in chapter 2, Ardent emphasizes the importance of including the Oil & Gas Authority its wish to reduce those costs by 35%, consequently a removal cost of 3,500 €/MT was defined as the benchmark used in this thesis. As explained in chapter 2, large error bars are given with the OGA data. These are added to the comparison graphs in this chapter.

Since the economic viability of every concept is highly dependable on the amount of jacket a concept removes, several scenarios are modelled. As explained in chapter 8, 30 different scenarios are checked for each concept. The concept is deemed economically viable if any of the modelled scenarios is below the benchmark. While this might sound as a loose criterion, it is actually quite strict. Alternative methods are designed to serve 30 years, securing more removals to break even. By using the buoyancy lifting concepts as a tool their lifespan is limited to five years, see chapter 8. With a maximum of ten jackets to remove, any scenario under the benchmark is an achievement and should be considered as an economically interesting opportunity.

To check the economic viability, the break even point is chosen as a comparison measure. Therefore, only costs are modelled and no profit or risk premium is added. This could be easily implemented in the model as a percentage of desired profit. To check the economic viability, however, the break even point is a clearer starting point than the figures with an arbitrarily chosen profit margin. To cope with the omission of profit, a scenario can be chosen that has enough margin for profit. Alternatively, the break even number of jackets can be found, and every extra jacket could be seen as profit (if executed in the same time span). The variability in risk assessment and profit margins is left to Ardent. To accommodate a scope for Ardent to asses the risk and adjust profit margins boundaries are added to the strict 3,500 €/MT benchmark. The boundaries are set up in accordance to the Oil & Gas Authorities benchmark at -55% and +75% (OGA, 2016).

Three scenarios are highlighted in this comparison. On one hand the idea to purpose build the concept for one removal. This is the starting point of the research, on which the BP Miller caissons were based. On the other hand the removal of three jackets in four year's time, as this is assumed to be the most realistic scenario. Lastly the removal of five jackets in three years is highlighted as this scenario was used in the feasibility study for Royal Dutch Shell.

As stated before, a concept is deemed to have economical potential if any of the 30 modelled scenarios is beneath the OGA benchmark. To check the economical viability, the least favourable scenario is checked. This is the scenario where the buoyancy lifting device is used for five years and for one up to ten jacket removals. This is the most pessimistic approach, because the operating costs are the higher if used longer, and, as explained in chapter 8, the cost are discounted heavier. That means that if the concepts show promise with the five year scenario, they most definitely show promise with the shorter lifespans.

9.1.1. DeltaLifter

Highlighted scenarios

When focusing on the highlighted scenarios, it becomes clear that the purpose build scenario is not feasible, as expected. In figure 9.1 the purpose build scenario rates with 4,800 €/MT even above the current benchmark figure. It is, however, between the error margins of the OGA benchmark. It could therefore potentially compete in the decommissioning sector, perhaps for the more complicated removals.

The second highlighted scenario, lifting three jackets in four years turns out underneath the benchmark of 3,500 €/MT. Taken into account that no profit is modelled yet, this scenario is marked as a plausible profitable option. Five removals in three year's time is well below the benchmark line and thus regarded as economically viable.

Economic viability

As can be read from the blue line in figure 9.1, the DeltaLifter concept needs at least three jacket removals to break even. Considering that the "in 5 years" scenario is the least favourable, the concept can be considered economically viable, provided that enough jackets are lined up for decommissioning.

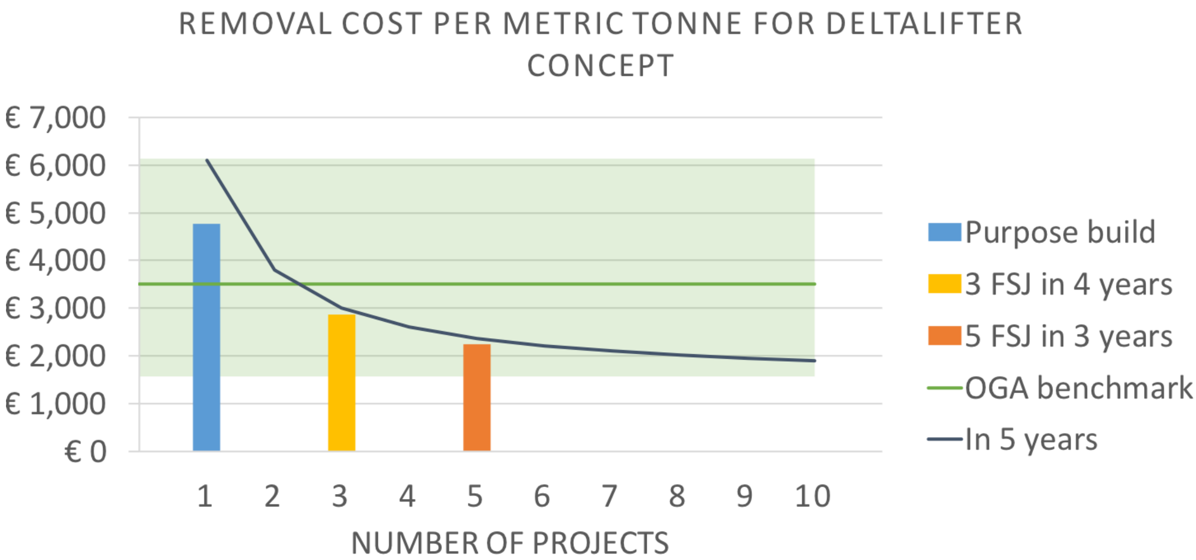


Figure 9.1: The DeltaLifter concept becomes economically viable from three projects onwards. (Value of 2017)

9.1.2. External buoyancy caissons

Highlighted scenarios

In previous research, it was clearly indicated that the purpose build of external buoyancy caissons was not economically viable (Ardent, 2016). Interestingly enough, it rates at 4,000 €/MT just above the OGA benchmark, as can be seen in figure 9.2. A smaller sized version of the BP Miller caissons seems to be able to compete at a break even rate with the current heavy lift vessels. Purpose build for a campaigned two jacket removal might just be an interesting business proposal.

As a result, the removal three jackets in four years is definitely an economically viable option, see figure 9.2. The removal of five jackets in three years is also well below the benchmark line, with enough margin for profits.

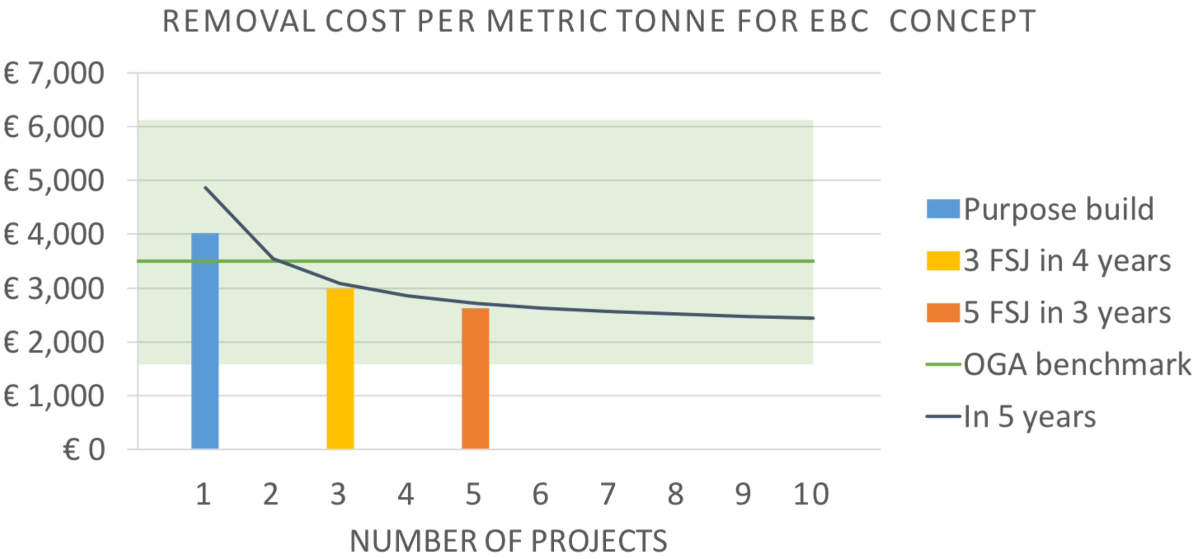


Figure 9.2: The External Buoyancy Caisson concept, as designed for the BP Miller jacket, would become economically viable if downscaled to 8,200 MT and assigned for at least two projects. (Value of 2017)

Economic viability

A downscaled version of the EBC concept, i.e. from 18,500 MT to 8,200 MT, can be economically viable from the moment it can align two decommissioning projects. This promises to be a better buoyancy lifting concept than the DeltaLifter.

9.1.3. External buoyancy tanks

Highlighted scenarios

The purpose build scenario is rated around the current removal cost of 4,700 €/MT, see figure 9.3. This is not considered an economical viable option, since no profit margin is present. Interestingly enough though, because the Frigg DP2 removal was completed with purpose build external buoyancy tanks. Rumours in the sector claim that the Frigg DP2 jacket removal, however, did not turn out to be profitable.

The three projects in four years scenario, on the other hand, scores just underneath the benchmark figure of the OGA, see figure 9.3. The five jacket removal in three years is again an interesting proposal. Just like the previous two concepts it is economically viable, but for the EBT a smaller margin for profits is present.

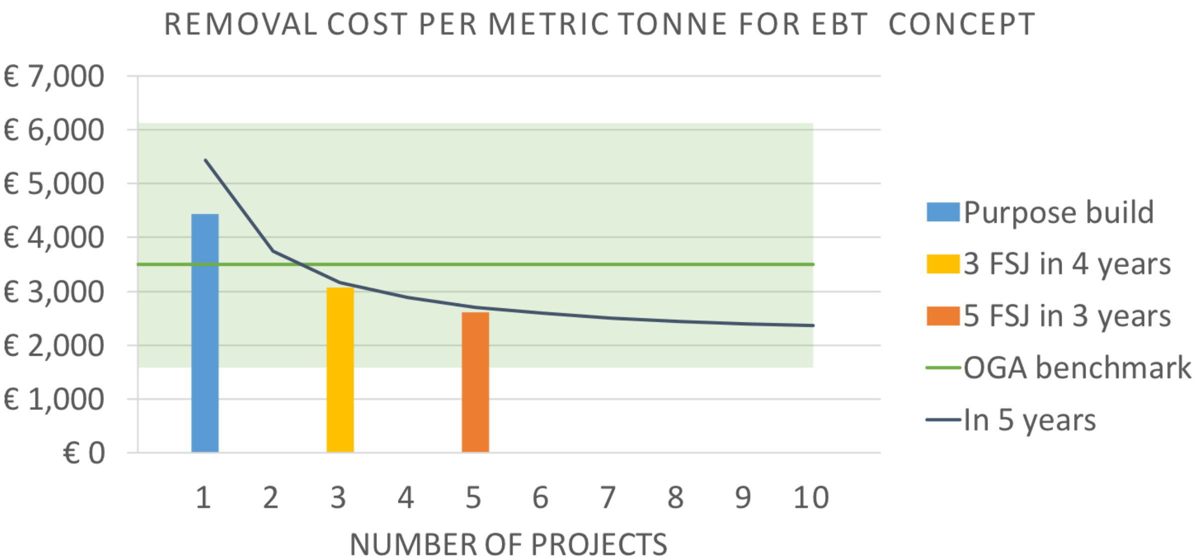


Figure 9.3: The External Buoyancy Tanks become economically viable for three jackets, and could be purpose build for two removals. (Value of 2017)

Economic viability

Similarly to the DeltaLifter concept the EBT break even from three projects onwards. The five year scenario scores just a little above the benchmark for a two jacket removal, at 3,700 €/MT. Unlike to the EBC this concept does not break even if purpose build for a two jacket campaign.

9.2. Concept comparison

Compared to the benchmark each concept proved to have economical potential. To find out which concept is the most promising of the three, a mutual comparison is carried out in this section. First the technical differences are compared to each other. This gives a qualitative expression of the best concept. Along with the qualitative aspects, different cost figures of the concepts are compared. Next, the economical performance of the three concepts is compared on the basis of the scenarios highlighted above. Derived from this mutual comparison a business proposal is made in the next section.

9.2.1. Technical comparison

The three buoyancy lifting concepts, presented in chapter 3, are noticeably different in their design. The difference in their technical capabilities normally translates to a different service provision or reduced costs. Since the decommissioning market stresses the cost aspect more than the service capabilities, cost reduction measures will be the main focus of the comparison.

As explained in chapter 3, the DeltaLifter concept has a smaller surface overlap with the jackets, limiting the clamping options. This could result in excessive shear stresses in the jacket during the lifting operation. The EBC and the EBT concept pose no structural integrity problems with the example jackets tested in this thesis. The EBT concept is the most versatile design. With no fixed width, the separate tanks are attached to the legs, and more tanks can be added for larger structures.

More tanks means that more structures have to build, resulting in longer building lead time and higher investment costs for the EBT. The EBC concept, with its simple square design and only two tanks has by far the lowest building costs, see chapter 5. The DeltaLifter, which is frankly oversized due to its eccentric shape in order to ensure waterplane area at all times, has the highest investment costs. The EBC concept has an advantage here over the other two designs.

Their operational implementation, however, is quite similar. As presented in chapter 6, they follow the same simple work breakdown structure to complete a buoyancy lifted removal. The only distinction in the three concepts is the rigging time and the assets they need to execute the operation. As stated before in chapter 6, this could be optimized at a later stage, by extending the voyage cost calculation to include concept specific process duration. For now the three concepts are similar in operations, with the DeltaLifter needing as little as three tugboats to accompany the operation, and the EBT requiring at least one tugboat for every tank. Combined with the longer required time for rigging, the EBT has a disadvantage relative to the other two designs.

The larger amount of buoyancy tanks result in higher voyage costs due to rigging, but also excessively higher storage costs, see chapter 7. The EBT concept has so many tanks, that storage costs even exceed the DeltaLifter concept. The DeltaLifter poses some problems with quayside storage, due to its immense width. The EBC is deemed the cheapest to store, as a quayside storage is feasible for this concept, and only 140 metres of quayside is needed. The ease of storage is a clear advantage for the EBC, the Deltalifter has a great disadvantage compared to the other two designs.

In the offloading procedure the concepts differ immensely. With the DeltaLifter concept the jacket lays on top of the device and can be skidded on to the quayside. With the EBC the jacket hangs in between the two caissons. An additional offloading asset is required to deliver the jacket to the dismantling yard. Several offloading options are discussed in chapter 6. Even though the jacket lays on top of the buoyancy device with the EBT, it is not clear if the jacket can be skidded off. From the offloading perspective, the DeltaLifter has a clear advantage over the other two methods. All in all the EBC scores the best in the qualitative comparison,

Name	Technical	Building costs	Operational	Storage	Offloading
EBC	•••	•••	•••	•••	•
EBT	•••	••	••	••	••
DeltaLifter	•	•	•••	•	•••

Table 9.1: The qualitative comparison of the three concepts shows most promise for the EBC concept, especially if the offloading procedure can be fine-tuned.

see table 9.1. The only pitfall is the uncertainty concerning the offloading procedure. If offloading is considered the main distincting criteria, the DeltaLifter beats the other two concepts. The storage uncertainty is a more foreseeable problem than the offloading process. The EBT is in every scenario a good runner up, but not a clear winner. From this qualitative technical comparison the EBC stands out as the best concept, unless offloading is considered as the main issue.

9.2.2. Economical comparison

For the economical comparison between the three buoyancy lifting concepts the highlighted scenarios discussed in the previous sections are compared. From the mutual comparison, presented in figure 9.4, it is confirmed that no concept can be economically viable if purpose build for one jacket removal. Scoring just above the OGA benchmark, the EBC concept could break even for a campaigned two jacket removal. Interesting to see is that in the next two scenarios the EBC scores best. The DeltaLifter concept starts out as the most expensive alternative, but beats the EBT concept with more than 3 jacket removals. In the long run, i.e. more than seven jacket removals, it even aligns with the EBC removal costs. Firstly, this can be explained by the high investment cost the DeltaLifter causes, it is by far the biggest structure to build. Secondly, the operational costs are lower, because only one caisson has to be rigged, resulting in less offshore time and less required tugs. The combination of these factors make the DeltaLifter the most economical in the long run. This buoyancy device should consequently be build to last a longer period. Two main concerns hinder

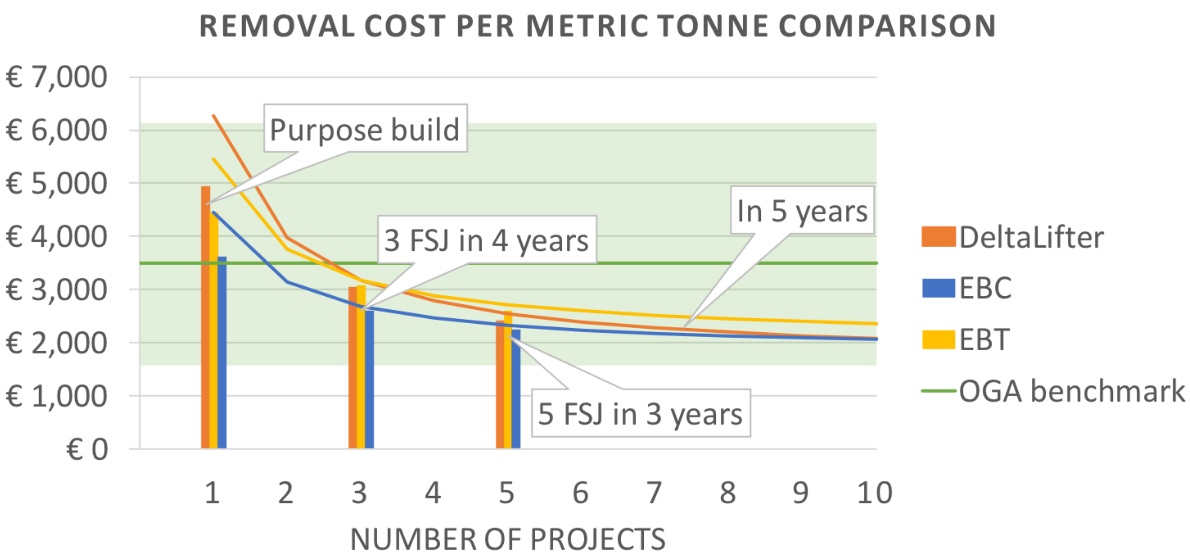


Figure 9.4: From the mutual comparison it becomes clear that the EBC concept is the most promising option. The DeltaLifter starts out as the most expensive option, but becomes economically more interesting in the long run. (Value of 2017)

the DeltaLifter from being the best concept, i.e. the storage uncertainty and the limited versatility. The immense width of the DeltaLifter raises some questions about the feasibility of a quayside storage. Moreover, the DeltaLifter needs several jackets to break even, but has the biggest problem of all three concepts to adapt to different jackets. For this concept specific jackets have to be lined up carefully to break even. Tendering for only a limited amount of jackets that come up for decommissioning in the coming 20 years is a risky venture. Since not every tender is won, and not every jacket can be addressed, the DeltaLifter is likely to lay idle for a long time. Most probably it will only decommission a jacket once every few years. This does not turn out to be a profitable business concept.

9.3. Business proposal

Taking both comparisons into consideration it becomes clear that the buoyancy lifting concepts all bear enough economic potential. All the three concepts are considered economically viable and from the mutual comparison it becomes clear that the EBC turns out to be the best concept. This depends heavily though on the feasibility of the EBC offloading procedure. As stated before, the decommissioning market stresses the cost aspect of operations. A feasible offloading procedure should reduce the costs of complicated jacket offloading. If no feasible offloading can be found for the EBC concept, it might not be the best concept for buoyancy lifted removals. In this section a business proposal is set up for the implementation of the EBC concept.

From the economical analysis it became clear that the EBC could break even for a campaigned two jacket removal. The strength of this concept is the low building cost, making it fit for such a purpose build campaigned project. The building costs are relatively low; two 3,600 MT caissons can be build for less than ten million euros. The strategy would be to recover this investment with the first two removals and then scrap the caissons. This will provide a proof of concept for the new technology, gain trust with the operators and a clear message to all stakeholders. For Ardent it is clearly an investment in a buoyancy lifting tool, rather than a commitment to a newbuild asset. For the operators it is an alternative to the expensive heavy lift vessels, and also a competitive advantage to other operators. It is build to remove their two jackets and then it is scrapped. This will also provide a proof of concept, and help Ardent with new buoyancy lifting decommissioning experience, which can help to optimize the next design.

From the market analysis it became clear that the best market segment to target was to build a device with 8,200 MT buoyancy capacity. Looking at the jackets targeted by this concept in table 2.5, the two Golden Eagle platform jackets make the perfect duo for a campaigned removal approach. The two platforms are identical, weighing both 6,200 MT and standing in 105 metres of waterdepth. With the current removal cost rate of 5,400 €/MT the project could return roughly 67 million euros. The removal costs of a purpose build EBC for this project would consist of the building costs, minimal storage and repairs, and voyage costs adding up to a total of 26 million euro. Even with the 35% cost reduction pursued by the Oil & Gas Authority, the project would generate more than 43 million euros, resulting in a 10 million euro income.

In the worst case scenario the heavy lift fleet saturates over the next few years, beating down the removal costs per metric tonne. If the removal costs fall another 35% compared to the OGA reducted benchmark of 3,500 €/MT the purpose build EBC concept would barely break even. The projected revenue would be a little more than 28 million euro. The net present value of this investment returns negative, hinting at a loss making investment. In this case the EBC still can be used to provide a proof of concept and learn from this first buoyancy lifting experience.

An overview of the three scenarios is given in table 9.2. All in all, the purpose build campaigned two jacket removal is considered to be a viable business proposition. Note that this is scenario comparison takes the

	Current situation	OGA 35% reduction	Worst case scenario
Removal rate per metric tonne	€5,400	€3,500	€2,275
Jacket size	6,200	6,200	62,00
Nr jackets	2	2	2
Possible revenue	€62,696,629	€40,636,704	€26,413,858
Investment costs	-€9,609,264	-€9,609,264	-€9,609,264
Voyage	-€21,634,619	-€21,634,619	-€21,634,619
Operating	-€200,749	-€200,749	-€200,749
No storage when sailing	€47,139	€47,139	€47,139
Scrap income	€1,011,236	€1,011,236	€1,011,236
NPV	€32,310,372	€10,250,447	-€3,972,400

Table 9.2: The purpose build EBC campaigned for a two jacket removal proves to be an interesting business concept. (Value of 2017)

offloading process for granted, as it is modelled now. That means that if the offloading procedure costs more than four million euros, the scenarios do not hold up anymore. If the offloading turns out to be double as costly as modelled now, the net present value of a purpose build EBC for a campaigned two jacket removal would be three million euro. This is still a healthy business proposal.

10 Conclusion and recommendations

10.1. Conclusion

In this thesis a model is set up to assess the economic viability of early stage buoyancy design concepts. The main research question is to find out if a versatile design approach to the buoyancy lifting concept, i.e. being able to take on multiple projects, can result in an economical viable solution for decommissioning offshore platform jackets in the North Sea, tested against the benchmark figure set by the current heavy lifting removal costs. Only the buoyancy solution for the removal of fixed steel jackets in the North Sea is considered in the scope of the model.

The conclusion of this thesis is that a versatile design approach to the buoyancy lifting concept, i.e. being able to take on multiple projects, does indeed result in an economical viable solution. All three concepts presented in this research break even under the benchmark for multiple jacket removals. Removal cost per metric tonne is significantly higher than the benchmark, however, for purpose build scenarios. The versatility is therefore essential for the economical viability. Of the three concepts presented in this report, the EBC concept turns out to be the most promising concept. It is the cheapest structure to build and operationally the best concept. It has a lower removal cost per metric tonne for every scenario modelled compared with the other two concepts. Only the offloading procedure still needs to be further analysed in more detail for this concept.

The economic model developed in this report allows for early testing of buoyancy lifting design concepts on their economic potential. Prior to this research no good understanding of the economic viability of buoyancy lifting concepts existed. This model quantifies the economic potential of different concepts and facilitates making the best choice between many first stage design concepts. Also, in later design stages, this model can be used to reiterate the actual costs related to a buoyancy lifted removal of fixed steel jackets and reevaluate the economic potential of designs. By simply substituting the cash flow inputs with accurate numbers that are available in a later design stage, a more accurate break even point can be calculated.

Besides the calculation of the removal costs per metric tonne and its comparison to benchmark figures, the model also offers an estimation for investment costs, voyage costs and operating costs for buoyancy lifting concepts. Without actually realized buoyancy concepts, there is no reference building cost estimation tool available for these concepts. This model can be used to provide reasonably accurate building cost estimations based on a few parameters available for early stage concepts. In addition to building cost estimations, also voyage costs and operating costs are estimated in this model. When other new buoyancy lifting ideas are brought up, costs can quickly be estimated using this model. For Ardent this provides a consistent framework to accurately test and compare buoyancy lifting concepts.

10.2. Further development

The buoyancy lifting removal of fixed steel jackets should definitely be further developed. This research demonstrates economic viability for practically all buoyancy lifting concepts examined. The EBC concept might even be economically viable for a purpose build campaigned two jacket removal. Any innovation should at least have a desirable design, feasible technology and a viable business to be valuable (Brown, 2009). The buoyancy lifting of fixed steel jackets appears to be desirable as multiple organizations have approached Ardent to further research the possibilities of buoyant removal. It was found that all concepts presented in this thesis have the potential to be technically feasible, so it is possible to use them. Finally, the main research question of this thesis, all three concepts were found to have economical potential. It is therefore stressed that the buoyancy removal of platform jacket should definitely be further developed.

The development of any innovation follows an iterative design spiral. The buoyancy lifting concept is no exception. This thesis started at the beginning of the spiral by defining initial dimensions for the buoyancy lifting concept and checking the economic viability of this size of contraptions. Now that it has been established that the concepts have economic potential, more focus should be put on the technical feasibility of the concept. Once the technical feasibility is better examined, the desirability will have to be re-iterated and an updated economic viability will have to be worked out, as can be seen in figure 10.1. In the further development it is recommended to take a deeper look into the offloading procedure. This is at this stage the main remaining hurdle for the most promising EBC concept. If the offloading procedure can be defined and economically quantified, a viable turnkey solution can be presented. Some ideas that came up at the end of the research were to combine the EBC and the EBT concept, i.e. using the staged buoyancy principle to get the jacket on top of the EBC. A smaller caisson, or EBT, may be used to facilitate this process. When the jacket can be positioned on top of the EBC, skid rails could be incorporated in the design and then the EBC can skid the jacket onto the quay side.

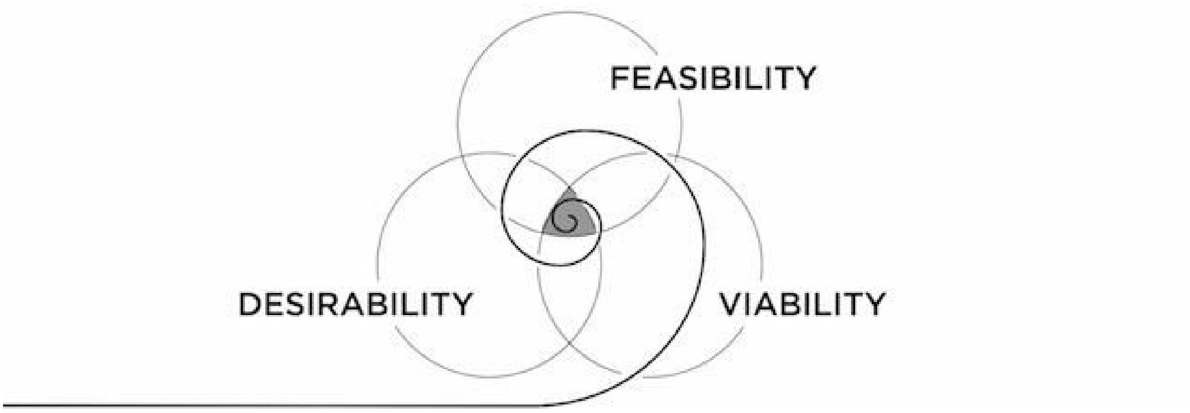


Figure 10.1: The design of a buoyancy lifting concept is an iterative process. *(Picture from ideou.com)*

Togehter with the development of the offloading procedure, also the lifting and rotating of the jacket should be carefully examined. The skidding to offload the jacket depends naturally on the process of getting the jacket on top of the EBC. Some ideas to ensure stability during the uplifting and rotating process are the use of anchors, the need for additional waterplane area or the help of heavy lift assets. Since the purpose of the development of a buoyancy solution was to avoid heavy lifters, and since the addition of buoyancy elements to add waterplane area quickly results in very large structures, confer the DeltaLifter concept, it is recommended to look into the use of anchors to guide the uplifting and rotating procedure. A quick sketch of this process is shown in figure 10.2. Early high level technical calculations show some concerns with this method as well. Alternative methods to add stability during the uplifting and rotating process should be investigated.

Finally, one should be cautious with the publication and/or marketing of the buoyancy lifting ideas as presented in this research or arising from further research. Different patents are present on buoyancy removal of offshore platform jackets, which could be enforced. Moreover, even though Ardent has a lot of experience with challenging refloating operations, the first to market benefit is of considerable effect in this sector.

10.3. Model improvements

The presented model provides a good estimation of the removal costs per metric tonne for early stage concepts. The calculation of the removal costs per tonne are solid and can be used in further design steps as well. The input data, however, could benefit from some improvements at various steps.

The investment costs give a good approximation of the building costs for a barge-like structure with a complex ballasting system. This could be improved by adding a more detailed specification of the additional costs for skidding and clamping systems. At this point no distinct clamping or offloading method is defined, and the costs are modelled as an add-on percentage. In further design stages the investment costs may be

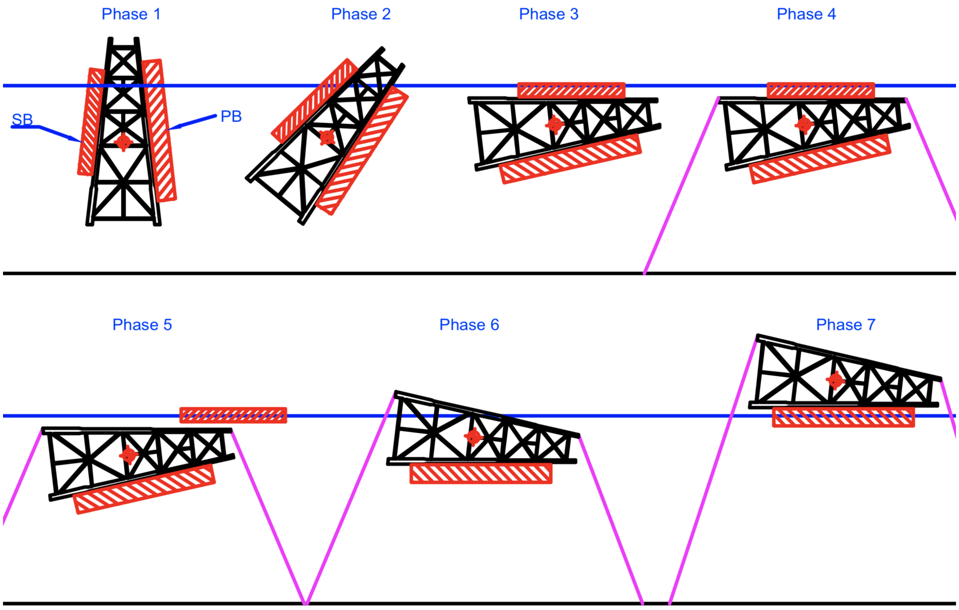


Figure 10.2: The use of anchors to guide the uplifting and rotating process of the jacket removal may result in a jacket on top of the EBC.

improved or substituted as a whole, if better estimations can be made. The economic model will still calculate the removal costs per metric tonne with a different input for the investment costs.

Also the voyage costs may be further improved. At this point the project duration differs for different jacket weight groups, but is held the same for every single concept. The difference in voyage costs is largely driven by the different assets that are assigned to the buoyancy lifting concepts. Gut feeling suggests that the voyage costs could be more of a differentiator for the different concepts than is currently modelled. It is therefore advised to detail the voyage cost calculation for every single concept that is tested. Moreover, similar to the investment costs, the economic model still calculates the removal costs per metric tonne, even if an alternative input for the voyage costs is defined.

Profit is now modelled as a percentage of the present value of the projected income. Throughout the report it was set to 0%. If profit is wished to be used in the economic model, it is recommended to model the profit as a percentage of the future value of the income as this is the most intuitive. This would require some minor adjustments to the model. Note that adding profit to the calculation, invalidates the interpretation of the break even net present values.

10.4. Recommendations on market analysis

To differentiate in a highly competitive market one should either provide a better and more comprehensive service or be cheaper than the current options. In the decommissioning market it is clear that the emphasis lies on the cost aspect of decommissioning operations. It is therefore crucial to be able to provide an alternative to heavy lifting which is significantly cheaper than the current removal options. For this reason the 35% cost reduction goal of the Oil and Gas Authority is taken as the absolute benchmark in this report.

For further market analysis, it is recommended to find more data on the time variable of decommissioning. The current market size presented in this research now only takes jackets older than 35 years into consideration. The market analysis is done with all installed jacket, regardless of their age. From close out reports it becomes clear that the age of the jacket does not necessarily define their decommissioning schedule. Some jackets as young as five years are already decommissioned, while other jackets installed the in 70's are still in place. Getting a hold on the decommissioning timeline would definitely be a huge advantage in this sector.

Finally it is recommended to reiterate the market analysis once the versatility range of the buoyancy concept is known. From this research it shows that 8,200 MT is the optimal size for an unknown versatility range, but once the concept's achievable versatility range is defined precisely, a more optimal design size can be found. Reiterating the market analysis with a fixed versatility range may result in a different, more ideal buoyancy size. By running the analysis once more, the most economical option can be chosen. As stated before, design is an iterative process.

A

OSPAR Inventory of Offshore Installations

A.1. OSPAR Database

The OSPAR offshore installations database can be delivered digitally, or retrieved from `https://odims.ospar.org/odims_data_files/`.

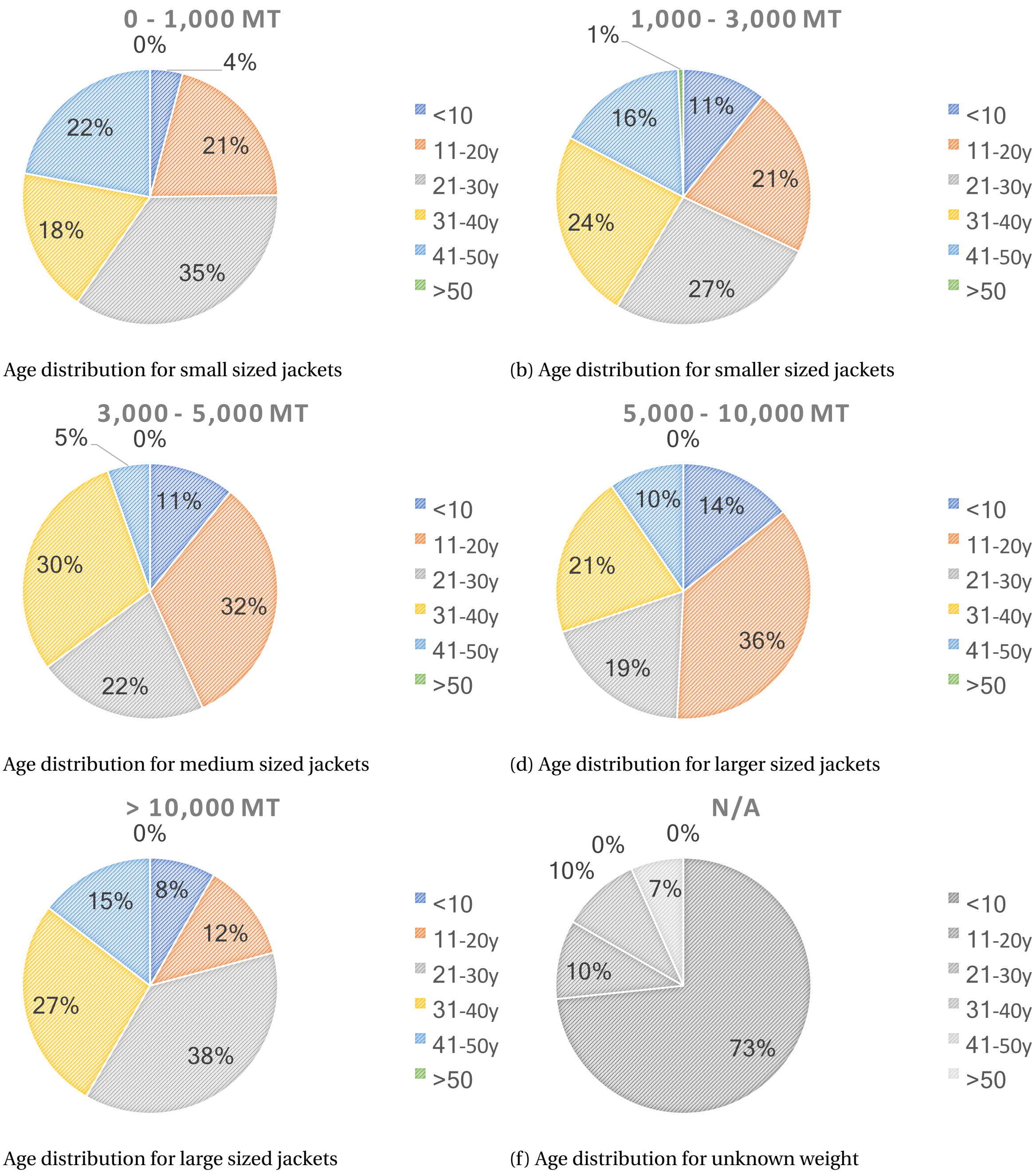
A.2. Age distribution for different sized fixed steel jackets

	Age [years]						
Weight [MT]	<10	11 - 20	21-30	31-40	41-50	>50	Total
>10,000	4	6	18	13	7	0	48
0-1,000	9	45	76	40	48	0	218
1,000-3,000	16	32	40	36	25	1	150
3,000-5,000	4	12	8	11	2	0	37
5,000-10,000	9	23	12	13	6	0	63
N/A	22	3	3	0	2	0	30
							546

Table A.1: The absolute number of fixed steel jackets in the North Sea filtered by weight and age (data from OSPAR)

	Age [years]						
Weight [MT]	<10	11 - 20	21-30	31-40	41-50	>50	Total
>10,000	8,33%	12,50%	37,50%	27,08%	14,58%	0,00%	100%
0-1,000	4,13%	20,64%	34,86%	18,35%	22,02%	0,00%	100%
1,000-3,000	10,67%	21,33%	26,67%	24,00%	16,67%	0,67%	100%
3,000-5,000	10,81%	32,43%	21,62%	29,73%	5,41%	0,00%	100%
5,000-10,000	14,29%	36,51%	19,05%	20,63%	9,52%	0,00%	100%
N/A	73,33%	10,00%	10,00%	0,00%	6,67%	0,00%	100%

Table A.2: The percentage of age for each weight group of fixed steel jackets in the North Sea (data from OSPAR)



(a) Age distribution for small sized jackets

(b) Age distribution for smaller sized jackets

(c) Age distribution for medium sized jackets

(d) Age distribution for larger sized jackets

(e) Age distribution for large sized jackets

(f) Age distribution for unknown weight

Figure A.1: Age distribution for different weight groups of fixed steel jackets in the North Sea (data OSPAR). Especially the very small (< 1,000 MT) and very large structures (> 10,000 MT) are relatively old and will be brought up for decommissioning soon.

B

MATLAB R2017b script for the market assessment

```
%% Afstuderen
clear all
close all
clc
plotON=1; % Turns on all plots if 1
%% Load OSPAR database
filename='OSPAR.xlsx';
OSPARdata=xlsread(filename);
Weight=OSPARdata(:,4);
Waterdepth=OSPARdata(:,8);
Age=OSPARdata(:,12);
OSPAR=[Weight, Waterdepth, Age];
%% Load HLV databe
filename='HLV.xlsx';
HLVdata=xlsread(filename);
h=length(HLVdata);
j=1;
for i=1:h
    if HLVdata(i,13)==1
    HLV(j)=HLVdata(i,9);
    j=j+1;
    end
end
%% Assumptions
MG=0.3; %Weight increase due to marine growth, piles and grout and conductors/risers
% Derogation is not any longer taken into account. See report.
%% Calculating jacket scores
N=length(Weight);
JS=zeros(N,2);
JS(:,1)=Weight;
for i=1:N
    Cmin=Weight(i)*(1+MG);
    countHLV=nnz(HLV>Cmin);
    if countHLV==0
        JS(i,2)=Inf;
    else
    JS(i,2)=countHLV;
    end
end
if plotON==1
    hold on
```

```
scatter(JS(:,1),JS(:,2))
histogram(JS(:,1),200)
set(gca,'FontSize',20)
xlabel('Jacket weight [MT]')
ylabel('Number of heavy lift solutions [-]')
xlim([0 16000])
end
%% Define lower range of jackets considered
Jmin=3000; %distilled from previous graph
Jmax=max(Weight);
%% Define range
WR=0.25; % Win-rate: at biddings KPI from Ardent
NP=4; % Number of Projects: Minimum number of projects to make it profitable, provided by Ardent
RN=NP/WR; % Required amount of FSJ
%% Find minimum and maximum range
range_min=0;
step=100;
n=0;
while n==0
    range_min=range_min+step;
    for i=Jmin:step:Jmax
    count=nnz(Weight>i & Weight<i+range_min);
    if count>RN
        n=1;
    end
    end
end
%% Max range definition
range_max=3000;
%% Market analysis example
ncolors=round((range_max-range_min)/step+1);
    col=hsv(3);
    k=1;
    sz=150;
for range=[500, 1500, 3000]
    j=1;
    clear ratio ratiopeak
for i=Jmin:step:Jmax
        Cmin=i*(1+MG);
        jamax=i+range;
        Cmax=jamax*(1+MG);
    countFSJ=nnz(Weight>i & Weight<jamax);
    if countFSJ>RN
    countHLV=nnz(HLV>Cmin);
    RR=countFSJ./countHLV;
    ratio(j,:)=[Cmax RR];
    j=j+1;
    end
end
h=length(ratio)-2;
if exist('iratio')==1
n=length(iratio);
else
    n=0;
end
m=1;
if h<7
    [M,I]=max(ratio(:,2));
    ratiopeak(m,2)=M;
    ratiopeak(m,1)=ratio(I,1);
```

```
else
for q=3:h
if ratio(q,2)>ratio(q-1,2) && ratio(q,2)>ratio(q+1,2) && ratio(q,2)>ratio(q-2,2) && ratio(q,2)>ratio(q+2,2)
    ratiopeak(m,:)=ratio(q,:);
    iratio(n+m,:)=ratio(q,:);
    m=m+1;
end
end
end
if plotON==1
        figure(2)
h1=scatter(ratio(:,1),ratio(:,2),sz,col(k,:));
hold on
h2=scatter(ratiopeak(:,1),ratiopeak(:,2),sz,col(k,:),'filled');
end
k=k+1;
end
edges = unique(iratio(:,1));
counts = histc(iratio(:), edges);
n=length(edges);
j=1;
if plotON==1
        figure(2)
        set(gca,'FontSize',20)
xlabel('Buoyancy capacity [MT]')
ylabel('Number of jackets per heavy lift competitor [-]')
xlim([Jmin inf])
legend('500 MT','Local optimum','1,500 MT','Local optimum','3,000 MT','Local optimum')
hold off
end
%% Market analysis 2
ncolors=round((range_max-range_min)/step+1);
    col=hsv(ncolors);
    k=1;
    sz=25;
for range=range_min:step:range_max
    j=1;
    clear ratio ratiopeak
for i=Jmin:step:Jmax
        Cmin=i*(1+MG);
        jamax=i+range;
        Cmax=jamax*(1+MG);
    countFSJ=nnz(Weight>i & Weight<jamax);
    if countFSJ>RN
    countHLV=nnz(HLV>Cmin);
    RR=countFSJ./countHLV;
    ratio(j,:)=[Cmax RR];
    j=j+1;
    end
end
h=length(ratio)-2;
if exist('iratio')==1
n=length(iratio);
else
    n=0;
end
m=1;
if h<7
    [M,I]=max(ratio(:,2));
    ratiopeak(m,2)=M;
    ratiopeak(m,1)=ratio(I,1);
```

```
else
for q=3:h
if ratio(q,2)>ratio(q-1,2) && ratio(q,2)>ratio(q+1,2) && ratio(q,2)>ratio(q-2,2) && ratio(q,2)>ratio(q+2,2)
    ratiopeak(m,:)=ratio(q,:);
    iratio(n+m,:)=ratio(q,:);
    m=m+1;
end
end
end
if plotON==1
        figure(3)
scatter(ratio(:,1),ratio(:,2),sz,col(k,:))
hold on
scatter(ratiopeak(:,1),ratiopeak(:,2),sz,col(k,:),'filled')
end
k=k+1;
end
edges = unique(iratio(:,1));
counts = histc(iratio(:), edges);
n=length(edges);
j=1;
for i=1:n
    if counts(i) > ncolors/3
        vertpeak(j)=edges(i);
        j=j+1;
    end
end
if plotON==1
    for i=1:length(vertpeak)
        xval=vertpeak(i);
        plot([xval xval],ylim,'color','k')
        txt=num2str(vertpeak(i));
        text(xval,6+i,txt,'Fontsize',20);
        hold on
    end
end
if plotON==1
        figure(3)
        set(gca,'FontSize',20)
xlabel('Buoyancy capacity [MT]')
ylabel('Number of jackets per heavy lift competitor [-]')
xlim([Jmin inf])
hold off
end
%% Smallest range for which a 8,200 MT buoyancy device works
BC=vertpeak;
Jmax=BC/(1+MG);
range_min=0;
n=0;
steps=10;
if BC==0
else
while n==0
    range_min=range_min+steps;
    Jmin=Jmax-range_min;
    count=nnz(Weight>Jmin & Weight<Jmax);
    if count>RN
        n=1;
    end
end
end
```

C

Dismantling yards

Name	Location	Country	Status	Acreage [ha]	Water depth [m]	quayside [m]	quay load [t/m2]	Scrapping capacity [t/yr]
Able Humber port	Humber	UK	Potential	No Data	17,5	1389	60	No Data
AF Environmental Base	Vats	NO	Operational	12	23	182	10,2	25000
AKD Engineering	Suffolk	UK	Existing	No Data	No Data	90	No Data	No Data
Ardersier	Moray Firth	UK	Potential	No Data	No Data	1150	No Data	No Data
Ardyne Point	Loch Striven	UK	Potential	No Data	No Data	No Data	No Data	No Data
Dales Voe	Shetland	UK	Existing	4,5	12,5	127	60	No Data
Damen Verolme	Rotterdam	NL	Existing	18	12	1850	10	100000
Eastport UK	Great Yarmouth	UK	Operational	1,5	10	1000	No Data	No Data
Harland and Wolff	Belfast	UK	Operational	30	6,4	1900	5,4	50000
Hoondert	Vlissingen	NL	Operational	3,5	7	200	10	No Data
Invergordon Service base	Invergordon	UK	Under construction	3,7	12	154	7,5	No Data
Kishon port	Kishorn	UK	Potential	26	8	160	10	No Data
Kvaerner	Stord	NO	Existing	7	16	620	No Data	No Data
Lewick Greenhead base	Shetland	UK	Operational	7,5	9	150	No Data	25000
Lutelandet	Lutelandet	NO	Operational	30	21	60	200	500000
Lyness and Golden Wharfs	Lunes Hoy Orkney	UK	Potential	30	7	160	5	No Data
Lyngdal Recycling	Vest Agder	NO	Potential	No Data	No Data	No Data	No Data	No Data
Montrose port	Montrose	UK	Potential	1,4	5	163	7,5	No Data
Nigg Energy Park	Moray Firth	UK	Existing	96	No Data	No Data	No Data	No Data
NorSea Group	Peterhead	UK	Under construction	1,6	7,5	400	No Data	No Data
North Sea Base Port	Thyboron	DN	Potential	15	No Data	No Data	23	No Data
Offshore Terminal Bremerhaven	Bremerhaven	DE	Potential	25	10,5	500	No Data	No Data
Port of Dundee	Dundee	UK	Existing	2,2	8,5	240	5,5	1000
Scandinavia Metal	Stord	NO	Existing	3,5	No Data	No Data	No Data	No Data
Scheepssloperij Nederland	s Gravendeel	NL	Operational	4	6	250	10	40000
Semco Marine & Hellig Teigen	Hanoytangen	NO	Existing	65	17	125	No Data	No Data
Smith Quay	Peterhead	UK	Potential	1,6	10	200	5	No Data
Stena Recycling AS Offshore	Stavanger	NO	Existing	2,2	25	300	No Data	No Data
Swan Hunter	Newcastle upon Tyne	UK	Potential	7	8,5	240	15	No Data
Teesside Seaton Port	Hartlepool	UK	Operational	51	9,5	306	40	300000

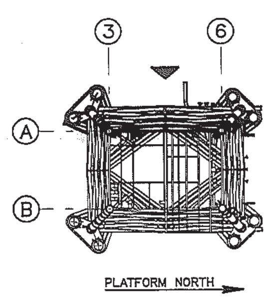
Figure C.1: A list of operational dismantling yards, existing yards and potential dismantling yard locations, all bordering the North Sea

D

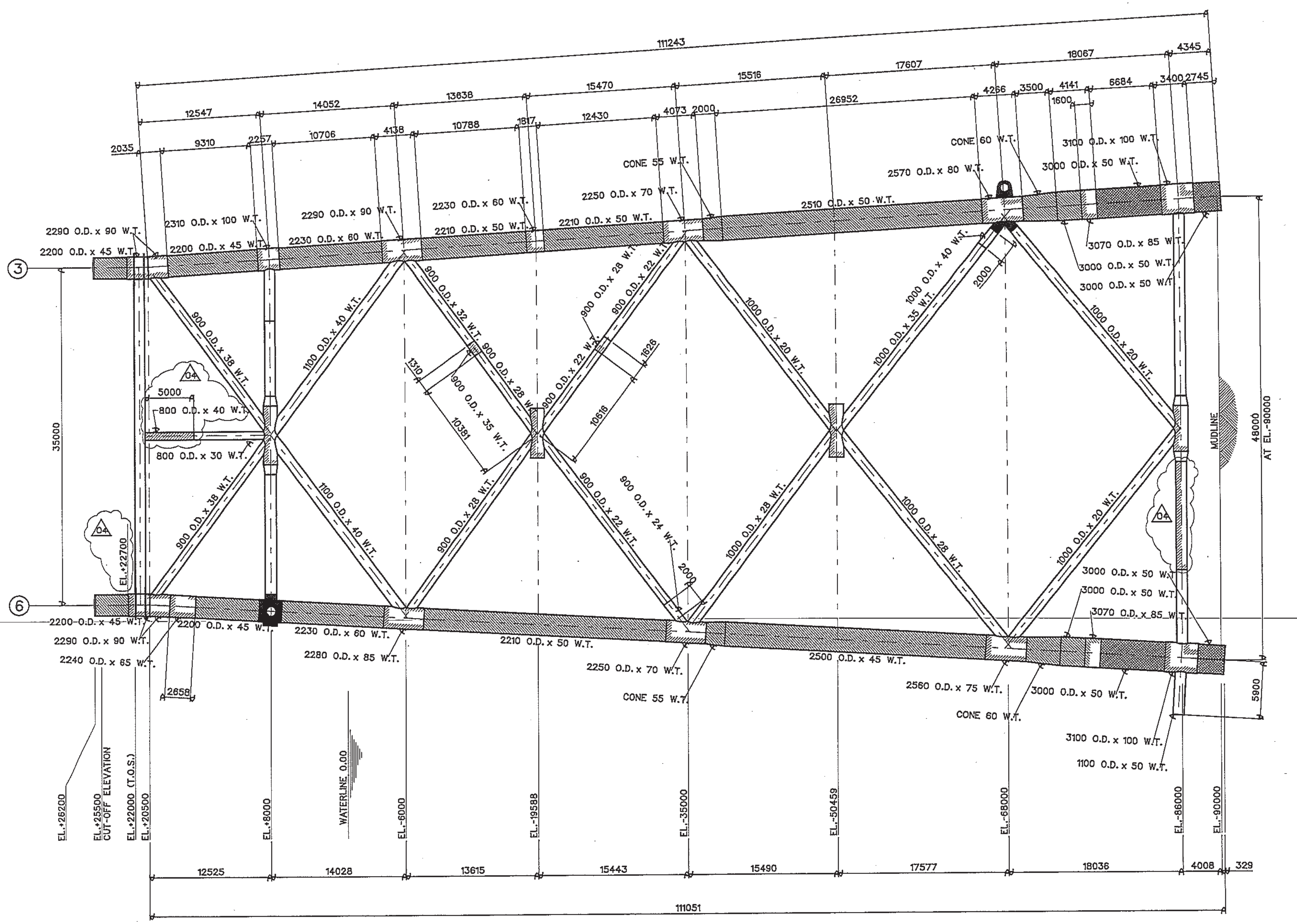
Example jackets as-built drawings

D.1. Shearwater C platform jacket

KEYPLAN



1. FOR GENERAL NOTES SEE DWG SW-S-34200-01.
2. INDICATES CAST ITEM.
3. SEE DRAWING SW-S-34211 FOR CAN AND STRAKE LENGTHS FOR LEG A6 U.N.O.



ROW A
(IN PLANE OF MEMBERS)

GRAPHIC SCALE 1:200 — 0 4 8 12 16 20 24 M

FOR CONSTRUCTION	
DATE: 25-7-97	REV. C1

DRAWING NUMBER	DRAWING TITLE
REFERENCE DRAWINGS	

REV	ISSUE DATE	DESCRIPTION OF REVISION	DRAWN BY	CHKD BY	APPD BY
C4	18-01-98	REVISED AS INDICATED	x	P	x
C3	24-9-97	REVISED AS INDICATED	NdV	P	x
C2	22-8-97	REVISED AS INDICATED	x	P	x
C1	25-7-97	FOR CONSTRUCTION	x	P	x
R1	21-3-97	FOR INFORMATION	x	P	[illegible]

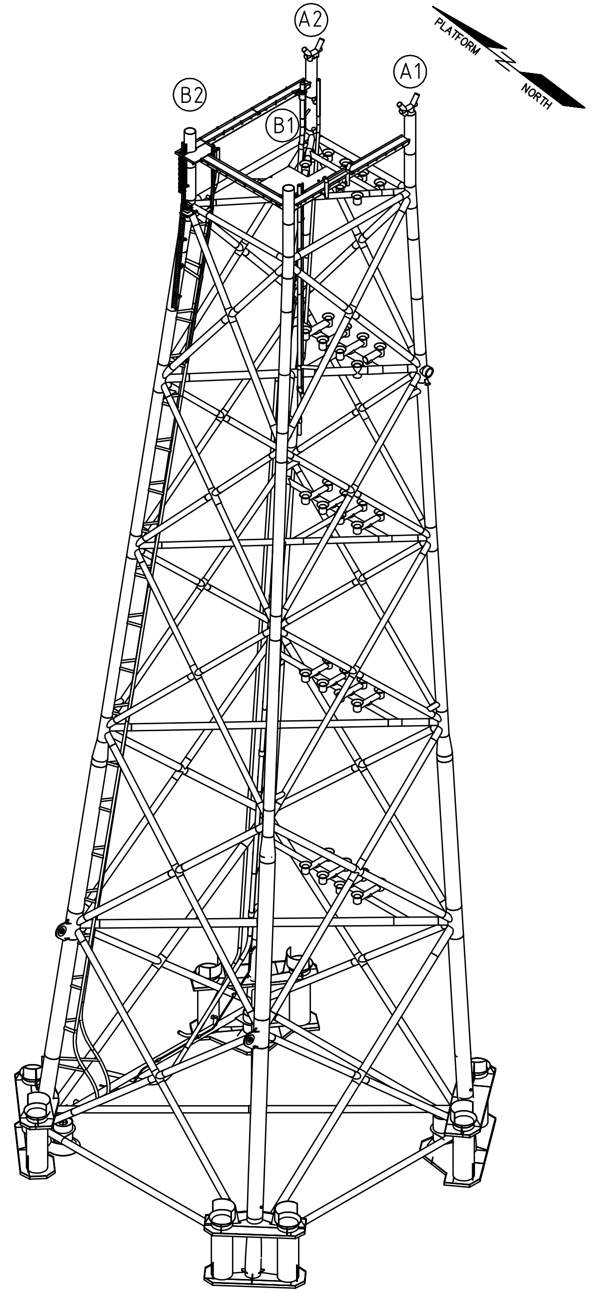
SHEARWATER DEVELOPMENT ALLIANCE

TITLE

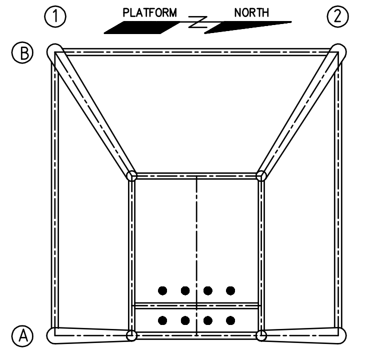
SHEARWATER C
JACKET ELEVATION AT ROW A

AREA CODE	SCALE 1:200	
DRAWING NUMBER SW S 34210	SHEET 01	REV C4

D.2. Goldeneye platform jacket



ISOMETRIC VIEW



COMPOSITE PLAN

WEIGHT/VEKT:

NOTES:

1. THIS DRAWING INCLUDES TEMPORARY ITEMS (WALKWAYS , PLATFORMS AND BRIDGE LANDING.)

REF. NO	SHOP DRAWING	DESIGN DRAWING
x		

REFERENCE

REV	ISSUE DATE	DESCRIPTION	REF. NO	DRAWN BY	RESP. ENG.	CHK'D BY	APPR. BY
C02	28.11.2002	RE-ISSUED FOR CONSTRUCTION		NCAa	TKT	AO	ØR
C01	25.09.2002	ISSUED FOR CONSTRUCTION		NCAa	TKT	AO	ØR
R01	08.05.2002	ISSUED FOR START DETAIL ENG.		NCAa	AO	TKT	ØR

AKER KVÆRNER

SHELL UK EXPLORATION & PRODUCTION

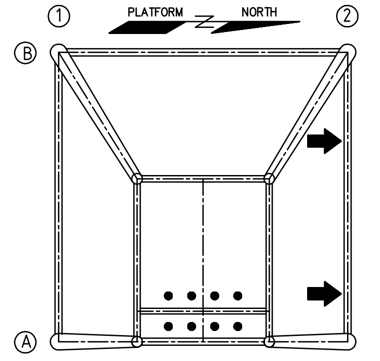
- SECTION NO.		DE-0003-01 CADFILE NAME	
N DISC. CODE	INFO TYPE	- AREA CODE	FUNC. CODE
1:600 SCALE	A3 SIZE	SYSTEM CODE	ORG. CODE

Goldeneye Jacket

GENERAL ARRANGEMENT ISO

DOCUMENT NO	SHEET	REV	STATUS
GOL-31-7009-AV-DE-0003	01	C02	

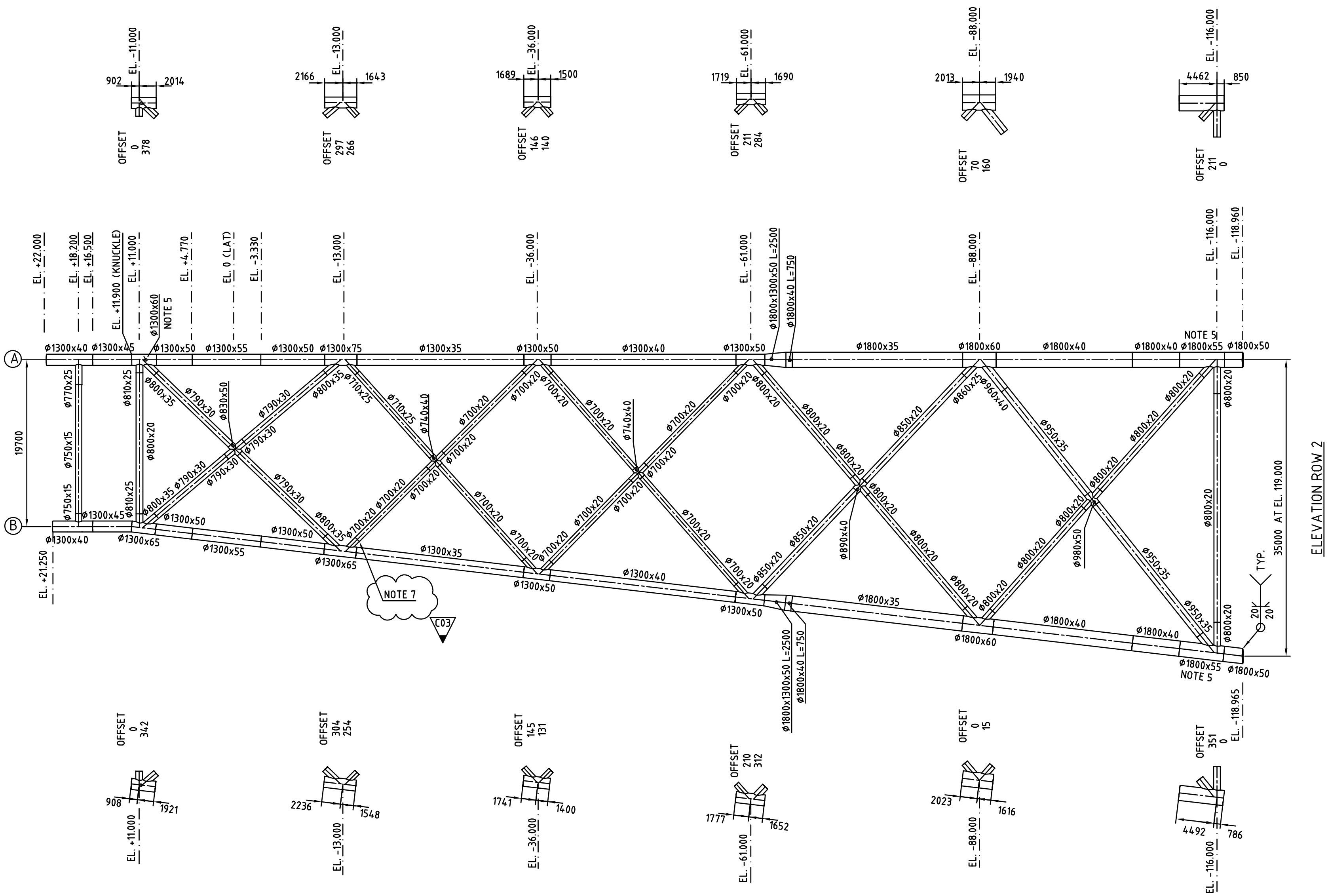
DRAWN BY/TELEPHONE XXXXXXXX XXXXXXXXXX Tel: XXXXX



WEIGHT/VEKT:

NOTES:

1. FOR GENERAL NOTES AND STANDARD ABBREVIATIONS SEE DRG.: GOL-31-7009-AV-DE-0002
2. FOR WELD DETAILS SEE DRG.: GOL-31-7009-AV-DE-0008
3. MATERIAL: GOL-Y30 (S420 Z)
4. OFFSETS AND LENGTHS ALONG CENTRELINE OF LEG.
5. f_y=405 MPa FOR TWO ϕ1800x55 AND ONE ϕ1300x60 LEG SECTIONS
6. STUBS TO LEGS : SINGLE SIDED FULL PENN. WELDS.
7. THE 15 HIGHEST FATIGUE UTILISED STUB TO BRACE WELDS TO BE UT EXAMINED TWICE , BY DIFFERENT UT OPERATORS. C03



x		
REF. NO	SHOP DRAWING	DESIGN DRAWING
REFERENCE		

REV	ISSUE DATE	DESCRIPTION	REF. NO	DRAWN BY	RESP. ENG.	CHK'D BY	APPR. BY
C03	24.04.2003	RE-ISSUED FOR CONSTRUCTION		NCAa	TKT	AO	ØR
C02	06.09.2002	ISSUED FOR CONSTRUCTION		NCAa	TKT	AO	ØR
C01	14.06.2002	ISSUED FOR MTO		MR	TKT	AO	ØR
R01	08.05.2002	ISSUED FOR START DETAIL ENG.		NCAa	AO	TKT	ØR

AKER KVÆRNER

SECTION NO.: -		CADFILE NAME: DE-1004	
DISC. CODE: N	INFO TYPE	AREA CODE: -	FUNC. CODE
SCALE: 1:500	SIZE: A3	SYSTEM CODE	ORG. CODE

SHELL UK EXPLORATION & PRODUCTION

Goldeneye Jacket

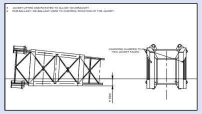
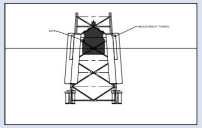
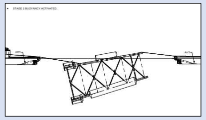
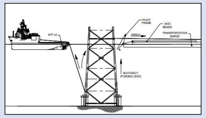
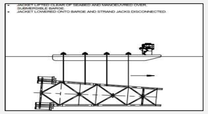
GENERAL ARRANGEMENT
ELEVATION ROW 2

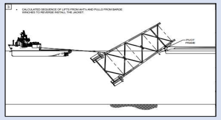
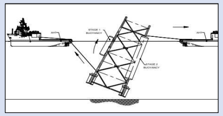
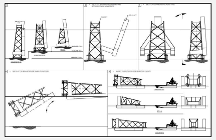
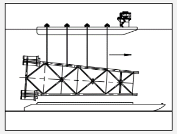
DOCUMENT NO	SHEET	REV	STATUS
GOL-31-7009-AV-DE-1004	01	C03	

DRAWN BY/TELEPHONE XXXXXXXX XXXXXXXXXX Tel.: XXXXX

E

Buoyancy lifting concepts SWOT analysis

Method		Concept	Sketch	Thumbnail	Strengths	Weaknesses	Opportunities	Threats	Comment
1. FLOAT	a	**EBC (External Buoyancy Caisson)**	P0129-SKE-0001-01		• Self-contained system (field to port) • No additional seafastening for transit • Modular to suit range of jacket types / sizes	• Most buoyancy required to rotate only • Additional buoyancy required to compensate for weight of caisson's • Storage & maintenance costs (OPEX) • Jacket interface challenges(clamp. cleaning etc.)	• Diverless method • Potential for innovative and cost effective (in comparison to traditional HLVs) approach	• Partially unproven technology Any patent / IP issues? • Handling at inshore/onshore facility complex • Large CAPEX expenditure • Long lead time (design & build) • High mob. / Demob cost	• Ardent in-house solution • Jacket Integrity Check
	b	**Frigg Buoyancy Caisson**	P0129-SKE-0002-01		• Proven method for vertical recovery in deep water	• Only suitable for vertical tow • Requires deep water port i.e. fjord; for onshore handling	• Lessons Learnt from Frigg decom • Caissons available for sale • Diverless method	• Patents in place • Handling at inshore/onshore facility complex	• Why has this method only been used once? What were the lessons from previous decom?
	c	**Inflatable Buoyancy (Marine Salvage Air Bags, Inflatable Pontoons / launching airbags)**	P0129-SKE-0009-01		• Proven technology • Cost effective solution • Redundancy due to quantity in event of local damage • Modular to suit range of jacket types / sizes • No additional seafastening for transit	• Time to install • Air control complicated? • Safety aspects of installation / transit and potential to break loose • Additional handling at inshore/onshore facility • Weather limitations on tow. • Limited jacket weight capabilities.	• Yokohama's / pontoons constructed with tough exterior suitable for impact / chafing • ROV installable (Diverless)	• Bespoke sizes and construction likely available? • Territory for "cheap" conventional HLV • Air control complications?	• ROV installable? • Safety aspects of installation? • Bespoke options available? • Jacket integrity check?
	d	**Purge / dewater Jacket legs / members**			• Substantial buoyancy available within existing structure • Tubular plugging technology existing. downhole plugs, cement, gels, pile plugs etc.	• Piles / grout / debris in legs could cause complications / obstructions. • Not an independent solution, requires additional mechanism to recover to suitable draught for port access.	• Good option in combination with other methods, e.g. toppling, top & tail, Deltalifter, etc. • Flooded Member Detection (FMD) survey possible to assess member integrity	• Poor / unknown condition jackets (perforated members) • Timeline for preparation (inspection etc.)	Method not considered for further analysis at this time
	e	**Top & Tail with transport barge and 2-off AHT's (reverse install)**	P0129-SKE-0003-01		• Proven technology • Transit and off-loading standard practice • Weather limitations not overly sensitive.	• Multiple vessel/asset operation • DP2 or anchored barge required as vessels working in close proximity	• Good availability of assets	• Extended weather window to include barge securing • Possible jacket weight limitation / practicality's. AHT winch capacity	• Approximate winch loads /bollard pulls? • Jacket installation method influence? • Could semi-sub barge minimise jacket steel out of water • Jacket integrity check?
2. LIFT	a	Single vessel c/w strand jacks	P0129-SKE-0008-01		• Proven technology (Kursk / Sewol recovery) • Potential low cost option • May suit DP class HLTV type vessels, e.g. SAL Lone • Standard strand jack equipment (depending on depth)	• Full recovery only feasible if fully submerged barge is feasible - ONLY TO BE CONSIDERED IF JACKET IS TO BE REEFED INSTABLE ..	• Good alternative for Rig to Reef projects	• Process used for Kursk recovery but less suitable for jackets dewater depth and inshore processing.	• Jacket integrity check? • Confirm availability of semi-sub barges? • AHC strain jacks required, check availability / complexity?
	b	Two barge lift and semi submersible barge c/w strand jacks	P0129-SKE-0006-01		• Proven technology (Kursk / Sewol recovery) • Good availability of assets • Transit and off-loading standard practice • Extended weather window to include barge securing • Method suits a wide range of jacket types / sizes	• Multiple vessel/asset operation • DP2 or anchored barge required as vessels working in close proximity • Weather wind to included barge securing • Access to lower chords of jacket required, could be embedded in seabed. • Potential clash of sheaves and top chord of jacket to be managed	• Good alternative for Rig to Reef projects	• Process used for Kursk recovery but less suitable for jackets dewater depth and inshore processing.	• Jacket integrity check? • Confirm availability of semi-sub barges? • AHC strain jacks required, check availability / complexity?

Method		Concept	Sketch	Thumbnail	Strengths	Weaknesses	Opportunities	Threats	Comment
3. FLOAT & LIFT	a	**Combination of buoyancy, AHT's and transport barge to reverse install**	P0129-SKE-0003-01 P0129-SKE-0004-01		• Proven technology • Transit and off-loading standard practice • Good availability of assets • Modular to suit range of jacket types / sizes	• Multiple vessel/asset operation • Barge needs anchoring system • DP2 or anchored barge required as vessels working in close proximity	• Weather limitations not overly sensitive.	• All forces acting in favour during launch, will naturally be acting against during recovery (gravity / friction etc) • Extended weather window to include barge securing	• Approximate winch loads /bollard pulls / buoyancy etc. • Jacket installation method influence? • Could semi-sub barge minimise buoyancy? • Jacket integrity check?
	b	**Combination of buoyancy and AHT's to float / rotate / tow**	P0129-SKE-0005-01		• Proven technology • Good availability of assets • Modular to suit range of jacket types / sizes • No additional seafastening for transit	• Handling at inshore/onshore facility complex (deep draft requirements) • Weather limitations on tow.	• Weather limitations not overly sensitive. • Potentially cost effective method	• CAPEX expenditure for buoyancy (if steel tanks) • Buoyancy tanks required for turning(assuming insufficient bollard pull) and more buoyancy to float the jacket.	• Approximate bollard pulls / buoyancy etc. • Jacket integrity check?
4. VESSELS	a	**Delta Lifter**	P0129-SKE-0007-01		• Self-contained system (Field to port solution) • Transit and off-loading standard practice • No additional seafastening for transit	• Risk of outer skin puncture if grounded on seabed? • Storage / maintenance due to large footprint, high OPEX • Port access due to width • Regional transit costs • Barge needs support vessels for anchoring / deployment / tow • Water depth between 60m and 120m • Jacket width restricted by pontoon geometry	• Potential for multiple use; installation projects, e.g. - Jackets; - Wind farms; - Monopods, etc. • Basic structure i.e. no engines / moorings etc Ballasting equipment only supply vessel TBC?	• Unconventional / new technology Any patent / IP issues? • Large CAPEX expenditure • Single sourcing (patented) • Limited versatility i.e. jackets size limited to greater than 4000Te and less than 8200Te	• Weather window TBC? • Single skin or double skin? • Ballasting equipment onboard? • Patent details?
	b	**Versabar**	-		• Proven method for jacket recovery in the G.o.M	• Weather restricted / suitable for benign waters • High mob/demob costs, slow speed transit to other regions.	• Potential for a MkII system based in another region (e.g. SE Asia)	• Concept dependant on specific asset, which resides in GoM.	• Anticipate similar disadvantages to conventional HLV's
	c	**Fully Submersible Barge**	P0129-SKE-0008-01 (Variation)		• All complicated lift activities to be kept close to seabed • Stable platform for lift, lower and transit jacket • Only one additional vessel c/strand jacks (Kursk vessel / system) • Simple structure i.e. no engines / moorings etc Ballasting equipment on supply vessel • Transit and off-loading standard practice • Method suits a wide range of jacket types / sizes • Clamps can be pre-installed to provide stability and seafastening, hence no additional seafastening for transit	• Current models limited to 12/15m water depth hence new build / modification / CAPEX • Jacket needs to be toppled • Barge needs support vessels for anchoring - UNSTABLE !! (no water plane area)	• Potential for other types of Subsea decommissioning, e.g. - Large manifolds, seabed templates; - Bundles, exposed pipelines (multi-cut & recover); - Mattresses, etc. • Proven technology? • Weather limitations not overly sensitive. • Multipurpose asset	• Risk of outer skin puncture if grounded on seabed • Existing semi-subs normally used in sheltered waters or under strict weather criteria	• Is a fully submersible barge possible i.e. to seabed? • Remote ballasting from vents / downlines? • Can semi-subs work offshore, environmental limitations? • Practicalities of water depth / strengthening? • Positive pressurisation (risky)? • Double skin to minimise strengthening requirements? • Clamps could be installed for fast seafastening /stability during surfacing? • Proven technology (jackets recovered with barges upended then ballasted, small scale)?
	d	**Self Propelled Jack-up Rigs**			• Cost effective – low day rate, regional availability; • Stable work platform; • Potential walk-to-work solution; • Large main deck for in-field preparation, and or self-transhipment to shore.	• Max. lift capacity <1200Te,therefore unsuitable for jackets considered in the scope of study	• Untapped potential for using this asset type for decommissioning, especially for smaller, shallow water Jackets. • Potential for use as a platform for P&A activities.	• Availability in buoyant market	
5. DECOMPOSITION	a	**Corrosion acceleration**	-		Minimal intervention? (Would there be a significant campaign of preparation i.e. equipment securing to a large number of members etc.?)	• Unconventional approach • Continual monitoring campaign • Similar to reefing, which is out with scope. Too many environmental questions marks.		• Structure partially decomposes, leading to requirement to recover jacket with significant integrity issues	Method not considered as Safety risks, Environmental Risks, ongoing liability to the Operator etc. are of significant concern

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