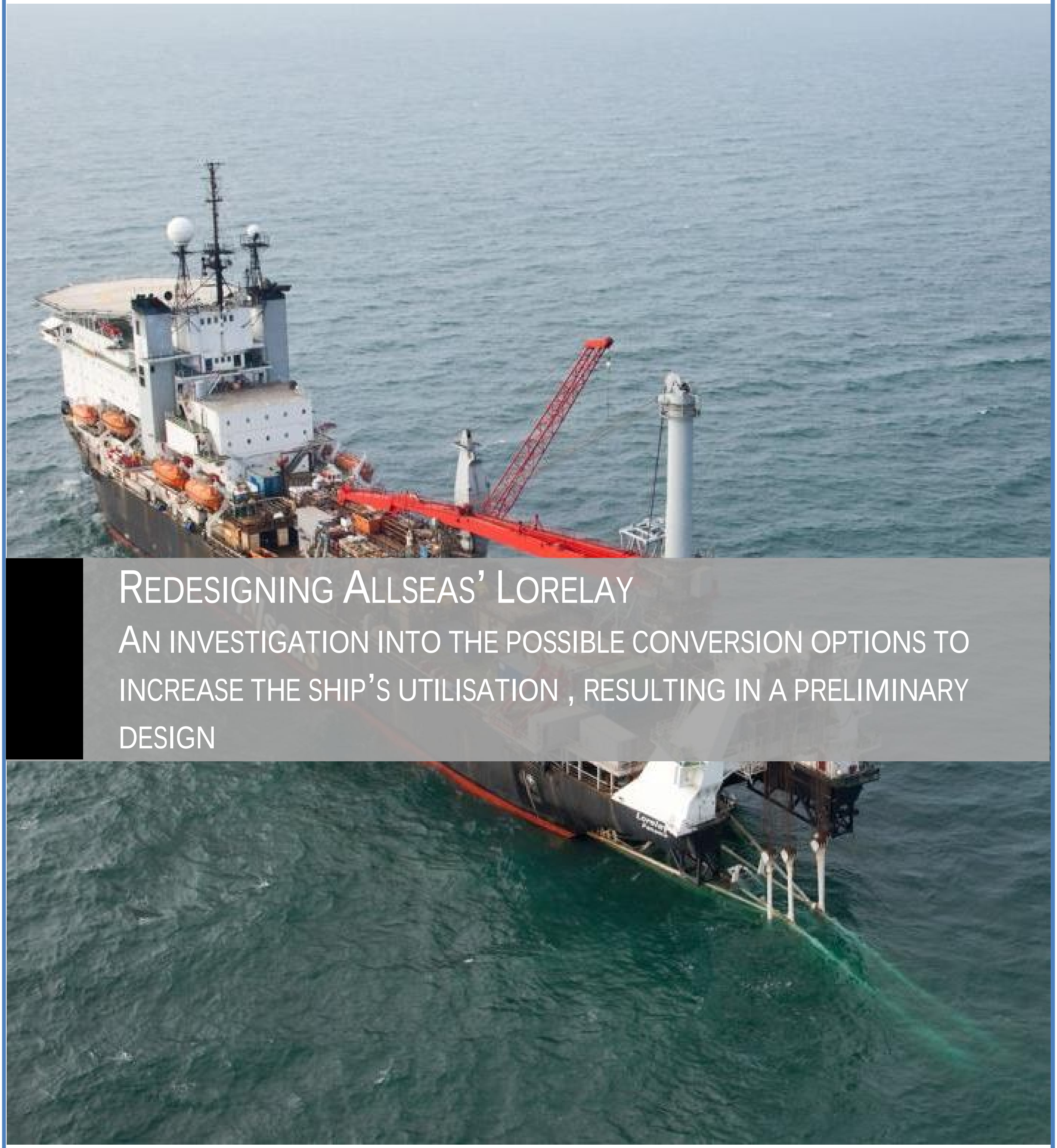
Redesigning Allseas' Lorelay

An investigation into the possible conversion options to increase the ship's utilisation , resulting in a preliminary design



Carmen Kooij
18 May 2017

Thesis for the degree of MSc in Marine Technology in the specialization of *Ship Design*

Redesigning Allseas' Lorelay
An investigation into the possible conversion options to increase the ship's utilisation, resulting in a preliminary design

By

Carmen Kooij

Performed at

Allseas Engineering BV

This thesis SDPO.17.008.m is classified as confidential in accordance with the general conditions for projects performed by the TU Delft.

18-05-2017

Company supervisors
Responsible supervisor: Marijn Dijk
E-mail: *MDij@Allseas.com*
Daily Supervisor(s): Stijn Nauta
E-mail: *SNa@Allseas.com*

Thesis exam committee
Chair/Responsible Professor: Hans Hopman
Staff Member: Robert Hekkenberg
Staff Member: Dingena Schott
Company Member: Marijn Dijk
Company Member: Stijn Nauta

Author Details
Studynumber: 1539698
Author contact e-mail: *carmen.kooij@gmail.com*

ABSTRACT

In the last year Allseas' *Lorelay* has had very little work. Due to a bad market, very little available projects and heavy competition the ship has laid idle for the better part of the year. Allseas is wondering how the utilisation of the ship can be increased without losing her pipe laying capabilities.

This question is reworked into the following research question:
Which task or refit possibility shows the most promise in improving the utilisation of the Lorelay*?*

To answer this, three sub-questions have been set up:

a) In which markets can an improvement of the *Lorelay's* utilisation be found?
b) Within the chosen direction, which tasks could the *Lorelay* perform?
    a. What capabilities should the ship possess to perform this task?
c) Which of the created concepts shows the most merit based on several decision criteria and under specific circumstances?

To answer these questions a literature study is conducted and experts are interviewed.

There are three possible directions in which a solution for *Lorelay's* utilisation problem can be found. The first possibility is increasing the pipe laying capabilities of the ship. However, since there is no significant amount of work for Allseas' larger vessels either, these changes are deemed unfavourable. The second option is expanding within the known markets, either the subsea installation market of which pipe laying is a sub section or the heavy lift market. In both of these markets there is a multitude of tasks that are currently performed by competitors or subcontractors. Many of these tasks could also be performed by the *Lorelay.*

The final option is to enter a completely new market. There are many markets in which some of the current capabilities of the *Lorelay,* such as her crane or het DP-system, could be an asset. However, research into these tasks showed that there are also many differences between the requirements for these tasks and the capabilities of the *Lorelay.* These differences could mean that the *Lorelay* loses her pipe laying capabilities in the conversion.

Therefore the solution to increasing *Lorelay's* utilisation is found in the subsea installation market or the heavy lift market.

The next step is to identify the different tasks that the *Lorelay* could perform within the two identified markets. By looking into company data as well as performing a literature study, a list of potential tasks that could be performed by the *Lorelay* is created.

This overview of potential tasks leads to seven potential concepts:

1. Installation of jumpers, spools and structures (Small refit)
2. Installation of jumpers, spools and structures (Large refit)
3. Allow for the installation of flexible pipelines and risers as well as rigid pipelines and risers by converting the ship to a reel-lay vessel
4. Cable laying
5. Precommissioning
6. Heavy lift support
7. A combination of all options mentioned above, by creating a modular ship

Additionally several of these concepts consist of multiple alternatives, due to the addition of smaller tasks or different approaches for the same task.

To make a decision on which concept to use in the conversion of the *Lorelay* a Multi Criteria Decision Analysis (MCDA) is performed. MCDA is a collective name for different methods to solve problems where several options are compared based on several criteria. For this decision process the Analytical Hierarchy Process (AHP) is chosen as the most suitable method.

The AHP makes use of pairwise comparison and multiple criteria to find the best solution. The criteria used in this analysis are:

- Size of the refit
    - Time; the estimated time it takes to complete the conversion of the ship. In this period the ship cannot make any money.
    - Cost; the estimated cost for the conversion.
- Market size; the estimated number of available contracts, and their size in the new market.

- Competitiveness; the new capabilities compared to the capabilities of the competitors within this market.

All the concepts are compared to each other via pairwise comparison on all four criteria. It is possible to assign weights to each of the criteria to show which criterion is the most important. Using this ability, three scenarios were created to simulate different market states. The three scenarios are the current market state, an improving market and a declining market.

The calculations for these scenarios result in two outcomes. For the declining market any investment is deemed undesirable. Therefore it is suggested to wait for the market to improve again before investing money in the *Lorelay.*

For the current market and the improving market it is concluded that converting the *Lorelay* into a vessel that can perform all of the tasks identified previously.

The next step is to create a concept design which shows how the *Lorelay* will be able to perform all of the listed tasks. As mentioned previously this is done by converting the *Lorelay* into a modular vessel. This means that the required equipment is easily installed and removed from the ship if necessary. This report focusses on the design of a modular firing line.

To provide the ship with more flexibility, the modular firing line units are stored in the hold of the ship when they are not in use. This means that the units have to fit through the ship's container hatch. To ensure that this is possible, the units have a length of 5.4 meters, a width of 2.4 meters and a height varying between 4.5 and 6.9 meters.

To further increase the ship's independence the units are all installed and stored in the hold by the ship's own crane. This means that only part of the firing line can be removed, a stretch of approximately 26 meters. This results in a free deck space of approximately 650 m^2

In addition to increased flexibility which the ship gains by taking its own equipment, another added benefit is the fact that the units can serve as ballast when they are placed inside the hold. This means that an additional load can be placed on the deck of the ship without compromising stability.

The largest difficulty with this concept is expected to be the manner in which the utilities are provided to each of the units. Since each connection between two units has to be made manually it is important to keep the number of connections to a minimum. In the current firing line that limitation did not exist. This means that there are many different cables and pipelines providing utilities to every part of the firing line. For the modular design to work the utilities in the whole firing line, not only the part that is removed, needs an upgrade to minimise the number of connections that have to be made.

Completing the design of the modular units starts with a detailed layout of the units. This includes the exact strength requirements based on the determined forces. This, together with a plan for the utility interface, the unit to unit interface and the unit to ship interface, should lead to a more detailed weight calculation. From there the stability of the ship can be calculated. Finally the focus can be placed on the smaller details of the unit such as the placement of doors and safety equipment.

By converting part of the firing line into modular units the ship gains more flexibility in which tasks are performed. This is very beneficial in the subsea installation market as it is very volatile. In this market one day there are many cables to install and the next there are only pipe lines to install. To have a ship that can quickly adapt to the many different wishes within the subsea installation market can significantly improve its utilisation.

PREFACE

Almost nine months ago I embarked on what I then assumed to be the final challenge of my academic career. When I heard about this project I was immediately enthusiastic, as looking into conversion options for the *Lorelay* would allow me to combine many aspects of my master Ship Design into one final project. Performing said project at an innovative and bold company such as Allseas, was an added benefit. Their “anything goes” attitude has inspired me a lot during my project.

I immensely enjoyed working at Allseas and working on my project. It allowed me to immerse myself in a world I was unfamiliar with and learn a lot in a short period of time. The willingness of my colleagues to explain their work greatly helped with this. For example, when I came into the coating department with some questions, these questions turned into an hour long class about what pipe coating is and how it works, including samples, movies and a PowerPoint presentation.

I would therefore like to thank all my colleagues at Allseas Engineering. I would especially like to thank Stijn, my direct supervisor, who always made time in his busy schedule to answer my questions and listen to my, sometimes somewhat uncoordinated, progress reports. His questions meant that I was forced to think very well about every decision I made. This meant I was able to keep my project on track and finish in time.

Special thanks are also in order for Marijn, who answered all questions when Stijn was not available, Bert, who seemed to know everybody in the maritime world and could get his hands on many interesting documents which could be useful for me, and Kenneth, my fellow graduate student, with whom I frequently discussed my design approach compared to the one he used in his project.

Finally I would like to thank my supervisor at the TU Delft, Robert Hekkenberg, who tirelessly read all my drafts and provided me with invaluable guidance and feedback.

During this project I learned that I very much enjoy being able to completely immerse myself in a subject and learn everything I can about it. This is one of the reasons that I will be continuing my academic career by starting on a PhD.

Carmen Kooij,
Delft, 4 May 2017

TABLE OF CONTENTS

PART 2: DESIGN

ACRONYMS AND ABBREVIATIONS

A&R winch	Abandonment and Recovery winch
AHC	Active Heave Compensation
AHP	Analytical Hierarchy Process
Allseas	Allseas Group
CAPEX	Capital Expenditure
CI	Consistency Index
CJ	*Calamity Jane*
CoG	Centre of Gravity
CR	Consistency Ratio
DP system	Dynamic Positioning system
FGT	Flooding, Gauging, Testing
FPSO	Floating, Production, Storage and Offloading
HPU	High Pressure Unit
IMO	International Maritime Organisation
IMPP	Injection Moulding Poly-Propylene
IMR vessel	Installation, Maintenance and Repair vessel
LCG	Longitudinal Centre of Gravity
MCDA	Multi Criteria Decision Analysis
MEG	Mono Ethelyne Glycol
MIF	Mattress Installation Frame
NDT	Non-Destructive Testing
OPEX	Operational Expenditure
PHC	Passive Heave Compensation
PIG	Pipeline Inspection Gadget
PLEM	Pipeline End Manifold
PLET	Pipeline End Termination
PLV	Pipe Laying Vessel
PS	*Pioneering Spirit*
PSS	Proposal Summary Sheet
PSV	Platform Supply Vessel
PTC	Pipe Transfer Crane
RI	Random Index
ROV	Remote Operated Vehicle
SCR	Steel Catenary Risers
SIF	Subsea Installation Frame
SOLAS	Safety Of Life At Sea
SPC	Special Purpose Crane
TCG	Transverse Centre of Gravity
TEU	Twenty-foot Equivalent Unit
TLP	Tension Leg Platform
UTA	Umbilical Termination Assembly
VCG	Vertical Centre of Gravity

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

The Swiss based Allseas Group (Allseas) owns several ship shaped pipe laying vessels. One of their vessels, an S-lay vessel called the *Lorelay,* is underutilised at the moment. This is, among other things, due to the fact that there are several other ships with the same capabilities and a very low oil price.

The subsea installation market, which includes the laying of pipelines, is a subsection of the oil and gas market, a market known for its volatility. This is not only seen in the oil price, which varies from day to day, but also in which types of contracts are available. A task that is profitable today might not be in demand the next day. At this moment, with the low oil price, new projects are scarce as companies have to cut cost and choose to wait for better times to start new projects. [1] On the other hand, the demand for oil and gas per person grows every year and is expected to continue to do so for the foreseeable future. [2] Analysts from Douglas Westwood [1] predict that offshore oil and gas will play an increasingly important role in the total production. The same goes for the deep water fields that will make up an increasing percentage of the total offshore fields. These elements together mean that, at some point in the future, the subsea hardware market will improve again.

In the oil and gas industry it is common to offer contracts to several companies to find the best price. Between October 2015 and October 2016 Allseas received 18 invitations to bid on a contract. Figure 1-1 shows that the *Lorelay* could be involved with 6 out of these 18 contracts.

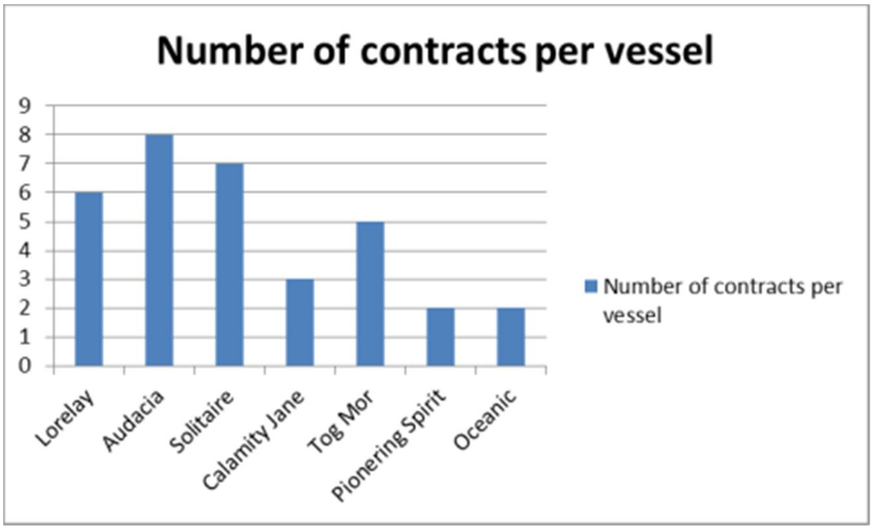


Figure 1-1 Number of contracts per ship in the period between October 2015 and October 2016 [3]

Compared to the other vessels it seems like a decent number. However, Figure 1-2 shows that on average the size of *Lorelay's* contracts is significantly smaller compared to the projects available for the other vessels.

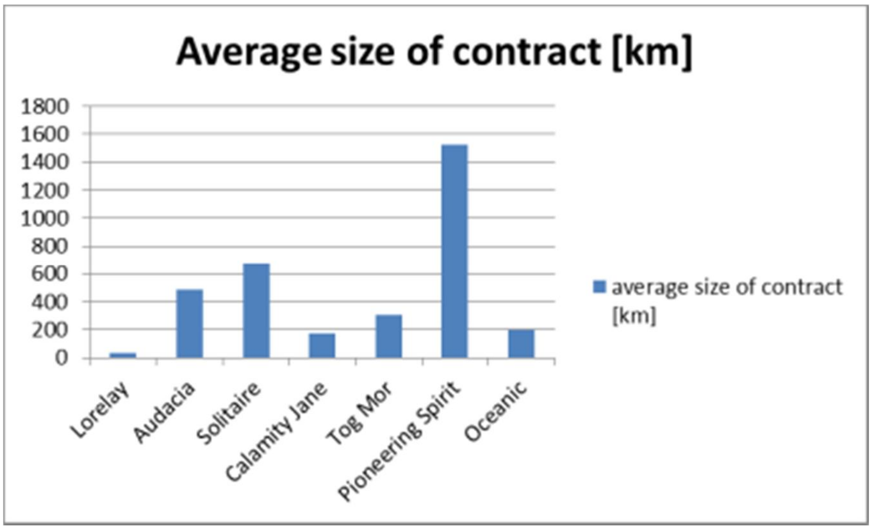


Figure 1-2 Average size of the pipe laying contract in kilometres pipeline and flowline [3]

1.1 Goals and research questions

With the information from Figure 1-1 and Figure 1-2 in mind Allseas is wondering the following:

How can the capabilities of the Lorelay *be adapted to increase her utilisation while still keeping her pipe laying ability?*

The reason Allseas wants to keep the pipe laying ability of the *Lorelay* is the fact that the market is expected to increase again. Thus Allseas is looking for additions or adaptations to the ship that do increase the utilisation but do not limit the pipe laying abilities.

The *Lorelay* is an old vessel which means that the highest costs are on the operational side. Even in port there is a large crew on board performing routine operations and maintenance. Additionally fuel is used to power the ship. With these two elements being the largest expenses performing any task might be cheaper than performing none.

The question posed by Allseas cannot be answered immediately. Capabilities are defined as requirements that are set for the ship and its equipment to perform a specific task, such as a crane to lift 300 tonnes. Adding capabilities to the ship without knowing what they are going to be used for is not practical. Therefore the research should start by identifying tasks, defined as a piece of work that has to be completed, that the *Lorelay* can perform, after which the required capabilities can be determined.
This leads to a new primary research question that is answered in this report:

Which task or combination of tasks shows the most promise in improving the utilisation of the Lorelay*?*

To answer this, three sub-questions have been set up:

a) In which markets can an improvement of the *Lorelay's* utilisation be found?
b) Within the chosen direction, which tasks could the *Lorelay* perform?
    a. What capabilities should the ship possess to perform this task?
c) Which of the created concepts shows the most merit based on several decision criteria and under specific circumstances?

The goal of this research is to answer the question posed by Allseas. This is done in two parts. The first part, called the research part in this report, consists of a market analysis and a decision process which leads to the most promising conversion out of several concepts. The second part, called the design part, leads to a concept design of the chosen vessel configuration.

1.2 Method

This paragraph discusses in short what methods are used during this project. Since the project consists of two parts, a research part and a design part, the methods used are discussed separately.

1.2.1 Research method

This paragraph explains the method by which the research questions are answered.
Each of the research questions is answered during the course of this report. The way this is going to be achieved and where the question fits into the overall view of the project can be found in Figure 1-3.

The first step is to get to know the general market that the *Lorelay* and Allseas operate in and to find the possible directions in which the *Lorelay's* capabilities could be expanded. This is done in the preliminary research phase. The preliminary research concludes by stating a direction where the improvement of the *Lorelay's* utilisation is going to be found.

To find the answers to the second sub question posed a further literature study is conducted to find a list of all possible tasks that could be performed within the defined market. In addition to the literature study, experts from within Allseas, as well as company data, are used to determine which tasks can be performed and what their requirements would be. This leads to an overview of all tasks that are feasible, together with the requirements that the ship has to meet.

The final element of the research is determining which of these tasks or which combination of tasks would hold the most merit for Allseas. This is done by conducting a Multi Criteria Decision Analysis (MCDA). This means that several different conversion alternatives are compared based on four criteria to find the on which shows the most merit. This process leads to a final decision which alternative is to be implemented and is further explored in the second part of this report.

The steps described above are visualised in Figure 1-3.

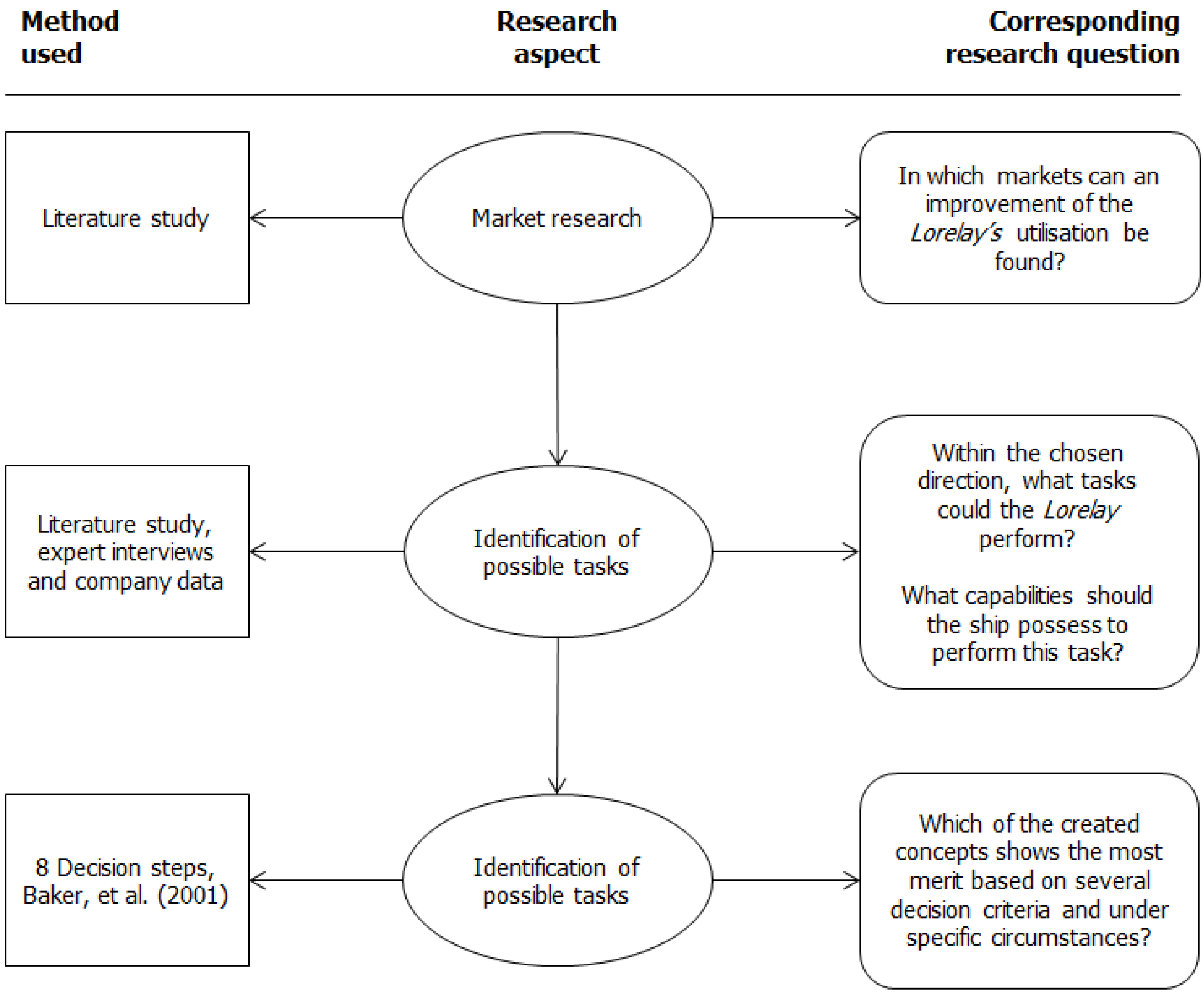


Figure 1-3 Visualisation of the followed research path

1.2.2 Design method

When a ship is designed, a design method such as the design spiral is used. In this method the mission parameters are used to determine the main dimensions of the ship and the design spirals into more detail from there, continuously changing the main dimensions of the ship to optimise them. In case of a conversion this is not a workable method since the main dimensions of the ship cannot change. In practice a conversion is seem more as product design. The ship is incorporated as requirements or conditions in the program of requirements.

The design process differs from project to project but there are several elements that return in every project. [4] The first step of any design project is to precisely define the problem. This also includes narrowing the problem.

With a clear problem statement and goal defined the next step is to define the requirements of the design. This is done by executing a thorough investigation of the current equipment and its functions. This functional analysis is than used to define the requirements.

The next step is to generate different concepts that meet the requirements set up in the previous phase. From these concepts, the most promising one is selected. This leads to a final concept design in which each of the requirements is met.

The last step of the design process is to evaluate the design and identify how the design can be completed.

The design process followed is depicted in Figure 1-4.

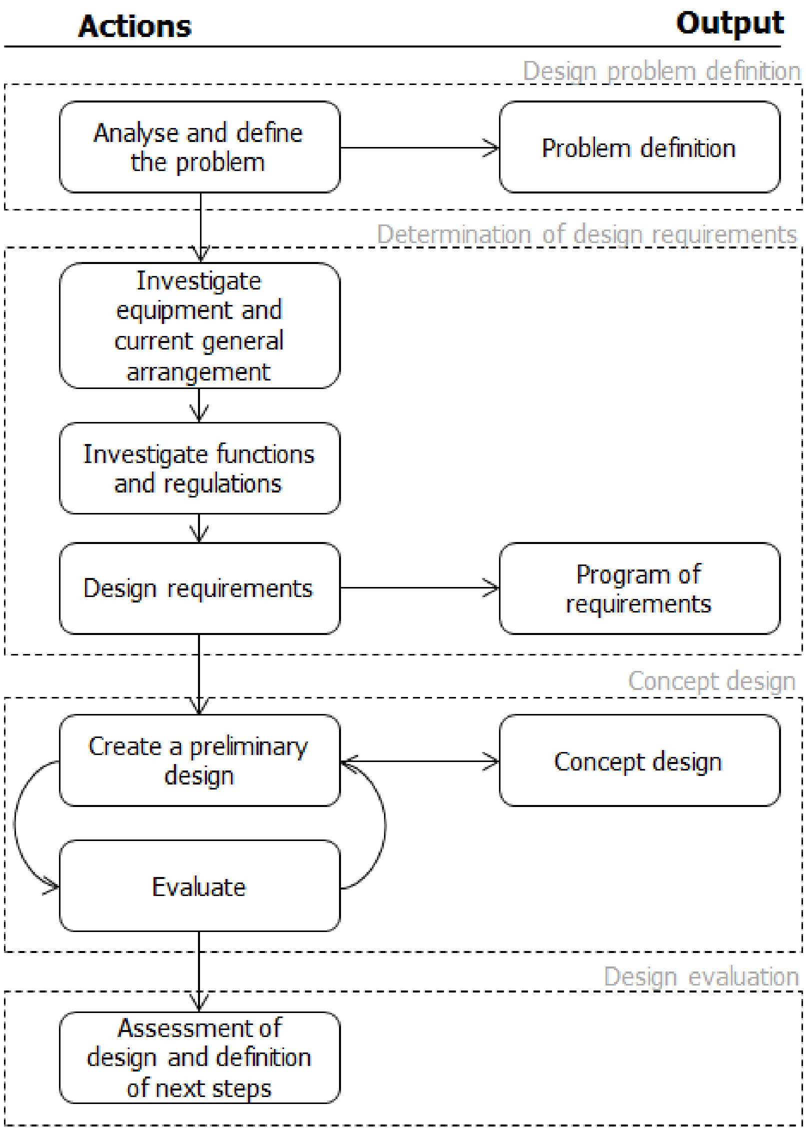


Figure 1-4 Visualisation of the followed design path

2.0 INTRODUCTION TO PIPELAYING WITH THE *LORELAY*

In the previous chapter it was stated that Allseas' vessel the *Lorelay* was underutilised. To find a solution to this problem several research questions have been determined. Before these questions can be answered some general knowledge about the ship and the pipe laying process is needed. This chapter is aimed at providing the necessary information to understand the rest of this thesis.

This chapter first looks into the *Lorelay,* its capabilities and the problems that could occur when the ship is redesigned. Next, the S-lay technique is explained. This is, and shall remain, the most important function of the ship and some understanding of how this process works is required to understand the challenges and decisions later on in this report.

2.1 The Lorelay

Before aiming to improve the utilisation rate of the *Lorelay* it is important to first be familiar with the current capabilities of the ship. This can be useful in determining a direction for the refit as well as in aiding to determine which tasks would require only a small refit and which would require a large refit.

The *Lorelay* is a pipe laying vessel that uses the S-lay technique. The S-lay technique is discussed further in paragraph 2.2.

The main dimensions of the ship can be found in Table 2-1.

Table 2-1 Main dimensions of the *Lorelay*

Vessel specifications	Dimension
Length overall (including stinger)	236 m
Length overall (excluding stinger)	183 m
Breadth	26 m
Depth to main deck	16 m
Operating draught	9 m
Maximum speed	16 kts

The ship is capable of laying pipes with a diameter between 2" and 28" in water depths up to 2750 meters at a maximum speed of 7 km a day, dependent on the pipe dimensions. The ship is also capable of installing several types of subsea structures.

To install the pipes the ship has a firing line on deck that covers the length of the ship. The firing line consists of seven welding stations, three tensioners, a coating station and a non-destructive testing station. The firing line ends in a stinger with a length of 70 meters.

For the installation of the subsea structures the ship is equipped with a 300t crane to lift and move the structures, a portal frame, with an active heave compensated (AHC) winch to lower the structures to the seabed and an ROV to monitor the installation.

Figure 2-1 The Lorelay laying pipe [5]

2.1.1 **Current issues**

The *Lorelay* is optimised to lay pipes in both shallow and deep water. If the ship is to be used for other activities, several problems have to be taken into account. The first is that the firing line is placed on deck, together with most of the other equipment. This means that there is not a lot of space to transport structures or to take on additional equipment. Figure 2-2 shows a view on the deck of the *Lorelay* in which the congestion problem is visible.

Besides the space problem, the ship also has a weight problem. With the current equipment on board and a hold filled with pipes the maximum weight of the ship is reached. Additional equipment placed on the ship means that the pipe carrying capacity of the ship, one of her selling points, decreases. Another problem that occurs with all the equipment on deck is that the ship becomes unstable due to the high centre of gravity (CoG), especially when the hold is empty. Currently the ship carries concrete beams in the hold to keep the CoG low enough to safely operate the ship.

Figure 2-2 View on the deck of the *Lorelay* from bow to stern *(*Authors own collection)

2.2 Introduction to the S-lay technique

The *Lorelay* lays pipe via the S-lay method. This method is named after the way the pipe is shaped during the pipe laying process. This paragraph discusses this method in more detail and looks into factors that influence the performance of this method.

The process starts with sections of pipe with a length of 12.2 meters long. The pipes are either stored in the hold of the vessel or immediately installed after delivery by a pipe supply vessel. This is the function of the second vessel next to the *Lorelay* in Figure 2-1. The first stop for the pipes is the facing and preheating station. Here the pipes are bevelled and pre heated to facilitate the welding process. The pipes enters the firing line, a horizontal work plane which ends at the stinger, at the line up station. As the name suggests the pipe is positioned in such a way that it can be welded onto the pipeline.

Next the pipes pass through several welding stations. Here the pipes are welded together using Allseas' own automated welding system *Phoenix*.

To test the welds the system is also equipped with a non-destructive testing (NDT) station. Here the welds are checked. If a faulty weld is detected, the pipe laying process is backed-up until the weld is removed.

To keep the pipeline in place the ship is equipped with three tensioners. The main function of the tensioners is to keep the pipeline in place. If a long pipeline is lowered to the seabed the weight of the pipe pulls the ship backwards. To compensate for moving backwards the Dynamic Positioning system (DP system) is continuously applying thrust to move forwards. The tensioners are meant to keep the pipeline on the ship and prevent it from being pulled off the ship by its own weight. The crew can also to control the angle at which the pipe touches down on the bottom. The angle is controlled by pulling more or less on the pipeline which is done by using both the DP system and the tensioners. The tensioners are placed between the welding stations.

To prevent corrosion the pipes are coated in a protective layer. To enable the pipes to be welded together the ends of the pipes are left bare. This means that the final step of the pipe laying process exists of applying this protective coating to the welds.

Finally the pipeline is lowered into the water via the stinger. The main function of the stinger is to prevent buckling of the pipes when it is bending from a near horizontal position to a vertical one when being lowered to the seabed. The position of the stinger is adjustable, allowing the ship to compensate for different water depths.

2.2.1 Performance influencing factors

There are several performance factors that determine how well suited a ship is for a certain job. In case of a pipe laying vessel (PLV) the main performance factors are:

- Laying speed
- Maximum achievable water depth

The laying speed of the vessel is limited by the number of welding stations that is installed on the firing line. This can be explained by looking at the welding process in more detail.

Pipes usually have a wall thickness that is no less than 20 millimetre. This means that the welding process has to be split up into several parts. At the first station, called the "beadstall", the pipes are lined up and the first weld, called the bead. This weld has to be strong enough to hold while the pipe is moved further into the firing line. This station determines the speed of the firing line, since both lining up and welding has to be completed here.

In the next stations several filler welds are placed between the two pipes. The welding stations consist of three welding heads moving in tandem around the two pipes to be welded together. This welding station is operational for as long as it takes to line up the pipes and lay the bead at the first station. When this station is done the ship is moved forwards 12 meters and the process starts again.

The way this influences the speed is as follows:

The time taken at the beadstall is the leading time for the other weld stations. If the ship is welding a wide but thin-walled pipe the first station takes a relatively long time as the welding stations have to move around the whole pipe once to lay the beadweld. Thanks to the small wall thickness only a few welds are needed to fill up the crevice between the two pipes. This means that the firing line requires only one or two additional welding stations.

In the case of a smaller diameter pipe with a thicker wall, for instance for deep water, the time it takes to lay the bead is significantly shorter. However, this pipe requires many more filler welds than the previous case and thus requires more welding stations to lay these fillers.

This means that the wall thickness of the pipe determines the length of the ship that issued and the interval at which the ship moves forwards.

The maximum achievable water depth is dependent on two factors. To be able to lay pipes in deep water the stinger must have the ability to reach a near vertical angle. To minimise the possibility for damage due to plastic deformity the stinger needs to be large. In practice, stingers used for deep water operations have a length in excess of 70 meters. This can be helped by trimming the ship backwards slightly to more easily achieve the preferred vertical position.

The second influencing factor is the maximum achievable tension the tensioners can deliver. The reason why this is important is explained above. However, only having powerful tensioners is not enough. The DP system must also be capable of keeping the tension on the pipeline. If this is not the case the ship will simply be pulled backwards by the weight of the pipeline. [6]

2.2.2 Installation of PLETs and PLEMs

During the pipe laying process it might be necessary to install either a pipeline end termination (PLET) or pipeline end manifold (PLEM). A PLET is used in a pipe to pipe connection, for example connecting two pipelines coming in from different wells. Each pipeline ends in a PLET and a connection is made between them. [7] A PLEM is used to connect a pipeline to another type of structure, for example a manifold or tree. [8]

On the *Lorelay* these connections are installed using the 300 t crane and the portal frame. The structure is connected to the portal frame using the crane. The portal frame is a large construction used to hold structures in place while the pipeline is attached in J-lay mode. In J-lay the pipeline is constructed in vertical position, which is also the direction in which it leaves the ship.

The PLET or PLEM which is about to be installed is either transported by the *Lorelay* or is brought in by a barge. It is lifted up, rotated 90 degrees to a vertical position and connected to the portal frame. The pipeline is lowered from the firing line and temporarily rested on the seabed. From there it is lifted upwards to the portal frame where it is attached to the structure waiting there.

The pipe and construction are then lowered into the water using the winch. Using a specially designed handle the construction rotates slowly until it has reached the seabed. Here the ROV that supervised the whole operation cuts the A&R cable. [9]

Installing a PLET or PLEM means that all pipe laying operations have ceased for the moment. This also means that most of the personnel on the ship have nothing to do at that moment as the most personnel is needed when the pipes are laid.

Part 1: Research

3.0 MARKET RESEARCH

This chapter discusses the answer to the first research question: "*In which markets can an improvement of the* Lorelay's *utilisation be found?*" This is done by first determining what other markets there are to operate in and then investigating the possibilities within this market. The chapter ends with a conclusion in which direction the conversion of the *Lorelay* is going to be found.

Expanding the capabilities of the ship can be done in three directions;

a) The current pipe laying-related capabilities could be improved. For example; making it possible for the ship to lay bigger pipes, at greater depths or at a higher speed.
b) The current capabilities could be broadened within the pipe laying market. The *Lorelay* could, for example, be used as a supply vessel or a construction vessel supporting projects in which other ships are laying the pipes.
c) It is also possible to choose a completely new direction. The ship has certain capabilities that might also be useful in other tasks.

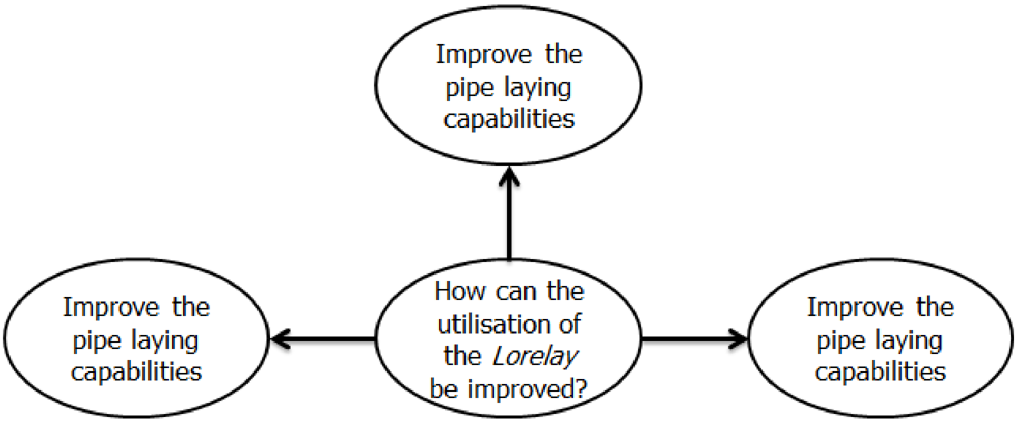


Figure 3-1 Visualisation of the possible directions for the conversion of the *Lorelay*

3.1 Improve the ship's pipe laying capabilities

The driving force behind the problem statement is that the *Lorelay* does not have enough work. The first question regarding improvement is; is there work for ships with better pipe laying capabilities? The answer to this question is rather simple. Allseas owns three other pipe laying vessels, the *Audacia,* the *Solitaire and the Pioneering Spirit (PS),* all of which can handle larger diameter pipes than the *Lorelay.* At this moment[1] there is some work for them but it is not available in abundance. Additionally, increasing the pipe laying capabilities of the *Lorelay* could mean that it is now competing for the same contracts as one of the larger vessels that Allseas owns. This could potentially lower the profit of both ships instead of just the *Lorelay.*

It might be possible to increase either the transit speed or the laying speed of the *Lorelay.* This has the potential to make the ship more competitive in the market. However, this would not necessarily increase the number of projects the *Lorelay* can be used on, and thus it is not a solution to Allseas' question. For these reasons this direction is not be investigated further.

3.2 Expand within the subsea installation market and heavy lift market

According to Allseas' proposal engineers there are not many capabilities that have to be on the ship permanently. In a good market the ship will be laying pipes as much as possible, in a bad market it preferably performs any and all tasks that will make the company money. This means that the ship has to be very flexible, allowing quick changes to accommodate a new task.

Due to the bad market Allseas, is already looking into other possibilities for the *Lorelay.* For example; at this moment the ship is being adapted to function as a construction ship for the Rota 3 project in Brazil. Instead of installing pipelines the *Lorelay* is used to install jumpers and perform the precommissioning of the pipeline. These tasks are normally left to a subcontractor or are not part of the contract at all.

To be able to perform these tasks the ship has to be adjusted. However, with the current design it is difficult to achieve since the deck is full of equipment and all this equipment is adjusted to the task of laying pipes instead of the more precise task of installing a jumper.

[1] October 2016

To make future projects like this possible a more flexible ship would be required. This can be done by either installing equipment that can be used for more projects or by making it possible to quickly adjust the ship for a new task.

Currently Allseas is a highly specialised company, specialised in pipe laying. All other aspects of the subsea installation that is required during the project are performed by other companies. Should the choice be made to expand within this market the company already has a foothold. This would ease the process of expanding the business as the clients already know the company and know how they work. This is an advantage compared to entering into a new market.

Another possibility is to have the *Lorelay* assist the *Pioneering Spirit (PS)* with heavy lift projects. A ship with the size of the *PS,* 382 meters long and 124 meters wide, is too expensive to perform preparatory tasks for the removal of the platform. These tasks could for example include; the transportation of equipment, installation of lifting hooks and the cutting of the legs prior to removal.

To summarise: it is possible to expand in the subsea installation market or the heavy lift market. There is room to grow and tasks that are now performed by competitors can also be performed by the *Lorelay.* Since Allseas is already a player in that market, clients know the company making it easier to expand than to enter a new market.

3.3 Expand into other markets

To find out if it is possible to branch out into other markets, the other markets must first be identified. The capabilities of the ship, such as the DP system and the offshore crane show a lot of similarities with the offshore construction market. This means smaller changes to the ship and a bigger chance that the pipe laying capabilities can be retained. Within the offshore construction market several submarkets can be identified:

- Cable laying
- Drilling
- Dredging
- Wind farm installation, operation and maintenance
- Accommodating crews

The installation of cables is a broad market. Cables that are installed on the seabed range from telephone cable to electric cables and hydraulic cables. The vessels used to install cables are similar to reel-lay vessels and some have the ability to install both, opening up a broader market for the vessel to operate in.

Both drilling and dredging, including dredging related tasks such as rock dumping, would require a large refit of the ship. The required equipment to perform these tasks is very different from the equipment required for pipe laying, for example dredging requires a large open hold, meaning the entire deck has to be removed. [10] [11] Transforming the ship to be able to perform these tasks would most likely violate the one given condition; the ship must retain her ability to lay pipe. For this reason these options are discarded.

Windfarm installation is currently done using jack-ups. The reason for this is that installation of wicks or a turbine at 80 meters high can only be done when the vessel lies completely still. This is much easier when using a jack-up than using a DP vessel. The workability of a DP vessel is much lower than that of a jack-up. [12] The largest jack-ups have a maximum operating draught of around 175 meters. [13] Given that the largest water depth in which a wind farm is planned is 50 meters and the average installation depth in the first half of 2016 was 25 meters it will take a while before jack-ups can no longer be used for installation work. [14], [15]

For operation and maintenance work crews and equipment are usually transported to and from the windfarms daily using small boats. A new development with windfarms further from shore and increasing in size is that larger vessels are stationed at the windfarm permanently as an accommodation vessel for the maintenance workers. These vessels carry workers, spare parts and equipment. While the *Lorelay* could be used for this type of work there is one main issue; the contracts for these vessels are usually long, approximately five to ten years. This means that the ship will be unavailable for this period of time. [16]

There is some business in the renting out of vessels to be used as accommodation for larger projects at sea. With a large accommodation for 230 persons as well as a large hold for some additional equipment, the *Lorelay* could be used for this task. However, this has the same problem as windfarm maintenance; the contracts are usually for a longer period of time.

To summarise; there is some potential in other markets. However, most options do not allow for the *Lorelay* to keep her pipe laying capabilities which is the one requirement given at the start of this project. For this reason a solution for improving the utilisation of the *Lorelay* is not going to be found in another market.

3.4 Conclusion of possible expansion directions

Using the preliminary research, the scope for this research can be narrowed. As mentioned above expanding the capabilities of the ship within the subsea installation market is the best option. As was mentioned before, in a bad market, an ideal ship is a ship that can be adapted to perform any required task quickly. Currently the *Lorelay* is not suited for a quick adaptation as the deck of the ship is congested by the firing line. These changes would have to be implemented while the ship is converted.

Expanding into another market requires large refits that might not even have the desired effect of increasing the utilisation of the ship.

Increasing the capabilities of the ship similarly does not increase the utilisation of the ship. This also has the added disadvantage of cutting into the market of the bigger ships Allseas owns.

4.0 EXPLORATION OF POTENTIAL TASKS

In the previous chapters the scope of the redesign was narrowed to tasks within the subsea installation and heavy lift markets in which Allseas already operates. The next step is to answer the next research question; *what tasks exist within the subsea installation market and the heavy lift market?* This question is directly followed by: *what capabilities are required to perform this task?* This question is answered for all tasks which are found by answering the first question.

The answer to the first research question is found by using company data about offers for projects as well as talking with company experts to find any potential other tasks.

To find the answer to the second question a literature study is conducted and experts are interviewed. The goal is to find the requirements for the ship to be able to perform the tasks in the form of equipment and deck space. This information can be used later on to find out which task shows the most promise.

For more details about the different offshore structure please refer to 0. For further details about the installation process discussed in this chapter please refer to Appendix B.

4.1 Determination of potential tasks

Allseas owns six highly specialised ships. If a contract is accepted that cannot be completed with just these ships there are two options; adapt one of the ships to perform the task or put out a tender for someone else to complete that part of the contract.

Information on the tasks that are performed for a specific project can be found in the proposal summary sheets (PSSs). These data sheets are set up for each project that Allseas receives and states the most important information about what the project entails. This also includes the work that is going to be done either by a partner or by a subcontractor. Investigation of 18 PSSs for projects that Allseas received between October 2015 and October 2016 provides a list of work that is done by subcontractors or partners. This list also includes tasks that Allseas is capable of doing themselves. This has two reasons, a partner or competitor received the contract for that part of the work or the vessel capable of performing these tasks, in most cases the shallow water barge *Tog Mor* or the support vessel *Calamity Jane,* is already involved in other projects.

The following tasks have been identified from the PSSs: [3]

- Rock dumping
- Surveys
- Jumper and spool installation
- SURF
    - Subsea structure installation
    - Umbilical installation
    - Riser installation
    - Flowline installation
- Above-water tie ins
- Retrieval of existing structures
- Landfall operations: Horizontal Directional Drilling (HDD)
- Mattress installation and crossing preparation
- Span rectification
- Precommissioning
- Dredging
- Shallow water pipe installation
- Trenching and backfilling

For the heavy lift market there is no precedent. Therefore the investigation into these tasks is based on company expectations on what is required.

4.1.1 Initial elimination

Based on the ship characteristics and the initial research done, several tasks can already be eliminated as either impractical or impossible.

Dredging and rock dumping were investigated during the preliminary research in Chapter 3.0. These tasks require extensive refits that will most likely compromise the pipe laying capabilities of the ship permanently. Therefore these tasks do not need further investigation.

With an operating draught of 9 meters the *Lorelay* can operate in relatively shallow waters but she is not capable of performing pipe laying duties near the shore. This means that shallow water pipe installation can also be eliminated from the list of potential tasks.

There are several methods that can be used to install the pipe as it gets to land. What method is used is dependent on many different factors such as sediment type, weather and location. [17] While the Lorelay could possibly perform a pull-in operation during which the ship is stationary and the pipe is pulled towards shore as it is laid the other methods should prove more difficult to complete. These tasks are eliminated from the list of potential tasks as well.

4.2 Current capabilities of the *Lorelay*

The *Lorelay* can already perform some of the tasks listed above, but in most cases she does not perform these tasks regularly or they can be done but inefficiently.

The *Lorelay* is first and foremost a pipe laying vessel. It is assumed that the pipe laying equipment on the vessel does not need to be changed and that no improvements can be found there. This is also assumed for the installation of inline structures, a semi-regular occurrence during the installation process.

In addition to the pipe laying the *Lorelay* has other capabilities. These are;

- J-lay structure installation
- Jumper installation
- Dewatering infrastructure; after the Rota 3 project the compressors will be removed but the piping system and required tanks remain on board.

Table 4-1 Equipment currently installed on the *Lorelay*

Feature	Requirements
Crane lifting capacity and features	300t, passive heave compensation (PHC)
Cable or winch requirements for deep water installation	AHC winch with a cable length of 3000 meters
ROV	Yes, 1
Deck space	Limited
Additional features	Portal frame for over-boarding of large structures, PLEM upending frame for transport and rotating PLEMs for installation, infrastructure for dewatering

4.3 Capabilities of the *Calamity Jane* and the *Oceanic*

Allseas owns two support vessels, the *Calamity Jane* (*CJ*) and the newly acquired *Oceanic.* To ensure that any new capabilities of the *Lorelay* are useful it is good to know their capabilities with regards to the tasks mentioned above.

4.3.1 Calamity Jane

The *CJ* is Allseas' pipe laying support vessel. As support vessel the *CJ* can perform a multitude of tasks that are necessary for the pipe laying process. She is capable of performing the following tasks:

- Pre-lay surveys
- ROV support
- Crossing preparation and mattress installation
- Trenching by using the *Digging Donald*
- Structure installation
- FGT operations

When comparing the list above to the tasks mentioned in paragraph 4.1, many similarities can be found. There are many possible reasons Allseas could have chosen to outsource tasks performed by the *CJ* instead of performing them themselves. For example; the ship could be busy with another project, it was predetermined that the tasks would be performed by a partner or the scope was either too big or too small for the *CJ.*

4.3.2 Oceanic

The *Oceanic* is a newly bought DP construction vessel. The vessel is equipped with a 300t knuckle boom crane and a large free deck area. [18]

At this point it is not entirely clear what the main function of the *Oceanic* is going to be. The vessel was bought to be used as a pipe laying support vessel together with the *CJ* and might replace her in a few years. However, it has also been suggested that this ship could assist with heavy lift operations performed by the *PS.*

For a coming project the *Oceanic* is to be equipped with a modular trencher to help with trenching activities. The choice for a modular version was made to ensure that the large free deck space could be regained after this project as it is one of the main reasons this ship was bought.

4.3.3 Conclusion

With two ships equipped with a trenching machine adding a third is a bit too much, since not every project requires that the pipeline is placed in a trench. For the other tasks, such as mattress installation, it might be worthwhile to have another ship with these capabilities.

4.4 Tasks in the subsea installation market

This paragraph discusses the different tasks that remain after the initial elimination in the previous paragraph. Each task is discussed separately and a choice is made if it is possible for the *Lorelay* to perform this task, if necessary after a refit.

4.4.1 Surveys

The installation of a pipeline on the seabed requires several different surveys of both the seabed and the pipeline. Before the project starts, an extensive survey of the seabed is done. The goal of this survey is to create a maps or 3D image of the seabed and to find specifics of the underwater geology such as soil type. This data is used to determine the best pipeline route, position of structures and necessary equipment for the job. [19]

The next step is to do a survey shortly before the pipeline is to be laid. During this survey the location of the pipeline is examined for any unexpected problems, ranging from unknown cables or pipes to geological formations that weren't charted and unexploded ordnance.

During the pipeline and structure installation ROV support is used for touch down support. In additional to this ROVs can be used to finalise installations, attach elements or inspect the completed elements. [20]

Finally, after installation is complete a final survey can be done, a post-lay survey to determine if everything is installed correctly. [20]

Currently Allseas performs surveys using the *CJ.* According to *CJ's* field engineer the pre-lay surveys are mostly done because the vessel is working on the project already. For example, the vessel could be tasked with crossing preparation and perform a survey during the execution of this task. The *CJ,* and with her probably also the *Lorelay,* is too expensive to only perform the survey tasks. For this reason surveys are not be looked into as a specific task that could to be performed.

4.4.2 Jumper and spool installation

Jumper and spool installation requires precision. The constructions have to be placed at exactly the right position hundreds or even thousands of meters below the waterline between two structures. This requires very little movement of the structure.

The difference between a jumper and a spool is that a spool is placed in a horizontal position and a jumper is placed in a vertical position. Due to the Rota 3 project the *Lorelay* is currently capable of installing jumpers and spools. However, the current method that is used to transport and install them might not be ideal.

The goal of a jumper or spool installation is to make a connection, either with a rigid or flexible pipe, between two subsea structures by placing it on two connection ports. Due to the precise nature of the final installation movements have to be limited during the final phase of the installation.

The crane is used to lift the spool or jumper off the deck. Dependent on the installation depth the crane or the A&R winch are used to guide the spool or jumper towards the seabed where an ROV is used to connect it to both structures. This can be done by one ROV, but two might be preferred as it allows for the simultaneous connection of both ends of the spool or jumper. To ensure that the ship movements do not influence the installation a crane or winch with active heave compensation is needed. This ensures that the structure remains stable even if the ship moves.

A summary of the required equipment is listed in Table 4-2. All this equipment is already available on the ship.

Table 4-2 Equipment requirements for jumper or spool installation

Feature	Requirements
Crane lifting capacity and requirements	50 t, No special requirements
Cable or winch requirements for deep water installation	Actively heave compensated
ROV	Yes, 1, preferably 2
Deck space	Yes, varies per project, transport on side of the ship might be more practical due to shape
Additional requirements	Transport frame for the spools or jumpers

4.4.3 Structure installation

As mentioned before the *Lorelay* is already capable of installing several types of structures, but she is not the most ideal ship for these tasks. Allseas has selected this as an appealing direction in which the capabilities of the *Lorelay* could be expanded further.

Structures are installed using the J-lay method, as explained in chapter 2.0. The *Lorelay* is limited in installing these structures as there is no space on deck to transport or store them safely. This means that only one structure can be installed after which another ship has to bring the next structure to install.

These structures can be many things, from anchors to manifolds and have many different weights associated with them. Their weights can vary between 40 and 350 tons. They can also have a large footprint and thus require a lot of space on deck or separate transport. [21] This means that the full extend, and more, of the crane is required.

The installation procedure is similar to that of the spools and jumpers, the structure is picked up and lowered towards the seabed. For the installation of structures passive heave compensation is sufficient since the installation is less precise.

The retrieval of structures is similar to the placing of structures and requires the same equipment. This might be a feasible option for the *Lorelay.*

Table 4-3 Equipment requirements for structure installation

Feature	Requirements
Crane lifting capacity and requirements	300 t, No special requirements
Cable or winch requirements for deep water installation	No special requirements
ROV	Yes, 1
Deck space	Yes, varies per project and structure type
Additional requirements	None

4.4.4 Flex lay

There are two types of pipelines in existence, rigid pipelines and flexible pipelines. Currently Allseas has the capability of installing the rigid pipelines but not the flexible pipelines. For the installation of the flexible pipes the ship needs to be equipped with a reel. Reels can also be used to install rigid pipelines up to a diameter of 18”. [22]

The main advantage using flexible pipelines is that, due to the reel-lay method, the installation speed is much higher than with S-lay or J-lay. Another big advantage is the fact that it is also possible to install cables or umbilicals with a reel-lay vessel. On the other hand, due to the installation process the maximum diameter of the flexible pipes is significantly smaller than that of rigid pipelines.

The reel-lay method works as follows. On a fabrication yard a pipeline is assembled and spooled onto a reel of the pipe laying vessel. This assembly includes the non-destructive testing as well as the final coating. From there, the vessel moves towards its target location where the pipeline is unreeled. The pipeline passes from the reel, across an A-frame which is equipped with straighteners and tensioners. From there the pipeline in lowered into the water. The angle of the A-frame can be adjusted to allow for either shallow or deep water. [23]
To streamline the pipe laying process it is also possible that the pipeline is spooled onto a supply vessel which transports the pipe to the pipe laying vessel. The supply vessel then reels the pipeline onto the reel of the pipe laying vessel. [24]

To keep up the profit from the quick installation process compared to other installation methods it is important to have a spool base near where the ships are operating. Otherwise the time it takes to transport the new reels to the vessels negates the profit from the faster installation.

There are some vessels that combine reel-lay with cable installation, allowing for a larger market to operate in. In this case the reel is adjusted to work either for cables or for pipelines.

Table 4-4 Equipment requirements for flex lay

	Requirements
Crane lifting capacity and requirements	300 t, No special requirements
Cable or winch requirements for deep water installation	No special requirements
ROV	Yes, 1
Deck space	A lot
Additional requirements	Reel, A-frame, spool base

4.4.5 **Umbilical and cable installation**

The method of installing umbilicals is the same as installing subsea cables. Therefore these are discussed together, even though cable installation was eliminated previously by falling out of the research scope. Umbilicals are installed using a reel, placed on the ship in a vertical direction, or carousel, placed in horizontal direction.
The most difficult part of installing umbilicals is that they are vulnerable. [19] Contrary to steel pipes they damage relatively easy when using tensioners or a stinger. Additionally it is difficult to reattach an umbilical if it is cut and left behind during bad weather or an emergency. This is due to the complex nature of umbilicals. An example of a cross section of an umbilical is shown in Figure 4-1.

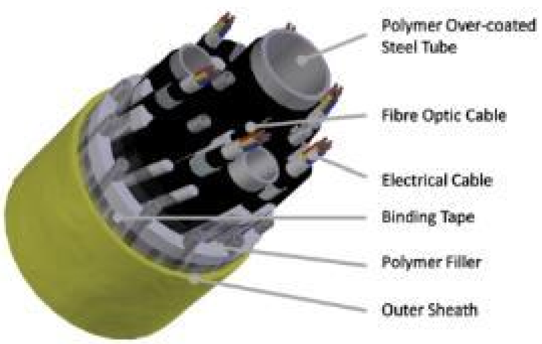


Figure 4-1 Cross section of an umbilical showing the many different elements

The installation of an umbilical starts either at an umbilical termination end sled or at a topside, just like with a pipeline. [19]
The umbilical is rolled onto a carousel and placed on the ship. From here the umbilical is fed through a tensioner and off the ship via a slide like stinger called a chute. When the final location is reached there are two options, either the umbilical is connected to a topside by a transfer operation between the installation vessel and the topside or a second umbilical end unit is installed. [25]

It is possible to install umbilicals using large carousels that can carry several thousand tons of umbilical. It is also possible to use smaller carousels that can carry only a few hundred tons of umbilical. [26] A system based on the smaller carousels would require less space but does require a steady supply of cables during the laying process.
It is possible to install a large carousel on the ship permanently but it is also possible to install a modular configuration on the ship that can be removed when it is not needed. The Drammen yard makes carousels in such a way that they can be lifted using a crane. The sizes range from a small carousel of 150

ton to a large one of 10000 ton. This construction makes it possible to turn an offshore support vessel into a cable laying vessel for as long as is needed. [27]

This configuration is a good option since a carousel has to be removable if the *Lorelay* has to be able to install pipes as well.

Table 4-5 Equipment requirements for umbilical and cable installation

	Requirements
Crane lifting capacity and requirements	300t, no special requirements
Cable or winch requirements for deep water installation	Yes, no special requirements
ROV	Yes, 1
Deck space	Yes, some
Additional requirements	Carousel, tensioner and chute

4.4.6 Riser installation

Simply said a riser is just another part of the pipeline. Installing a riser can be done using all pipe lay methods, S-lay, J-lay and reel-lay. However, installing them with an S-lay vessel is not ideal. Somewhere during the riser installation, either at the start or at the end the riser has to be connected to the topside. The stinger increases the difficulty of this process. The riser is welded together in the firing line. From there it is lowered overboard using an A&R cable. Next the riser is hoisted towards the ship again via the portal frame used for J-mode installation. From this location it can be connected to the topside.

The risers are rather heavy and it requires a lot of pulling force to connect it to the topside. With the 300t crane this is not always possible. To increase the capabilities of the *Lorelay* in this regard a larger lifting capacity is required.

Table 4-6 Equipment requirements for riser installation

	Requirements
Crane lifting capacity and requirements	300t, more might be required
Cable or winch requirements for deep water installation	No special requirements
ROV	Yes, 1
Deck space	No additional space required
Additional requirements	Some adjustments to the welding system might be required

4.4.7 Above water tie in

An above water tie in operation is a method to connect two parts of a pipeline together above the water. A vessel lays the pipelines with additional length to facilitate a ship picking up both ends and bringing them to the surface. At the surface the two pipe-ends are lined up and welded together. Once the welding is complete the pipeline is lowered to the seabed again while the vessel is moving sideways to prevent overstressing the pipe. [28]
These operations can only be done in shallow water, otherwise the weight of the pipe becomes too large, and are thus not interesting as an expansion for the *Lorelay.*

4.4.8 Mattress installation and crossing preparation

Mattresses are used to protect existing pipelines and cables from stresses and loads caused by the installation of a new pipeline crossing the existing pipeline. These mattresses consist concrete blocks netted together by steel or synthetic wire.

A mattress installation starts with equipping the crane with a special mattress installation frame. Allseas owns two types of frames, a small frame that picks up one mattress at the time and a larger ROV type frame, equipped with its own thrusters, lights and cameras, which can carry four to six mattresses at the same time. This frame is attached to the ship by an umbilical and therefore has a depth limit of 400 meters. The frame is then attached to the mattress and this combination is lifted overboard. To keep the motions of the mattress to a minimum, to prevent damage to the pipe or cable by a hard impact and to control the position of the mattress an AHC crane could be useful in this case but it is not necessary. When the mattress is in place the ROV is used to release the mattress from the frame. [9]

If the larger frame is used it can control its own position and the operator can monitor the progress without the need for a separate ROV.

The biggest advantage of the smaller frame is the storage. It can be placed on top of a pile of mattresses and be secured there without any problems. [29] The larger frame needs a different location to be stored. On the other hand the installation speed of a larger frame is four to six times larger.

Table 4-7 Equipment requirements for mattress installation

	Small mattress installation frame	**Large mattress installation frame**
Crane lifting capacity and requirements	25t, no special requirements	35t, no special requirements
Cable or winch requirements for deep water installation	Actively heave compensated needed for connection with ROV	Necessity depends on the length of the current crane cable
ROV	Yes, 1	N/A
Deck space	Dependent on the amount of mattresses that is to be installed.	Dependent on the amount of mattresses that is to be installed.
Additional requirements	Small mattress installation frame.	Large subsea mattress installation frame with ROV capabilities. Storage for frame and umbilical reel

4.4.9 Free span rectification

Free span occurs when a pipeline is installed on an uneven seabed. Due to the bending stiffness of the pipe, it does not touch the seabed everywhere. If the unsupported length, or free span, becomes too large it could potentially damage the pipe. To ensure this does not happen, span rectification is done to protect the pipeline. [30]

Generally supports are developed using a pile of sand-, concrete- or grout filled bags. [31]
For small heights the bags filled with grout or other sediments are used. If the distance between the seabed and the pipeline becomes higher it is also possible that different supports are used. [32]

The bags can be installed by ROV or by a diver. Divers have more precision when working as they can easily adjust to circumstances. However, they can work up to a maximum of 300 meters, making a ROV guided installation more suitable for deep water operations.

Simply said a frame with grout and bags is lowered towards the seabed. There the bags are placed underneath the pipeline, either by an ROV or by a diver. Then the grout hose is attached and the bag is filled with grout. [32]

Table 4-8 Equipment requirements for free span correction

	Diver installed	**ROV installed**
Crane lifting capacity and requirements	No crane required	Weight of frame unknown, no special requirements
Cable or winch requirements for deep water installation	N/A	No special requirements
ROV	No ROV required	Yes, 1
Deck space	Yes, diver equipment and command need location	Location for installation frame
Additional requirements	Storage tank for grout, mixing unit, pumps, umbilical, diver equipment	Storage tank for grout, mixing unit, pumps, umbilical, frame to carry the bags and grout umbilical down.

4.4.10 Precommissioning

Precommissioning is the testing of the pipeline after it has been laid on the seabed and preparing it for use. This is done to ensure that the pipeline was not damaged during the installation process and to ensure that it will hold the high pressures that might occur during transport. It is also important to clean the pipe before use.

Flooding, gauging and testing
Flooding, gauging and testing (FGT) is a process that is performed before the pipe is taken into service. First the pipe is filled with water, combined with chemicals such as anti-corrosion and anti-fouling and a pigment. The water is run through the pipe until it comes out at the other end. This is the flooding of the pipe.
When the pipe is flooded the next step is to clean and gauge the pipe. This is done by running several PIGs through the pipe. Cleaning pigs consist of either a brush or a rubber skirt to push out any remaining debris. The gauging pigs are disk shaped and made from aluminium. This pig is pushed through the pipe. If the pig comes out the other end without any large damage the pipeline is in good shape. Damage to the pig could mean an untidy weld, a piece of steel that has deformed or even a buckle in the pipeline.
The final step is to test if the pipe is intact. To this end the pressure in the pipe is built up to the design pressure. This pressure is held for 36 to 48 hours. If the pressure remains stable the pipe is intact, if the pressure drops the pipe is leaking, which has to be fixed. [33]

There are two methods that are generally used, a vessel based method, effective up to 300 meters water depth, and a subsea based method, useful in all water depths, but the process is generally comparable. [34]

Table 4-9 Equipment requirements for FGT

	Vessel based system	Subsea system
Crane lifting capacity and requirements	No crane required	20t, no special requirements
Cable or winch requirements for deep water installation	N/A	Yes, necessary in case of deep water precommissioning
ROV	Yes, 1	Yes, 1
Deck space	Yes, test cabin and other equipment need to be placed on deck	Space required for unit
Additional requirements	Storage tank, pumps including additional power units, skids, hose reel. [34]	ROV with enough power to power the subsea unit

Dewatering, drying and purging
Dewatering is the final step before a pipeline is deemed ready to be handed over to the client. The level of dewatering is mostly specified by the client and the product they are going to transport through the pipeline. [34]
These rather specialised tasks are usually left to a subcontractor but equipped with the necessary equipment the *Lorelay* could perform these tasks as well.

The dewatering, drying and purging process can be lengthy and complicated, dependent on the method that is chosen. To get the most of the water out a dewatering pig is used. Its function is to push most of the water out of the pipe, leaving only a bit behind. However, not all the water can be removed and it is possible that so much water remains that problems could still occur during the start-up especially in gas lines which are required to be completely dry. [30] To remove the final bit of water several different methods can be used, for example using low pressure to vaporise the remaining water, or using mono ethylene glycol (MEG) as a dehydrating agent. [33] These processes require a lot of equipment. For example; for the Rota 3 project the *Lorelay* will perform the drying. To this end, 35 containers with compressors are placed on the ship, which are needed to provide enough pressure to push the MEG through the pipeline.
A dewatering installation consists of multiple compressors, their size and strength dependent on the project, as well as a break tank, a pump, control cabin and hose reel. [34]

Table 4-10 Equipment requirements for dewatering

Equipment	Requirements
Crane lifting capacity and requirements	N/A
Cable or winch requirements for deep water installation	N/A
ROV	Yes, 1
Deck space	Yes, space required for equipment
Additional requirements	Compressors, break tank, pumps, control cabin, hose reel.

4.5 Tasks in the heavy lift support

With the *PS* Allseas also operates in the heavy lift market. While the *PS* is capable of performing the entire scope of the project a ship as expensive as this should only be used when absolutely necessary. To this end the heavy lift operations would benefit from assistance by another ship.

Allseas has conducted prior research into the possibility to use the *Lorelay* or another vessel as dedicated support vessel for the *PS.* The tasks within the heavy lift market can be divided into three parts:

a) Topside removal preparations; preparing the topside to be removed by the *PS.* It is possible that the platforms are live during the removal, which means that the accommodations as well as the crane can be used. If this isn't the case a ship with a high crane as well as enough accommodation can be used.
b) Jacket surface preparations; installation of necessary equipment and removal of others. To prepare the jacket for removal several installations are required above water. These structures include an access platform, a pad-eye and the removal of the conductor. This too could be done by the *Lorelay* using her 300t crane. Additionally, due to the removal of the topside accommodation is required, which the *Lorelay* could also perform.
c) Jacket subsea preparations; preparing the jacket for removal under water. This scope includes ROV survey work, removal of small obstructions, creating drain holes, leg cutting and leg excavation (dredging). The weight of these structures is low. It is suggested that a fast, 45 – 65 ton knuckle boom crane is the best option to perform these tasks.

The addition of a larger crane could increase the capacity of the *Lorelay* in this respect but there are no further changes required.

4.6 Summary of potential tasks

After analysis of the potential tasks as well as the capabilities of the other ships that Allseas owns several tasks remain. These tasks are:

- Structure installation
- Umbilical and cable installation
- Riser installation
- Jumper and spool installations
- Retrieval of existing structures
- Mattress installation and crossing preparation
- Span rectification
- Precommissioning
- Topside removal preparations
- Jacket removal and installation support
- Flex lay

In the next chapter a decision has to be made to determine which of these tasks holds the most promise and should be installed on the *Lorelay.*

5.0 CHOOSING THE BEST ALTERNATIVE

The previous chapter ended with a shortlist of tasks that could be performed by the *Lorelay* in addition to the pipe laying she can already do. It is not possible to install all equipment necessary to perform all these tasks at the same time. Therefore a founded decision has to be made to determine what equipment is installed on the ship and which equipment is not. There are multiple criteria that have to be taken into account regarding several combinations of tasks that are not easily compared. These types of problems are generally solved with an MCDA. This method helps the user organise the requirements and solutions and combine them to find a satisfying solution.

Baker, et al. [35] divide the decision making process into eight steps, which can also be found in Figure 5-1. This chapter follows these eight steps to ensure that a suitable solution is found.

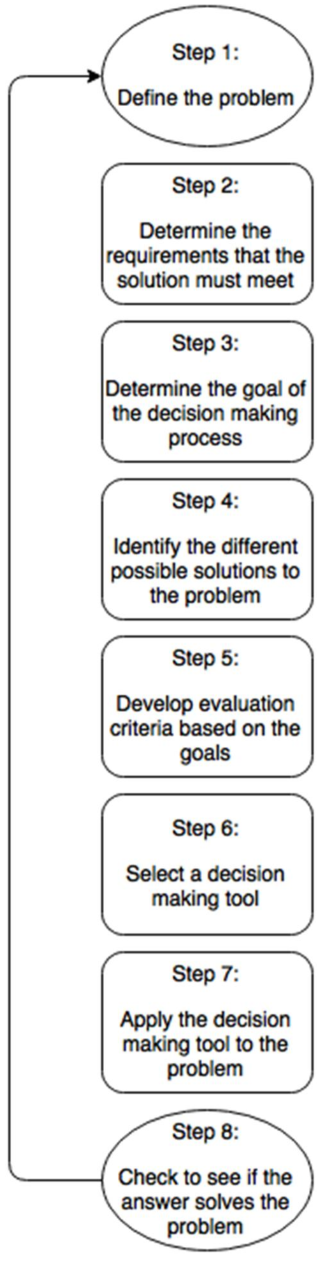


Figure 5-1 Decision making process, adapted from (Baker, et al., 2001)

5.1 Step 1: Problem definition

To find a good solution to a problem it is important to first determine what the problem is. That is the only way to determine of the solution is in fact an answer. [35] The tasks determined in chapter 4.0 are all possible answers to the research question posed at the beginning of this report: *What are possible tasks that the* Lorelay *could perform that can benefit Allseas?* Here benefit is mostly expressed as increasing the utilisation of the *Lorelay.* The question that remains is: *Out of these options what is the best solution given a certain set of circumstances and requirements.* The circumstances are added to the question due to the fact that the offshore construction market is volatile and predictions for the future vary. To ensure that a wide spectrum of solutions is analysed multiple scenarios have to be analysed to find the solution that hold the most value in most or all of these scenarios.

5.2 Step 2: Determination of requirements

In a decision process requirements are used to weed out the impossible solutions. All requirements are qualitative criteria. If the criteria are not qualitative but quantitative it is a wish, not a requirement. This means that requirements provide a binary solution; either a pass or a fail whereas wishes are quantified on an ordinal scale, in essence, better or worse than another. [4]

Simply said, requirements find the possible solutions from a larger set while wishes finally determine which solution is the preferred one.

From the preliminary research several requirements have already been set:

a) After the refit the ship shall still be able to lay pipe at a comparable rate to its current capabilities
b) The solution shall be found within the subsea installation market or the heavy lift market
c) The solution shall be found within a task that Allseas cannot perform at this moment or which is performed in a less than ideal manner
d) The solution shall increase the utilisation of the *Lorelay*

The additional requirements are based on the requirements for the ship; stability, available space and maximum weight.

The ship is known to have a relatively high CoG and thus a low stability. This means that it is not possible to place an unending amount of weight on the deck of the ship without placing enough ballast low in the ship to counter this. Whether or not this is possible is also related to the maximum weight the ship can carry.

The ship is designed for a certain summer draught as well as a maximum weight at which this draught is reached. Since all structural calculations are based on these two numbers they cannot be exceeded. The corresponding values can be found in Table 5-1. [36]

Table 5-1 Weight of the ship at summer draught

Description	Value
Summer draught	9.024 [m]
Displacement in seawater	29269 [t]
Light weight of the ship	14438 [t]
Maximum allowable deadweight	14830 [t]

Next is the available deck space. As mentioned in Chapter 2.0 there is very little deck space available on the *Lorelay.* More space can possibly be created by removing, moving or replacing specific equipment but there is a maximum on the amount of space available. If all equipment, save for life saving equipment cranes and hatches, is removed from the ship a maximum of 1500 m^2 is available. [37]

The final requirement is practicality. This means that it must still be possible to work on and with the ship after the refit. For example, should the ship be outfitted with a reel, it cannot be so large that passing it is not possible. This is mainly a requirement that has to be taken into account in the design phase but it should also be considered when looking at different concepts.

The requirements placed on the capabilities of the ship are:

e) The total weight of the ship shall not exceed 29000 t
f) The ship shall meet the requirements set by the classification society
g) The required space shall not exceed 1500 m^2
h) The design of the ship shall be practical in use

5.3 Step 3: Establish goals

For this analysis method goals relate to the goals for the solution to the problem defined in step one. These goals should go beyond the requirements and towards wishes for the design. Goals are broad statements that are narrowed in the fifth step: Definition of criteria. [35]

Simplified it can be said that Allseas is interested in two things with regards to a refit: what will be the cost, and what will be the gain. Together these two questions cover most of the goals that could be set for the refit of the *Lorelay.* This means that the main goals for the solutions are:

a) The cost of the conversion and subsequent use of the vessel should be minimised
b) The benefit of the conversion should be maximised

5.4 Step 4: Identify alternatives

The next step is to identify the possible solutions to the problem defined above. The alternatives are tested to both the requirements and the goals that have been set up to create an overview of feasible solutions to continue with.

From the previous chapter a list of possible tasks has been created. The remaining tasks are:

- Structure installation
- Jumper and spool installations
- Umbilical or cable installation
- Retrieval of existing structures
- Mattress installation and crossing preparation
- Span rectification
- Precommissioning
- Topside removal preparations
- Jacket removal and installation support
- Installation of flexible pipelines and risers

There is a large difference between these tasks, some are small and require only a small addition to the vessel while others require a large refit to be possible. It is also possible that some tasks require the same equipment which means that if the ship is able to perform one of these tasks it is also possible to perform the other. To find these connections and possible combinations an overview of all tasks and the main required equipment is made. This table can be found in Appendix C.

5.4.1 **Current layout of the ship**

To get an idea of the changes required to perform the alternatives that are mentioned in this chapter it is important to know what the ship looks like in its current configuration. Figure 5-2 shows the current layout of the ship with its most important equipment named.

There are some difficulties when looking at ways change the ship. One of them is the boom rest for the special purpose crane (SPC). When in transit the boom of the crane has to be lowered and placed in a boom rest. This boom rest is currently installed on top of the firing line to save space. When parts of the firing line are removed this could cause problems as removing the base of the boom rest means that it either has to be moved or a base has to be placed on deck.

Another important thing to note is that the firing line lowers towards the water after the boom rest. From here it passes through an opening in the deck towards the water line. This means that when the equipment is removed a large hole is present in the deck. Thought has to be given to the manner in which this area is going to be utilised.

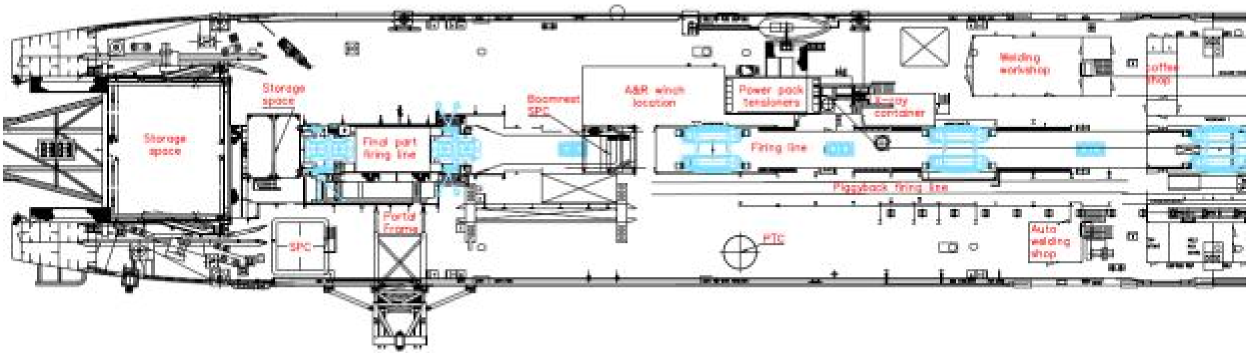


Figure 5-2 Current deck layout of the *Lorelay*

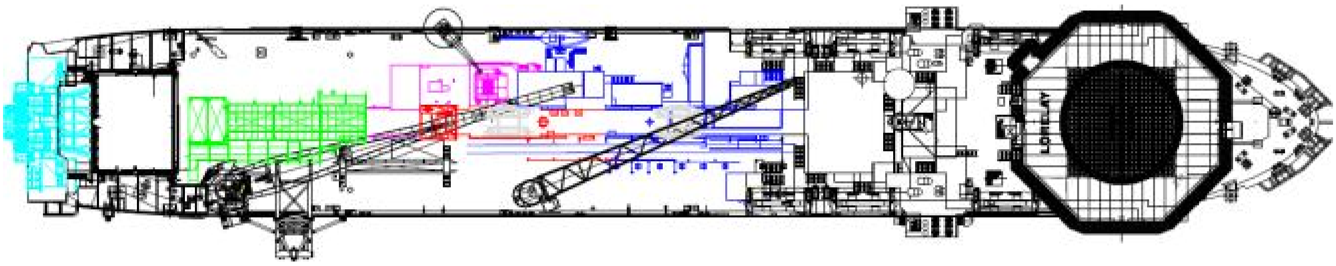


Figure 5-3 Visualisation of suggested removals of equipment

5.4.2 **Alternative 1: Installation of jumpers, spools and structures**

From the table in Appendix C, it is clear that the requirements for the installation of jumpers and spools and structures are the same. The only way they differ is in the way the different constructions are placed on the ship. This means that if the ship can install structures it can automatically install jumpers and spools as well. In this case there are two options; transporting the jumpers, spools and structures on board or having them brought to the ship using a barge. The preferred method is transporting the structures on the ship as it saves money, increases workability and decreases the risk of delay due to unforeseen circumstances.

Small upgrade

There are three options for an upgrade to the ship with regards to jumper, spool and structure installation. The first is a small refit where the A&R winch is moved to the crane and the rest of the storage deck is emptied out as much as possible. This option provides a minimal increase in available deck space compared to the current situation and thus provide only a minimum improvement.

Modular firing line

The next option is to remove the aft part of the firing line to create more space. This would require a significant change to the firing line, which has to be made removable. In Figure 5-4 an impression is given on how the transport of jumpers, spools and structures would look on the ship. In this case, the space that is currently used for general storage is utilised to transport structures. In additional to using the general storage space, the A&R winch has been moved from its original location on the portside of the ship to the crane.

A part of the firing line, starting aft of the boom rest is removed. This part of the firing line is denoted in green in Figure 5-3. This opens up the space aft of the ship for structures, jumpers or spools. Since the firing line moves towards to waterline at the aft side of the ship a solution is needed to close this area off and create a level deck to transport the structures. The jumpers and spools can also be transported on both sides of the ship, within reach of the crane.

In this situation it is possible to create around 650 m^2 of deck space for structures on deck as well as space for several jumpers on the side of the vessel.

The removal of part of the pipeline creates an additional challenge. If the ship is to be used as a pipe laying ship these elements will have to be replaced on the ship. This means that both the firing line and the adaptations that are made to the ship to enable the transport of the structures will have to be adjusted in such a way that they are easily removed from- and placed on the ship.

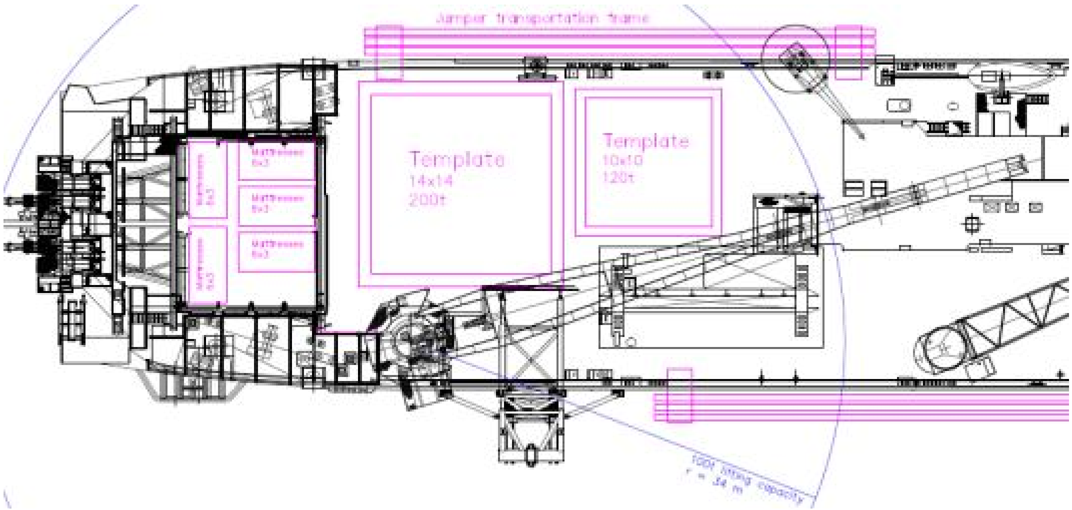


Figure 5-4 Impression of the *Lorelay* carrying several large structures

Increased crane size

The final concept is to crease the capacity to carry structures even more by increasing the crane capacity and making a larger part of the ship modular. Increasing the crane capacity, means that the reach of the crane also increases. This in turn means that the total size of the crane also increases. It is not possible to only increase the range of the crane, except by increasing the whip hoist. However, the whip hoist does not have enough capacity to lift the required elements. A whip hoist is made for lifting light elements such as a container. For the *Lorelay* the capacity of the whip hoist is 20 t, which is not enough for lifting and installing structures. To increase the weight of the structures that can be lifted, a scale increase of the crane is required. This is visualised in Figure 5-5.

When the crane is scaled up to a larger size, the mast and its foundation also increase in size. This means that the structure under deck that supports the crane also has to be redesigned and replaced. This requires a lot of engineering since the new foundation has to be connected to the existing ship to ensure a good distribution of the weight and corresponding forces.

With the crane size increased a larger part of the deck can be used for the transport of structures. It might be an option to remove the firing line up to the second tensioner. This is visualised in Figure 5-3 where for this alternative both green, purple and red elements are removed from the ship.

In order to create more space the boom rest for the crane is moved to the top of the power pack.

In this alternative, the third tensioner is removed from the vessel. To keep the ships pipe laying capabilities it has to be possible to replace the tensioner back on board relatively quickly. Since this is not possible at this point a redesign of this tensioner and its supports is also required.

Figure 5-5 shows the *Lorelay* with a 30% larger crane. This scale figure is based on the reach of the crane, especially the 100t range and the available space on board of the ship, both around the foundation of the crane as at the tip of the crane. This leads to a crane with a maximum reach of 65 meters and a 100t range of around 50 meters. It is important to note that this figure is not based on hard calculations and is mostly meant as an indication of the possibilities.
Removing all elements suggested above would lead to a deck area of around 1000 m^2.

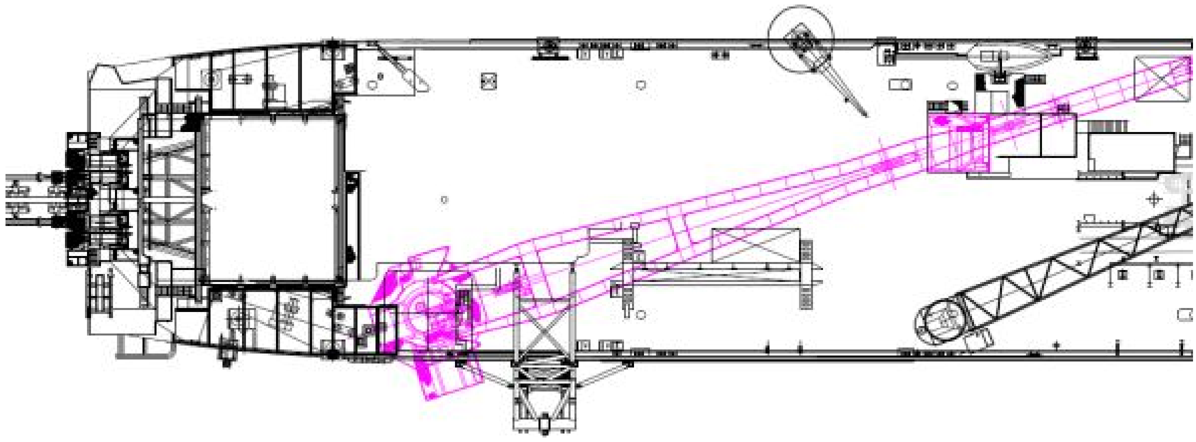


Figure 5-5 Impression of the *Lorelay* equipped with a 30% larger crane in structure transport mode

5.4.3 Alternative 2: Flex lay

In order to install flexible pipelines and risers the *Lorelay* has to be converted into a reel-lay vessel. To do so, the whole firing line is removed from the ship. This is possible since the pipe laying capabilities of the ship are taken over by the reel. This creates a lot of space underneath the deck house, where the firing line starts. Several workshops that are removed from the deck to create space for the reel can be placed there. This can be seen in Figure 5-6 and Figure 5-7.

To improve the amount of work for the ship in this concept it is possible to create a reel that can also be used for the installation of cables. This would mean a much larger market for the ship to operate in.

Figure 5-6 and Figure 5-7 show an impression of the *Lorelay* as a reel-lay vessel. To make this impression, equipment information from the *Seven Oceans* from Subsea 7 is used. The ship is comparable in size to the *Lorelay* and its equipment fits on board. The *Seven Oceans* is equipped with a reel with a diameter of 28 meters and a capacity of 3500 tons, allowing it to lay up to 120 km of pipe. [38]

To lower the centre of gravity of the ship with the heavy reel on board, the reel is not placed on deck but it is lowered into the hold. This means that a large part of the deck has to be removed, the tank top might require additional stiffening to be able to support the reel and side walls around the reel need to be constructed. It might also be necessary to strengthen the deck that remains around the reel since the removal of a large part of the deck might cause problems for the longitudinal- and torsional stiffness. In short this means that all equipment shown in colour in Figure 5-3 is removed from the ship.

In addition to the reel an A-frame is needed on the back of the ship. This A-frame is equipped with a straightener and tensioners and is used to guide the pipeline overboard. This means that the stinger is obsolete and can be removed.

For this configuration the A&R winch has to be removed from deck. For this reason it is placed in the crane. It is also necessary to move the boom rest. In the original position the crane would collide with the reel. The specifics of a solution for this can be determined in a later stage of the design process.

The main disadvantage of using the reel-lay technique instead of the S-lay technique is that the pipe laying capabilities of the ship diminishes. The maximum diameter that can be installed decreases and the ship loses its capability to install concrete covered pipes. On the other hand the ship gains the capability of laying flexible pipelines as well as cables.

Combination with other concepts

If the ship is not laying pipe it could be used to install structures. If the A-frame is in an upright position a space of around 700 m^2 is available for the transport of structures without any further adaptations.

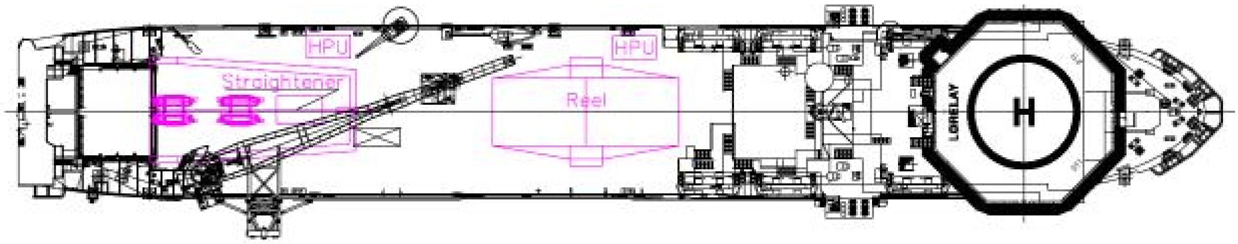


Figure 5-6 Impression of the *Lorelay* as a reel-lay vessel - top view on main deck

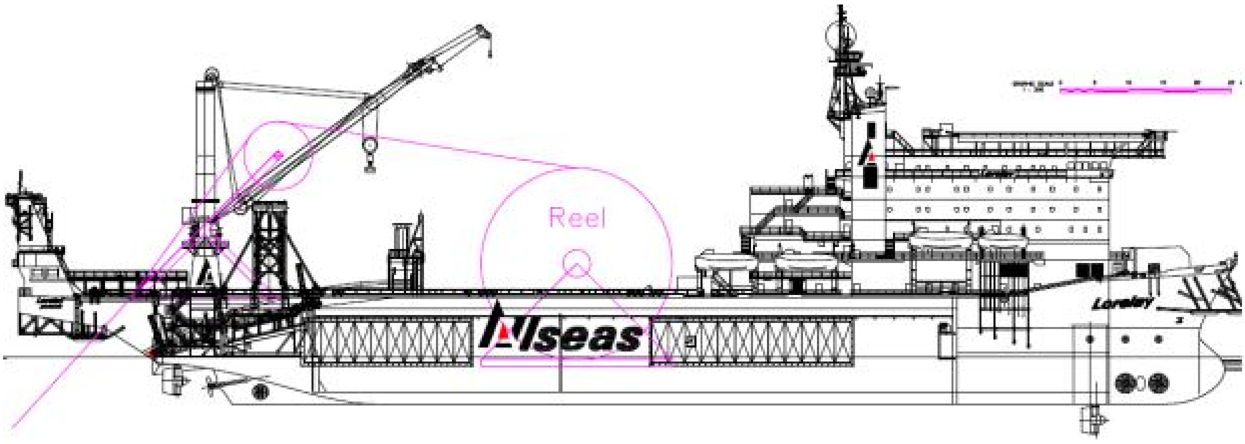


Figure 5-7 Impression of the *Lorelay* as a reel-lay vessel - side view

5.4.4 Alternative 3: Cable laying and umbilical installation

There are two options when using the *Lorelay* to install cables and umbilicals. It is possible to create space for a small carousel or reel and store several more nearby. The second option is to use a large carousel, either installed on deck or in the ship's hold.

Using a small carousel

Reels are available in sizes from 150 t, carrying only a few kilometre of cable or umbilical, up to more than 10000 t, carrying hundreds of kilometres of cable. [39] The largest carousel that could be lifted by the crane would weigh 300 t and can carry approximately 12 kilometre of cable. The biggest downside to using small carousels is that cables have a maximum bend radius. Thus the carousel has a minimum radius which means that a small carousel takes up a lot of space that is not useful when compared to a larger carousel.

Additionally the reach in which the crane can lift 300t is very small, allowing for only a small number of additional reels to be carried by the ship.

This concept does not meet the practicality requirement and is thus discarded.

Using a large carousel

The best place for a large carousel on deck is on the aft of the ship as shown in Figure 5-8. This would require the least amount of equipment removed from the ship, keeping the refit cost low. From here the cable or umbilical can be routed via main deck into the firing line and to a tensioner placed at the location originally meant as reserve location during the pipe laying process. From there the cable is guided overboard using a chute.

To make this solution possible the carousel is placed on a part of the ship that is currently used for container storage. Since the weight of the carousel is much larger than that of a few containers this location might require additional strengthening.

In this configuration the firing line can remain mostly on board. However, the cable does require an entrance into the firing line from the side of the ship. This is shown in Figure 5-8.

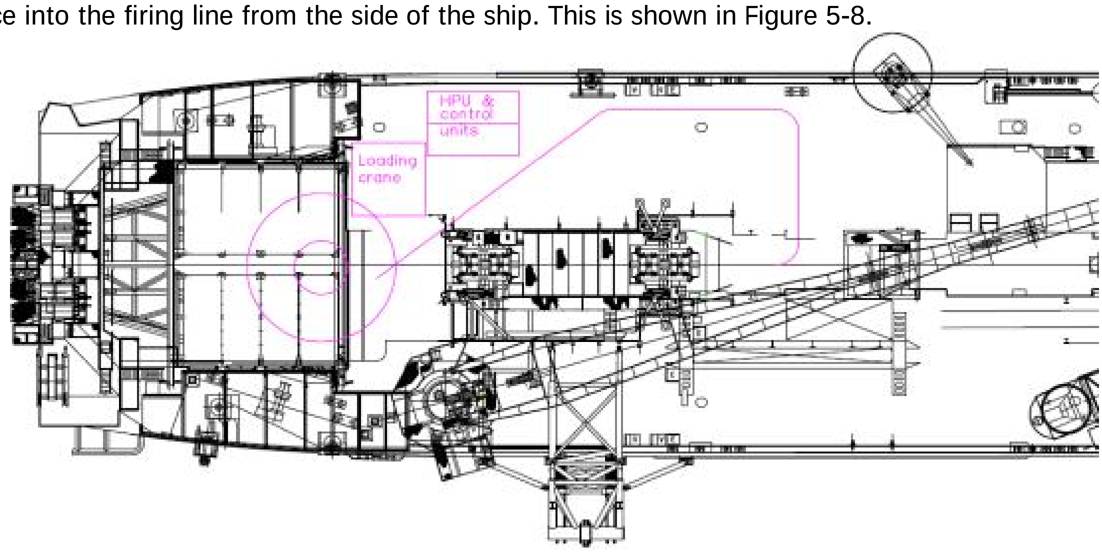


Figure 5-8 Impression of the *Lorelay* with a 10 m diameter carousel on deck

Modular cable reel

Another possibility is to choose to use a modular reel. By removing part of the firing line the reel can be placed further forwards on deck as well. Removing part of the firing line also means that the diameter of the reel can increase, allowing the ship to install more cable without stopping. An example of this is shown in This once again required that the firing line can be removed from the ship easily.

The stinger is not necessary when installing cables or umbilicals. Therefore the stinger could be removed from the ship but it might not be the best course of action. The removal of a stinger is not a simple task. For shorter projects it might not be worth it to remove the stinger from the ship, especially if the firing line can remain on the ship.

In addition to the carousel a loading crane, an HPU and a control unit are required to transport the cable from the carousel to the chute. [39]

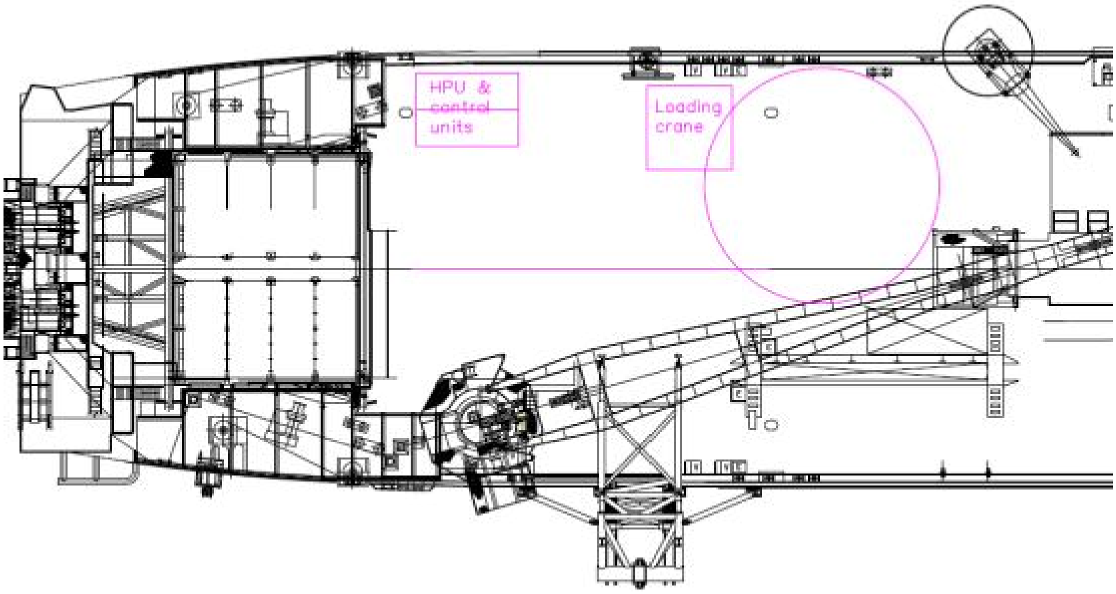


Figure 5-9 Impression of the *Lorelay* with a 14 m reel in modular configuration

Placements of a reel in the vessel hold

It is also possible to install a carousel, or multiple, in the hold of the ship. The Drammen Yard [40] offers a solution where the carousel is lowered into the hold in parts, up to the diameter of the carousel wide, through an existing opening. The hold of the *Lorelay* is approximately 12 meters wide at the bottom, allowing for a carousel of approximately 10 meters in diameter.

The main disadvantage of this concept is that the carousel is installed in the hold on a more or less permanent basis. It would take a few days if the carousel is to be removed from the hold again if the pipe carrying capacity of the ship is required again. On the other hand it is better for the stability of the ship, as well as for its cable carrying capacity to place one or two carousels in the hold of the ship.

5.4.5 Alternative 4: Precommissioning

The requirements for precommissioning differ greatly between the three options suggested in paragraph 4.4. Therefore the options are discussed separately.

Vessel based FGT operations

When FGT operations are performed from the ship it requires storage tanks, pumps with corresponding power units and a reel with a hose for the delivery of the fluids. The tanks, pumps and corresponding pipelines through the ship are all placed under deck. In order to have enough tank space some tanks might have to be converted or newly created.
To transport the fluids for FGT down towards and through the pipeline large pumps are needed. These pumps are available in container size that can be placed on deck. These can be placed either on the storage space at the back of the ship or aft on the port side of the ship.
The last element that has to be installed on the ship is the hose reel. Since the reel requires access to the water it should be placed somewhere near the side of the ship.

Subsea based FGT operations
When FGT operations are performed in deeper water a subsea unit can be used. This unit is placed on deck and lowered to the seabed using the crane. [34] Having a separate unit also means that it can be stored somewhere when not in use and does not have to stay on the ship continuously.

The subsea unit has to be supplied with the same materials and chemicals as a vessel based system. Therefore the vessel has to be equipped with storage tanks for these chemicals and fluids, and a network is needed to transport them to the deck to be placed in the unit.

The unit is small and it should be possible to place it on the ship without making any changes to the deck.

Dewatering
The third option for precommissioning is adding equipment to perform a dewatering operation. For Rota 3 the dewatering process is performed using MEG. The tank, the monitoring equipment and the transport system for this material remains on board of the vessel.
To transport the MEG down towards the seabed a significant amount of pressure is required. The containerised units that provide this pressure can be placed on the ship and be removed at will. However, with these containers on board there is little room for anything else. To create enough space for the containers it might be necessary to remove or move other equipment. Additionally the heavy and numerous which means that stability might be an issue. This would also require adjustment.

Based on the high amount of required equipment, it is best if this equipment can be removed from the ship when not needed as it is likely that it will obstruct the

5.4.6 **Alternative 5: Heavy lift support**
There are three tasks identified for the *Lorelay* with respect to heavy lift support; assisting with a topside removal, assisting with a jacket removal and operating as an accommodation vessel during these operations. For both topside removal and jacket removal an accommodation vessel could be required. Additionally the requirements for topside and jacket removal are relatively similar. For this reason the three tasks are combined into one concept. An impression of how this would look on the vessel is found in Figure 5-10.

The ship is equipped with a hydraulic gangway to facilitate easy transfer of personnel. The hydraulic gangway is placed on the starboard side of the vessel to ensure that it is possible to connect the hydraulic gangway as well as use the crane to its full capacity. If the hydraulic gangway is placed on the opposite side of the vessel the maximum height the crane can reach decreases.
The hydraulic gangway, in the drawing assumed to be an Ampelmann A-type, requires a TEU for spare parts as well as a TEU containing the HPU. [41] These walkways can either be placed on the ship permanently or can be rented on project basis. In principle an Ampelmann hydraulic gangway can be installed on every vessel without a lot of changes and within a day.

The A&R winch is once again moved into the crane, freeing up deck space and allowing for the required AHC for jacket preparations.

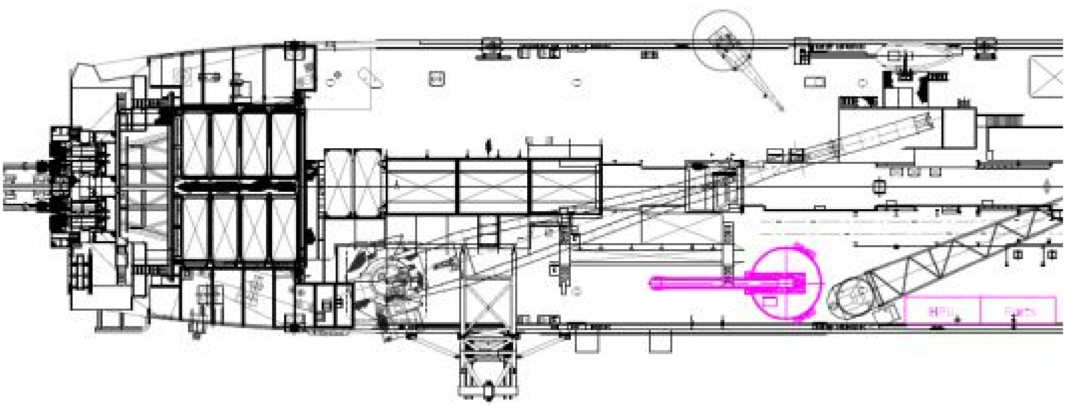


Figure 5-10 Impression of the *Lorelay* equipped with a hydraulic gangway

Increasing available deck space

In this concept there is some deck space available for the placement of necessary equipment. Should the available space not be sufficient it is also possible to remove the last part of the firing line. This, once again, requires that replacing it on the ship is easily done.

Combination with jumper, spool and structure installation
With the removal of the last part of the firing line it is possible to create around the same amount of available deck space as in the first concept of alternative 1.

Increased crane length
To increase the number of topsides that can be worked on by using the ships own crane instead of the crane installed on the topside the reach of the crane has to be improved. The details of such a modification have already been discussed above for the concept of an increased crane for jumper, spool and structure installation.

Increased crane length combined with jumper, spool and structure installation
It is also possible to increase the crane capacity and install a hydraulic gangway on the vessel to enable the vessel to perform both heavy lift support operations as well as install jumpers, spools and structures. In this case the same elements are removed from the ship as were described for the alternative of increasing the crane capacity for jumper, spool and structure installation.
In this case the free deck area is approximately 900 m^2 due to the installation of the hydraulic gangway and its required parts.

5.4.7 Alternative 6: Performing all tasks mentioned above
The final concept is to have the ship perform all of the tasks mentioned above. For many of the alternatives it is suggested that making the firing line modular would improve how well the task can be performed. If the firing line is redesigned in a modular configuration and it is removed from the deck, the now empty deck can be used for any of the named options, as well as perhaps other that are outside the scope of this research.

In the rebuilding options mentioned above it was suggested that the firing line is removed aft of the boom rest or the third tensioner. This would allow the SPC to reach every part of the newly created deck.

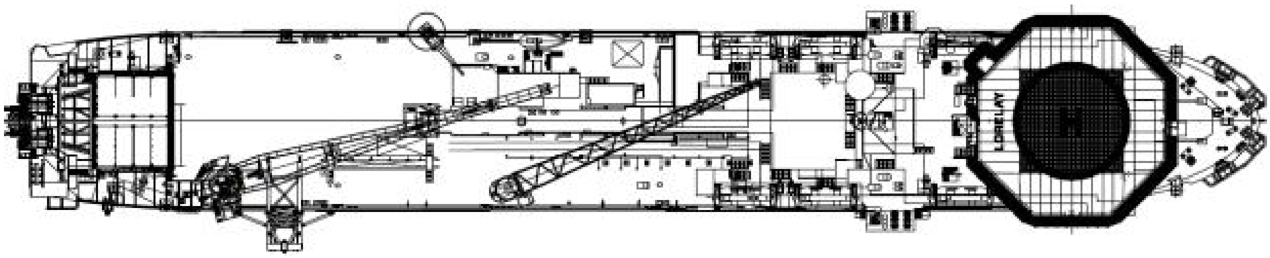


Figure 5-11 Impression of the *Lorelay* in modular conversion

5.4.8 Additional tasks
In addition to the 6 options mentioned above, two alternative tasks could also be performed by the *Lorelay.* These tasks are too small to be performed added as a separate alternative but can be combined with others.

Mattress installation
The installation of mattresses is only a small task. It requires a location where the mattresses can be stored, for example as they are placed in Figure 5-4 and a mattress installation frame (MIF) or subsea installation frame (SIF). An additional requirement for the use of a MIF is that AHC is needed for the crane to allow the ROV to connect to the frame in order to control it. Should a SIF be chosen as the best option, it would require a storage location.

The final choice on which of the two installation options is used, is made based on the other tasks that the ship can perform and the capabilities that are required for that task. For example; if a lot of deck space is required a small frame might be preferred over the larger subsea frame.

Span rectification
Span rectification has the same disadvantage as mattress installation. It is only a small task, but it has to be done. Just like with the installation of mattresses the task is too small to stand alone but could be combined with other alternatives and still prove useful there.

5.4.9 Summary of alternatives

To summarise, the following alternatives, with all subdivisions have been suggested:

1. Installation of jumpers, spools and structures (Small refit)
    a. Small refit; cleaning up the ship and moving the A&R winch
    b. Combined with mattress installation
    c. Combined with span rectification
    d. Combined with both mattress installation and span rectification
2. Installation of jumpers, spools and structures (Large refit)
3. Allow for the installation of flexible pipelines and risers as well as rigid pipelines and risers by converting the ship to a reel-lay vessel
    a. Performing reel and cable laying activities
    b. Reel-lay combined with installation of jumpers, spools and structures
    c. Any of these alternatives combined with mattress installation, span rectification or both
4. Cable laying
5. Precommissioning
    a. Vessel based FGT
    b. Subsea based FGT
    c. Dewatering
6. Heavy lift support
    a. Heavy lift support
    b. Heavy lift support and jumper, spool and structure installation
    c. Heavy lift support with a larger crane
    d. Heavy lift support and jumper spool and structure installation with a larger crane
7. A combination of all options mentioned above

5.5 Step 5: Determination of criteria

With the goal and requirements determined, the next step is to determine the criteria on which the final choice is based. Before the criteria are set up, it is important to know what requirements they must meet:

a) The criteria have to be independent of each other, meaning they cannot depend on the same factors. Should the two dependent criteria be necessary for making a good analysis it is possible to work with sub criteria. In that case it is acknowledged that the criteria are dependent. By working with sub criteria a score can be determined for the overarching criterion. This score is then divided across the different sub criteria. [35]
b) It has to be possible to determine a value or score for each alternative for each criterion, otherwise a comparison is not possible [42]
c) The ideal number of criteria is between four and six. With three or less criteria the analysis becomes very susceptible to small changes in scores which cause large effect. Making a consistent comparison between more than six criteria is very difficult for a human brain. This also holds true for the number of alternatives. When a lot of alternatives are compared it is difficult to set up a consistent analysis. [43]
d) It is possible to assign weights to each criteria to show that a criteria is deemed more, or less, important than the others. [44]

Based on the requirement and the main goals determined in step 3 the following criteria are chosen.

- Size of the refit
    - Time it takes to perform the refit
    - Cost of the refit
- Market size
- Competitiveness

Each of these criteria is discussed below, explaining why it is used, how a value or score can be determined and what the possible pitfalls are.

With the goals of the MCDA based on money it seems a logical step to also use money as a decision tool. This is possible when using a cost benefit analysis which focusses on the monetary cost and benefits. However, defining capital expenditure (CAPEX), in monetary units, is very difficult at this stage. The alternatives are still in an early stage, making it impossible to determine the exact changes that have to be made to the ship. In this stage it is only possible to make rough estimations with regards to, for example, the required materials and man-hours. Since the estimations are so rough it is not possible to make a meaningful decision that holds up to scrutiny. To be able to do that a detailed design of all the alternatives is required. Within the time constraints of this project this is not deemed feasible. Additionally it would negate the need for an analysis at this stage of the project. Therefore this method is not chosen.

Not being able to quantify the criteria is a continuous struggle within this, and many other decision processes. The MCDA allows for these uncertainties by offering numerous solution methods based on the manner in which the criteria can be determined. Not being able to quantify the results is not necessarily a problem.

5.5.1 **Size of the refit**

The size of the refit means the amount of changes that have to be made to the ship, as well as the type of changes that have to be made. This includes the equipment that has to be bought for the completion of the refit. The size influences two important aspects in the decision process, the cost of the refit and the time it takes to complete the refit.

The cost is important as it stands in direct relation to the goals of the company and this analysis. By using the size of the refit as a measure for the cost a very basic, unquantified, determination of the cost can be made. In essence, it is possible to state that concept A requires less work than concept B. As stated before, making a detailed overview of the expected cost is not possible. However, it is possible to estimate if there is a small or a large difference between the costs of two different concepts.

The time a refit takes is also important since the ship is not making money while the ship is in dock. In the same simplified manner as with the cost the assumption is made that a larger refit automatically means more time in dock for the ship.

As both the time and the cost are dependent on the size of the refit they cannot be seen as separate criteria. However, in different market situations they do have a difference importance based on different situations. For example, when the market is bad and the ship lays idle, the time a refit takes is not very important. However, the cost of the refit is more important due to the decreased income. This means that each of the criteria have their own weight factor, determined by the state of the market and the investment strategy. To this end, these two elements are taken as sub criteria of the size of the refit, allowing for their own weight factor with.

5.5.2 **Market size**

When entering a new market it is important to know what the state of this market is. Questions such as "how many contracts are available?" arise.

The thing to keep in mind with this criterion is that the markets are subject to change, making it hard to determine something that holds true for longer periods of time. To solve this it is possible to work with multiple scenarios, each representing a different stable market state, allowing for a well-founded conclusion based on multiple market situations. This possibility is further explored in paragraph 5.7.

In some cases, the capabilities that are added to the ship might not have a direct influence on the number of contracts that are available as the tasks are already part of pipe laying contracts. In that case it is more important that it is not necessary to include a subcontractor or to hire an additional vessel. This element is covered by the next criterion.

5.5.3 **Competitiveness**

The decision to enter a market is not solely made based on the size of the market. The ship also needs to be competitive in order to win the available contracts. For example, being able to lay cables does not automatically mean that the ship receives contracts. If all competitors average a much higher laying speed or much lower cost they are the preferred contractors for projects. This information can be found by comparing the proposed alternative to the main competitors in that market.

5.6 Step 6: Determination of analysis method

There are many options to solve a multi criteria decision problem. What method is used depends on aspects such as the complexity of the problem, the experience of the users and the type of answer that is needed from the analysis method. [35], [43] In this step the ideal solution method is determined based on these aspects.

5.6.1 **Defining the problem**

To determine which method is the best the first step is to determine the type of decision problem that is to be solved. This knowledge can then be used to narrow down the most appropriate method.

Ishizaka and Nemery [42] define four types of problem in their book;

a) The choice problem; this problem leads to a single best option or to the reduction of the number of options.
b) The sorting problem; in this case the options are sorted into ordered and pre-defined groups. It can be used as an initial screening to reduce the number of options.
c) The ranking problem; options are ordered from best to worst by scores or pairwise comparison.
d) The description problem; the goal is to describe the options and their consequences. This is done as a first step to understand the characteristics of the decision problem.

The goal of the decision process is to not only find the best solution but to also know how it is ranked with regards to the other options. It is also important to know how large the difference between the options is and how stable the solution is. Therefore this problem is approached as a ranking problem.

5.6.2 Selecting the most suitable method

Within the MCDA there are many different methods, suitable for solving one or several of the problem types described above. To find the best method that is to be used a preliminary investigation of the decision problem is proposed. [42]

Looking at the data available for this decision problem a few notes can be made:

a) There is very little quantifiable difference between the alternatives.
b) There are only general thresholds available to determine what is and isn't possible in detail.
c) The solution should give a complete ranking of all possibilities as well as the difference between each of them.

There are a multitude of different methods that can be used. Some of these are listed in Figure 5-12 together with the requirements and outcome of each of these methods. The methods mentioned in Figure 5-12 are all based on calculations. Baker et al. [35] suggest three methods that are more logic based. These methods are:

- Pro and con analysis
- Kepner-Tregoe Decision Analysis
- SMART

The final method worth mentioning is the cost-benefit analysis, which is also a MCDA method.

To select the best method, first the three observations about the data are used to discard methods that cannot be used.

The first observation made about the data is that there is no quantifiable difference between the alternatives. This means that MAUT cannot be used. This method requires utility functions as an input. A utility function is a function that creates a relationship between a criterion and a normalised score. This requires both the worst value and the best value. [35] It is not possible to determine utility functions for the criteria selected, thus MAUT is discarded as an option.

The second observation about the available data is that there are only general thresholds available which make up the criteria. When using either ELECRE or PROMETHEE a preference threshold is required. A preference threshold is a minimum value for the criteria that is required for every solution. [45] This rules out ELECTRE and PROMETHEE as suitable analysis methods.

Goal programming and TOPSIS are based on a similar principle. They use an ideal solution, which scores the maximum amount of points to compare the other solutions to. [42] This means that using these methods is also not possible.

The DEA method mentioned in Figure 5-12 is used to determine the efficiency of different companies or departments. This method does not provide a clear best solution, it only provides a range in which the solutions fall. Since the goal is to find one solution this method is discarded.

	Inputs	Effort input	MCDA method	Output
Ranking/choice problem	utility function	Very HIGH	**MAUT**	Complete ranking with scores
	pairwise comparisons on a ratio scale and interdependencies		**ANP**	Complete ranking with scores
	pairwise comparisons on an interval scale		**MACBETH**	Complete ranking with scores
	pairwise comparisons on a ratio scale		**AHP**	Complete ranking with scores
	indifference, preference and veto thresholds		**ELECTRE**	Partial and complete ranking (pairwise outranking degrees)
	indifference and preference thresholds		**PROMETHEE**	Partial and complete ranking (pairwise preference degrees and scores)
	ideal option and constraints		**Goal programming**	Feasible solution with deviation score
	ideal and anti-ideal option		**TOPSIS**	Complete ranking with closeness score
	no subjective inputs required	Very LOW	**DEA**	Partial ranking with effectiveness score

Figure 5-12 Required input for ranking or sorting problems [42]

The three remaining methods; Analytic Hierarchy Process (AHP), MACBETH and ANP, are all similar methods. Using MACBETH is not possible due to the use of an interval scale. An interval scale is a scale like the Celsius scale for temperature rating; two points are known and the scale between this is divided into equal intervals. Since there are no set points available for the analysis that has to be done this method cannot be used.
The main difference between the AHP and the ANP is the dependency of the criteria. The AHP aims to create independent criteria while the ANP provides a way to take the interdependencies into account. To lower the possibility of accidentally assigning a higher importance to one criterion, dependencies are avoided, thus the AHP is preferred over ANP.

The pro and con analysis is a very basic analysis. Each alternative is ranked for each criterion and the best and worst solutions are listed as pros and cons. The solution that has the most pros and the least cons is the best solution. [35] This method requires very well defined criteria with a clear answer to the question which is better. If this isn't the case this method is in danger of becoming very subjective. This means that this method is not suitable for this problem.

The Kepner-Tregoe Decision Analysis is an expansion of the pro and con analysis and is comparable to the AHP method. It gives the possibility to rank different criteria by introducing a scoring system. This method is comparable to the AHP due to the possibility of assigning weight to criteria and scoring the alternatives on all of the criteria. The main difference is that AHP uses pairwise comparison which leads to a more mathematical and structured approach whereas the Kepner-Tregoe Decision Analysis uses a score system out of 10 where all alternatives are ranked simultaneously. For this reason AHP is preferred over the Kepner-Tregoe Decision Analysis.

The SMART analysis further quantifies the analysis by introducing a scoring rule of thumb. The best solution scores a maximum score which decreases by using the rule of thumb. The total score of the alternatives is than calculated using this score and a criterion weight factor. [35] The introduction of a rule of thumb makes this method unsuitable for the problem that is to be analysed as it is very difficult if not impossible to determine a consistent rule of thumb due to the large differences between the alternatives.

After analysis of the different available methods the AHP method is chosen as the most suitable analysis method. This method is further explained in paragraph 5.7.

5.7 Step 7: Performing the Analytical Hierarchy Process

The AHP is one of the most widely used MCDA methods. It is based on a pairwise comparison between the alternatives over the predetermined criteria. This paragraph first provides an explanation of the way AHP works. All calculations explained in this paragraph have been calculated using a combination of Matlab and Excel. The Matlab code used can be found in Appendix F. The Excel sheet can be found in Appendix G

5.7.1 Method used

AHP is used to solve multi criteria problems for which the criteria are difficult to quantify. To obviate this, the AHP makes use of an ordinal scale. To find the best solution to the decision problem it makes use of a capability that all human possess; the ability to compare two options with each other based on a single criterion.

The way AHP works is explained by walking through the process for one group of alternatives for one scenario. The alternatives are divided into groups to keep the number of comparisons manageable and different scenarios are used to take the volatility of the market into account. The first step is to determine the criteria weights for all the criteria.

Assigning weight to criteria and alternative scoring

It is possible that the decision maker favours one criterion over the others. To that end it is possible to assign weights to the criteria, also using pairwise comparison.

To make a comparison between the criteria Thomas Saaty, the creator of AHP, [46] suggests using a 9 point scale. This scale, together with the meaning of each score is given in Table 5-2. Since the conception of the AHP changes have been made to the explanation of the scores to suit individual projects. Any explanation of the scores can be used, as long as it is used consistently. Table 5-2 also shows a second explanation for the scores, suggested by Lootsma [43]. These are used for the comparison in this analysis since this phrasing matches the problem better.

The pairwise comparison is made in the manner denoted in Figure 5-13. After determining which criterion has preference over the other a score is given to the size of this preference. This process is repeated until all comparisons are made.

The answers gotten from the pairwise comparison are placed in a matrix. The matrix is positive and reciprocal, meaning that [47]:

$$a_{ji} = \frac{1}{a_{ij}}$$

When comparing the options with themselves there is no difference between them and thus the score is one.

Table 5-2 Intensity of importance scale suggested by T. Saaty [46] and Lootsma [43]

Intensity of importance	Definition	Explanation given by [46]	Comparative judgement according to [43]
1	Equal importance	Two activities contribute equally to the objective	Equal importance
3	Week importance of one over another	Experience and judgement slightly favour one activity over the other	One activity is somewhat more important than the other
5	Essential or strong importance	Experience and judgement strongly favour one activity over another	One activity is more important than the other
7	Demonstrated importance	An activity is strongly favoured and its dominance demonstrated in practice	One activity is much more important than the other
9	Absolute importance	The evidence favouring one activity over the other is of the highest possible order of affirmation	One activity is vastly more important than the other
2,4,6,8	Intermediate values between two adjacent judgements	Used when compromise is needed.	Not specified

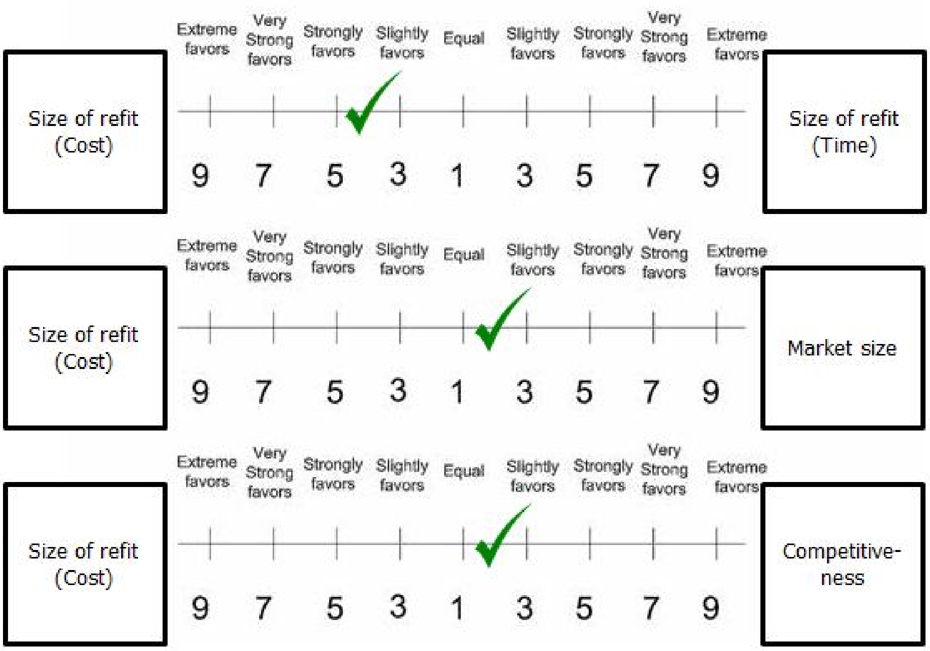


Figure 5-13 Pairwise comparison example

The example above, expanded by the other comparisons not shown, leads to the following matrix:

Table 5-3 Criteria scoring table - example

	Size of refit (Time)	Size of refit (Cost)	Market size	Competitiveness
Size of refit (Time)	1	$\frac{1}{4}$	$\frac{1}{7}$	$\frac{1}{6}$
Size of refit (Cost)	4	1	$\frac{1}{2}$	$\frac{1}{2}$
Market size	7	2	1	$\frac{3}{2}$
Competitiveness	6	2	$\frac{2}{3}$	1

The process is repeated for each of the alternatives for each criterion, the matrices with these scores can be found in Alternative scoring.

Consistency check

The success of the AHP is largely dependent on the consistency of the pairwise comparison. Consistency means eliminating mistakes in the comparison logic in the shape of:

$$A > B$$
$$B > C \text{ but,}$$
$$C > A$$

Saaty and Vargas [48] state that the comparison matrix is said to be consistent if:

$$a_{ij} \cdot a_{jk} = a_{ik}, for\ all\ i, j\ and\ k$$

In which a is the score for of alternative i comparted to alternative j.

However, using this statement is difficult to combine with the scoring scale proposed in Table 5-2, since the scores in this table are not mathematically determined. The fact that the size of the refit (Cost) scores 4 points with regards to Size of the refit (Time) does not mean that cost is four times more important than time. This means that it is very difficult to assign a fully consistent score to each of the alternatives. To solve this, the AHP allows for some inconsistency within the matrices as human judgement is more likely to be inconsistent than to be consistent. [48]

Saaty and Vargas [48] define the following mathematical theorem concerning consistency:

"For a given positive matrix A, the only positive vector x and only positive constant c that satisfy $Ax = cx$, is a vector that is a positive multiple of the Perron vector (principle eigenvector) of A, and the only such c is the Perron value (principle eigenvalue) of A."

In simple terms this means that the matrix is consistent if and only if the largest eigenvalue of matrix A is equal to the size of matrix A.

For a matrix that is neither completely consistent nor contradictory Saaty defined a consistency index (CI) to determine if the matrix is consistent enough. The CI is calculated via [49]:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

In which λ_{max} is the highest eigenvalue and n is the size of matrix A and n is the number of alternatives.

In a completely consistent matrix the highest eigenvalue and the size of matrix A is the same and the CI is 0. However, as said before the chances of that happening are very slim. To define an acceptable limit for the inconsistency Saaty defined a consistency ratio (CR) as [49];

$$CR = \frac{CI}{RI} \leq 0.1$$

The RI, or random index, is an average value of the value for CI determined using randomly generated consistency matrices. [49]

The RI value for different matrix sizes is given in Table 5-4.

Table 5-4 Random consistency index (RI)

N	1	2	3	4	5	6	7
RI	0	0	0.58	0.9	1.12	1.24	1.32

Calculating preference

With the scores known the next step is to determine the normalised scores for each criteria and alternative. It is possible to calculate either a weighted mean or a geometric mean. The weighted mean is calculated by first determining the normalised relative weight of each of the values by dividing each element in each column by the sum of all elements in said column. Then the score of each row can be determined. The final step is to normalise this sum.

The geometric mean of a matrix is calculated by taking the n^{th} root of the product of n elements in a row. These values can then also be normalised.

$$\left(\prod_{i=1}^{n} x_i\right)^{\frac{1}{n}} = \sqrt[n]{x_1 x_2 \dots x_n}$$

These two methods lead to the following scores:

Table 5-5 Weight factors calculated by weighted mean and by geometric mean

	Size of refit (Time)	Size of refit (Cost)	Market size	Competitiveness	Weighted mean	w_i Geometric mean
Size of refit (Time)	1	$\frac{1}{4}$	$\frac{1}{7}$	$\frac{1}{6}$	0.054	0.054
Size of refit (Cost)	4	1	$\frac{1}{2}$	$\frac{1}{2}$	0.197	0.196
Market size	7	2	1	$\frac{3}{2}$	0.419	0.420
Competitiveness	6	2	$\frac{2}{3}$	1	0.330	0.330

As can be seen in Table 5-5, there is only a small difference in the calculated values of the weighted mean and the geometric mean. Since the conception of the AHP in 1980, further research has been conducted into the scoring system, resulting in different calculation methods. Research into the calculation of the weights has shown that using a geometric mean provides a better answer than working with the normalised principle eigenvector in any analysis.

Calculating alternative scores

In the same manner as for the criteria a comparison between the alternatives can be made. For each criterion a pairwise comparison is made between each of the alternatives. Next, the geometric mean for each alternative is calculated.

Table 5-6 shows the scores for the jumper, spool and structure installation (small refit) . There are three more tables, found in 0. These scores together are used to calculate the total score.

Table 5-6 Scoring table: installation vessel (small refit), CR = 0.014

	Small refit	+ mattress installation	+ span rectification	+ mattress installation and span rectification	Do nothing	s_i Normalised score vector
Small refit	1	3	3	5	$\frac{1}{2}$	0.30
+ mattress installation	$\frac{1}{3}$	1	1	2	$\frac{1}{3}$	0.12
+ span rectification	$\frac{1}{3}$	1	1	2	$\frac{1}{3}$	0.12
+ mattress installation and span rectification	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{1}{2}$	1	$\frac{1}{5}$	0.06
Do nothing	2	3	3	5	1	0.40

Calculating the total score

When all the weight factors, w_i, for the criteria and the score vectors, s_i, for the alternatives are known the total score can be calculated.

$$Total\ score = \sum_{i=1}^{n} w_i \cdot s_i$$

Table 5-7 Calculation of the total score for structure, jumper and spool installation

	Size of refit (Time) w = 0.05	Size of refit (Cost) w = 0.20	Market size w = 0.42	Competitiveness w = 0.33	Total score
Small refit	0.30	0.30	0.09	0.14	0.16
+ mattress installation	0.12	0.12	0.23	0.26	0.21
+ span rectification	0.12	0.12	0.23	0.26	0.21
+ mattress installation and span rectification	0.06	0.06	0.4	0.26	**0.27**
Do nothing	0.40	0.40	0.05	0.08	0.15

Sensitivity study

To determine if the given scores result in a stable system that does not change drastically when the situation changes a sensitivity study is performed. This sensitivity study is twofold, determining the stability of the criteria weights and determining the stability of the alternative scores. For this sensitivity study the method suggested by Triantaphyllou and Sánchez [50] is used.

Sensitivity of the criteria weights

The goal of this part of the sensitivity study is to determine how much the weight factor of one criterion must change in order to switch the ranking of two alternatives. This leads to the determination of the critical criteria, the criteria that has the largest influence on the outcome of the whole process.

This is done by determining the minimal change in one criteria, $\delta_{i,j,k}$, needed to switch the position of two alternatives. The required changes can be determined either in absolute values or in relative value. As absolute values are hard to interpret, a change of 0.05 is much more significant is the starting value is 0.1 or 0.7. Therefore relative changes, in percentage, are used.

The relative value at which the change occurs can be calculated by:

$$\delta_{i,j,k} = \frac{P_j - P_i}{a_{jk} - a_{ik}} \cdot \frac{100}{W_k}$$

With;
P = Total score of alternative i and j
a = alternative score for alternative i and j with regards to criteria k
W = weight factor of criteria k

For the value of $\delta_{i,j,k}$ to be feasible there is one additional criterion that has to be met:

$$\frac{P_j - P_i}{a_{jk} - a_{ik}} \leq W_k$$

This is necessary since the total score for criteria k can never be higher than $1 \cdot W_k$ due to the normalisation process. If the required score to switch the two alternatives around is higher than that the switch is not possible.

Repeating this process for each set of alternatives in the example used above leads to:

Table 5-8 Sensitivity of the criteria scores, in percentage, for structure, spool and jumper installation

Alternative 1	Alternative 2	Criteria 1 - Time	Criteria 2 – Cost	Criteria 3 – Market size	Criteria 4 - Competitiveness
1A	1B	-587.9	-49.0	145.5	N/A
1A	1C	-587.9	-49.0	145.5	N/A
1A	1D	-959.8	-80.0	136.4	N/A
1A	1E	-234.3	**-19.5**	105.4	181.8
1B	1C	N/A	N/A	N/A	N/A
1B	1D	-2181.4	-181.8	129.1	N/A
1B	1E	-465.4	-38.8	136.5	N/A
1C	1D	-2181.4	-181.8	129.1	N/A
1C	1E	-465.4	-38.8	136.5	N/A
1D	1E	-750.2	-62.5	132.8	N/A

As is clear in Table 5-8 there are positive and negative values. The positive values mean that the criteria weight factor has to be lowered, while negative values mean that the criteria weight has to be increased.

The two alternatives that can be switched with the smallest change in criteria weight can be found by looking for the smallest value. In this case it is switching alternative A and E by making a 19.5 % increase to the weight factor of criteria 2. This value is called the Percent Any value. In Table 5-8 this is the bold value.

The smallest required change in criteria weight to change the top solution, called the Percent Top value can be found by looking at the rows that involve the best criteria, in this example it is criteria 1D, as shown in

Table 5-7. In this case the smallest change is an increase of 62.5% for criteria 2, the underlined value in Table 5-8. The other values required to change the best solution are larger.

A change of approximately 20% is significant. Therefore it is concluded that this is a stable system.

Sensitivity of the alternative scores
The next part of the sensitivity study is determining if the alternative scores also form a stable system. The manner in which this is done is similar to that of the previous part of the sensitivity study.

In this case the threshold value is calculated. The threshold value shows how much, in percentage, the score of alternative A has to change for the preference to change to alternative B.

The threshold value is calculated by:

$$t_{ijk} = \frac{P_i - P_j}{(P_i - P_j + W_k \cdot (a_{jk} - a_{ik} + 1)} \cdot \frac{100}{a_{ik}}$$

In which;
P = the total score for alternative i and j
W = the weight factor for criteria k
a = the scores for alternative i and j with regards to criteria k

In addition to this there is an additional criterion that has to be met:

$$t_{ijk} \leq 100$$

This criterion is required since it is impossible to lower a score to something lower and zero by decreasing it by 100%. This is what the 100 stands for in the formula above.

These calculations can be used to find the smallest change that results in a change of position for each alternative, as well as the second alternative that is involved in the switch. For the example, these values can be found in Table 5-9.

Table 5-9 Most sensitive alternative scores - installation of structures, spool and jumper installation

	C1	C2	C3	C4
1A	51.5 (1D)	**16.1 (1E)**	28.5 (1E)	24.6 (1E)
1B	N/A	384.9 (1D)	54.7 (1A)	58.2 (1A)
1C	N/A	384.9 (1D)	54.7 (1A)	58.2 (1A)
1D	N/A	N/A	36.0 (1B/1C)	57.8 (1B/1C)
1E	71.7 (1A)	16.5 (1A)	48.3 (1A)	39.5 (1A)

Once again it is possible to determine a percent any and percent top value.
The percent any value for this example is 16.1% which switches the positions of 1A and 1E by changing the score for criteria 2 for alternative 1A, once again denoted by the bold value.
The percent top value for this example is 36.0%, which switches the positions of alternative 1D with either alternative 1B or 1C. This is achieved by changing the score for criteria 3 of alternative 1D.

With these values known a determination can be made if the system is deemed stable, and thus the results reliable. In this case a change of 30% to change the top value is deemed significant.

5.7.2 Determination of criteria weights

As was explained in the example above the first step of an AHP is usually the determination of criteria weights. The criteria, defined in step 5, are:

- Size of the refit
  - Time it takes to perform the refit
  - Cost of the refit
- Market size
- Competitiveness

One of the biggest pitfalls of a MCDA, independent of the method used, is that the user is able to adjust the outcome to suit what they feel is the best solution. In addition to this the subsea installation market is volatile. This means that what seems like a good idea today might not be a good idea in a month. To counteract both these problems this analysis uses several scenarios to make a broader analysis and find a solution that might work in several predicted markets. These scenarios are used during the sensitivity study to determine how stable the results are.

The first scenario used is the strategy that Allseas would most likely follow at his point. The other two are strategies based on changes to the market, an improving market and a market that is further declining.

The weight factors for the four criteria for all scenarios that are described below can be found in Table 5-10.

Scenario 1: Current Market
The first scenario is based on the investment strategy best suits the market conditions in December 2016. To determine the correct criteria weights the market should first be characterised.

Currently the oil and gas market is not doing well. Due to the low oil price, it currently fluctuates around 55 dollars per barrel[2] [51], the investments from oil producing companies have dropped. This means that there are fewer fields in development and thus fewer contracts available. The contrarian investment strategy states that investing when the market is bad is a good idea to a point.

A good sized market and competitiveness are more important in this case. Due to the depressed state of the market any investment made has to be a good one. For this reason the size of the market is deemed the most important criteria, with competitiveness at a second place.

The cost of the refit and the time the ship spends in a dock are ranked third and fourth respectively. With the market at a low point it does not matter that the ship spends some time in dock as the alternative is lying in port. Of course a shorter time in dock is still preferred as the ship can start making money in its new market immediately.

Scenario 2: Improvement of the market
If the market improves, the importance of time increases, as money is to be made and the time spend in dock means the vessel cannot generate any income. The cost of the refit is of less importance as a better market means there is more money to spend.

Due to the improving market, the competition increases. This makes it more important to have a competitive vessel as the number of competitors increases as well.

The size of the market is less important than in the current market state, as most markets are expected to have an increasing number of contracts available but it is not negligible.

Scenario 3: Further decrease of the market
In a further decreasing market the cost of the refit is the all-important factor. The only way an investment is considered is if it costs a little and causes a lot of gain. The second most important factor is the market size. It is expected that in case of a further decreasing market many companies do not survive. This means that a market with more contracts can provide more possibilities than having a very competitive ship.

In an extremely depressed market taking a long time with a refit is not important. Competitiveness is also not valued very highly since competitors are expected to drop out, leaving space for less ideal ships.

Scoring factors
The proposed market scenarios are translated into scores using the method described above. The scores for each criterion for each scenario are found in Table 5-10. The full scoring table can be found in Appendix D.

Table 5-10 Scoring factors per criteria for all three alternatives

	Current market	Improving market	Declining market
Size of the refit (time)	0.05	0.28	0.05
Size of the refit (cost)	0.20	0.06	0.58
Market size	0.42	0.25	0.26
Competitiveness	0.33	0.41	0.11

[2] These values were determined in November and December 2016. At the beginning of 2017 the price increased to approximately 58 dollars per barrel and then dropped again.

5.7.3 **Scoring of the alternatives**

With the score for the criteria known, the next step is scoring the alternatives on each of the criteria. Since it is impossible to differentiate a score between the time of the refit and the size of the refit this is once again combined into one criterion, after splitting it to determine the individual score.

To decrease the number of alternatives that have to be compared to each other at the same time, each of the six main categories of alternatives are first compared to each other. This leads to the six best solutions, which are than in turn compared to each other.

To ensure that the suggested changes to the ship are in fact an improvement each alternative is also compared to the concept “do noting”. All concepts that score worse than this one are deemed a bad idea and are discarded.

The scoring matrix for each criterion, as well as a motivation for this matrix, can be found in Appendix D. This appendix also provides the scores and outcomes of the AHP.

Size of the refit

For the determination of the size of the refit the descriptions of the alternatives created above are used. Here an indication of the changes to the ship is made which forms the basis for the scores.

Market size

To determine the size of the market, the views of company experts as well as other sources are used. Articles about the state of the market as well as predictions for the future give a broad view of the state and size of the market while expert fill in the details.

Competitiveness

To determine the competitiveness of a concept a reference is made between vessels from important competitors which operate the same types of ships. Their capabilities are compared to the proposed capabilities of the *Lorelay.* The company’s view on what the required capabilities are, based on old projects and experience, is also taken into account.

5.7.4 **Total score per alternative group**

After calculating the total scores for each alternative for all three scenarios the best solutions for each set of alternatives can be found.

Table 5-11 Best solutions per set of alternatives and per scenario

Alternative group	Scenario 1	Scenario 2	Scenario 3
Structures, jumper and spool installation, small refit	Small refit, mattress installation and span rectification	Small refit, mattress installation and span rectification	Do nothing
Flex lay	Do nothing	Do nothing	Do nothing
Precommissioning	Subsea FGT and dewatering	Subsea FGT and dewatering	Do nothing
Heavy lift support	Increased crane capacity and structure installation	Increased crane capacity and structure installation	Do nothing
Structures, jumper and spool installation, large refit	Large refit, mattress installation and span rectification	Do nothing	Do nothing

Based on the best solutions denoted in Table 5-11, a few observations can be made.
If the market further decreases, none of the alternatives provide a suitable solution, making no adaptions to the ship is the winner in each case. This means that the third scenario can be disregarded when determining the final solution.

There is only one difference between the other two scenarios in in the alternative group of the large refit. Here, mostly due to the increased time required to install a larger crane, not changing anything to the ship is the preferred solution for the second scenario.

5.7.5 Final scores

For scenario 1 and 2 a combination of all alternatives listed in Table 5-11, as well as cable laying and creating a modular vessel, which didn't need a preselection since there is no choice to be made, are once again scored to find a final solution for the refit of the *Lorelay.*

Table 5-12 Final scores for combination of best alternatives

Alternative	Score scenario 1	Score scenario 2
Small refit, mattress installation and span rectification.	0.15	0.14
Large refit, mattress installation and span rectification	0.11	-
Subsea FGT and dewatering	0.12	0.10
Cable laying	0.13	0.10
Combination of all options	**0.34**	**0.29**
Heavy lift support and structure installation	0.14	0.15
Do nothing	-	0.24

For both scenarios creating a fully modular vessel is the best solution. To see if this result is based on a stable system that is not easily influenced the final step is to perform a sensitivity study.

5.8 Step 8: Evaluation

The final step is to evaluate the results that are calculated. This is done by a sensitivity study. Afterwards the results are compared to the goals of the analysis determined in step 3.

5.8.1 Sensitivity study

To find out if a stable system was created a sensitivity study is performed. Most of the results of the sensitivity study can be found in 0.

This sensitivity study shows that in the preliminary comparison lowest percent top value, or the most unstable solution, is found in the jumper, spool and structure installation (large refit). In scenario 2, a change of 15.3% to criteria 1 swaps the best solution from "do nothing" to mattress installation and span rectification. While this is not a large change, neither solution plays a role in the final decision process. Therefore this lower than preferred required change is accepted.

To make changes to the final decision process much larger changes are required. This shows that the system is stable and cannot be easily changed. Table 5-13 and Table 5-14 show that large changes, to both the criteria weight and the alternative scores are required to change the outcome. It is relatively easy to change other solutions that the best outcome but these are of little significance for the final outcome of the result.

Table 5-13 Percent any and percent top values for the criteria weights

Scenario	Percent any	Percent top
1	8.1	-292.2
2	6.0	-48.6

Table 5-14 Percent any and percent top values for the alternative scores

Scenario	Percent any	Percent top
1	-6.8	85.5
2	4.4	34.0

5.8.2 Comparison to the set goals

In step 3 the goals for this analysis were set. The solution had to be one where the cost are minimised and the benefit is maximised. The choice for a modular vessel means that there is a high potential for earning more money. However, it is a rather radical change to the ship which means that there is significant cost associated with this conversion.

However, due to the decision process it can be said with some certainty that a modular vessel has the best balance between those two.

5.9 Summary of the decision process

Via the MCDA analysis the best conversion solutions for the current market, an improving market and a declining market have been found from a previously determined list of concepts. The analysis has shown that for the current market and an improving market a conversion in which the ship is capable of performing all of the identified tasks instead of just one of them is the best solution. The benefits in terms of market size and competitiveness weigh up against the cost of the conversion and the time the conversion is expected to take.

For the declining market the analysis shows that none of the suggested options are a suitable choice. In that case the advice is to wait for the market to improve before a large conversion is attempted.

The sensitivity study has shown that the results are stable and cannot be easily changed to result in a different outcome.

6.0 CONCLUSION, DISCUSSION AND RESEARCH RECOMMENDATIONS

In this chapter the results of the research are summarised. In the second part of the chapter the effect of some of the choices made over the course of the research are discussed. Finally recommendations are made for future research.

6.1 Conclusions

At the start of this research Allseas posed the question: *How can the capabilities of the* Lorelay *be adapted to increase her utilisation while still keeping her pipe laying ability?*

To answer this question, chapter 1.0 states the following research question: *Which task or combination of tasks shows the most promise in improving the utilisation of the* Lorelay*?*

To answer this question three sub-questions are used:

a) In which markets can an improvement of the *Lorelay's* utilisation be found?
b) Within the chosen direction, which tasks could the *Lorelay* perform?
    a. What capabilities should the ship possess to perform this task?
c) Which of the created concepts shows the most merit based on several decision criteria and under specific circumstances?

6.1.1 Market research

The first sub-question is aimed at determining in which market the conversion possibility is going to be found. In short, there are three directions that are investigated; improve the ships capabilities, expand the capabilities of the ship within a known market that Allseas already operates in or expand the capabilities of the ship in a new market.

A literature study and expert testimonies show that the best option is to expand the capabilities of the ship within a known market, either the subsea installation market or the heavy lift market. There are several tasks that are currently performed by either subcontractors or by competitors. Some of these tasks can be performed by the *Lorelay* as well. This increases the possibility of winning a contract and opens up the possibility to bid on more contracts. An added benefit of remaining in the same market is that the clients already know the company, negating the hassle of making new contacts.

Expanding the pipe laying capabilities of the *Lorelay,* for example by increasing the maximum pipe diameter or the maximum working depth of the ship, is a possibility. However, there are currently not a lot of contracts available for Allseas' larger ships. This means that increasing the *Lorelay's* pipe laying capabilities does not wield a significant increase in the ship's utilisation. Additionally it cuts into the potential profits of the other ships.

Several other markets, such as the windfarm installation and maintenance market, also show some promise. However, the requirements for ships that are capable of these tasks are differ too much from those of a pipe laying vessel, making it impossible to combine these tasks.

6.1.2 Determination of possible tasks

The next step in the research process is to find the different tasks that the *Lorelay* can perform in the subsea installation market and the heavy lift market.
To find the possible tasks company data, as well as expert testimonies are used. The following tasks are found:

- Structure installation
- Umbilical and cable installation
- Riser installation
- Jumper and spool installations
- Retrieval of existing structures
- Mattress installation and crossing preparation, not as a standalone task
- Span rectification, not as a standalone task
- Precommissioning
- Topside removal preparations
- Jacket removal and installation support
- Flex lay

For the exact requirements that are placed on the ship and the required equipment please refer to chapter 4.0, Appendix B and Appendix C.

6.1.3 Decision process

The last step is to determine which task shows the most merit. This is done by performing an AHP on several possible concepts. The AHP process is performed in two parts. First the best solution per alternative group is determined and second these outcomes are compared to each other to find the final solution.

The following alternative groups have been set up:

1. Installation of jumpers, spools and structures (Small refit)
    a. Small refit; cleaning up the ship and moving the A&R winch
    b. Combined with mattress installation
    c. Combined with span rectification
    d. Combined with both mattress installation and span rectification
2. Installation of jumpers, spools and structures (Large refit)
3. Allow for the installation of flexible pipelines and risers as well as rigid pipelines and risers by converting the ship to a reel-lay vessel
    a. Performing reel and cable laying activities
    b. Reel-lay combined with installation of jumpers, spools and structures
    c. Any of these alternatives combined with mattress installation, span rectification or both
4. Cable laying
5. Precommissioning
    a. Vessel based FGT
    b. Subsea based FGT
    c. Dewatering
6. Heavy lift support
    a. Heavy lift support
    b. Heavy lift support and jumper, spool and structure installation
    c. Heavy lift support with a larger crane
    d. Heavy lift support and jumper spool and structure installation with a larger crane
7. A combination of all options mentioned above

To ensure that the conversions have merit they are compared to the alternative “do nothing”. Each alternative that scores worse than “do nothing” is discarded.

Scenarios

Due to the volatility of the subsea installation market, it is difficult to make a decision that holds true for a longer period of time. Therefore three different scenarios are used. The first scenario is a market that stays at the level it is now. The second scenario is an improving market and the final scenario is a market that is declining further.

Outcome per scenario

Table 6-1shows the outcomes of the preliminary comparison between the different groups of alternatives. It is clear that for scenario 3 no viable solution can be found, for every alternative group the best solution is “do nothing”.
For the other two scenarios the best solutions are taken and a comparison is once again made between the best options. This now includes a combination of all options and a cable laying concept, which did not require a preliminary decision process. Flex lay is discarded as “do nothing” was the best course of action in all three scenarios. The same goes for structure, jumper and spool installation (large refit) in scenario 2.

Table 6-1 Best solutions per scenario and per alternative

Alternative group	Scenario 1	Scenario 2	Scenario 3
Structures, jumper and spool installation, small refit	Small refit, mattress installation and span rectification	Small refit, mattress installation and span rectification	Do nothing
Flex lay	Do nothing	Do nothing	Do nothing
Precommissioning	Subsea FGT and dewatering	Subsea FGT and dewatering	Do nothing
Heavy lift support	Increased crane capacity and structure installation	Increased crane capacity and structure installation	Do nothing
Structures, jumper and spool installation, large refit	Large refit, mattress installation and span rectification	Do nothing	Do nothing

Final results
The final results show that a modular vessel is the best solution in both the current market state and an improving market, as can be seen in Table 6-2.

Table 6-2 Final results for scenario 1 and 2

Alternative	Score scenario 1	Score scenario 2
Small refit, mattress installation and span rectification.	0.15	0.14
Large refit, mattress installation and span rectification	0.11	-
Subsea FGT and dewatering	0.12	0.10
Cable laying	0.13	0.10
Combination of all options	**0.34**	**0.29**
Heavy lift support and structure installation	0.14	0.15
Do nothing	-	0.24

The sensitivity study has shown that this decision is based on a stable system that cannot be easily changed.

6.1.4 Summary of conclusions
To summarise; the best solution for the current market and an improving market is a ship that can perform a combination of tasks. For a market that is further decreasing the best solution is to wait for the market to increase, investing in the ship is deemed a bad idea in this market.

6.2 Discussion
There are many aspects that can be discussed in a discussion, ranging from the whole research approach to the influence of minor details. This discussion takes the research approach as a given and discusses the effect certain decisions could have had on the outcome of the research. The elements that are discussed are the elimination of markets made in chapter 3.0 and the choice of criteria and method for the MCDA process. Finally some suggestions for further research are given.

6.2.1 Elimination of other markets
In the first part of this research, all markets that Allseas does not already operate in are eliminated by adjusting the scope of the research. In order to get results the scope of the research has to be determined, sometimes excluding potential options.

To determine the scope of the project several of the larger or growing markets outside of the subsea installation market were investigated. Based on the findings about these markets the whole segment was eliminated. This does not mean that there are no possible tasks that the *Lorelay* could perform outside of the subsea installation market or the heavy lift market. Intensive research into other markets could still wield potentially interesting results.

Should this research be conducted and wield results there is a possibility that the tasks could be performed by the *Lorelay* due to her new modular design.

6.2.2 The use of MCDA
MCDA is a much used method to solve complex decision processes. However, it is not without its issues. Due to its design, this method is inherently subjective. This means that it is very possible that two people solving the same problem get vastly different results.

Choice of criteria and subsequent choice of method
Which criteria are used has a large influence on the outcome of the MCDA. Additionally the choice of criteria influences the choice of the solving method and vice versa. This leads to an iterative process to find the best combination of criteria and method.

There is a chance that using different criteria can lead to another outcome. However, there are several guidelines for the way criteria are determined and each method also places its own restrictions. If the users adhere to the guidelines and restrictions, similarities emerge.

For this analysis the goals have been clearly defined. They play a large role in the determination of the criteria. Every criterion that is chosen must say something either about the potential cost of the conversion or about the potential benefit.

The chosen criteria also allow for a wide coverage of the project. If the criteria are too detailed on a specific area a skewed solution is found. A detailed criteria causes focus on one alternative that meets that criteria and causes the other to be scored worse for it.

Finally the criteria are equally balanced, two criteria on the cost side and two criteria on the benefit side. Having, for example, one cost criteria and three benefit criteria carries the risk that the benefit criteria is overrepresented, favouring the concepts that have the largest benefit without properly representing the cost that come with that.

Although every care has been taken to find usable criteria, it is possible that another user creates a completely different outcome, by using different criteria and perhaps a different method. Due to the fact that MCDA inherently subjective, differences are not ruled out.

Use of AHP over other methods

There are many different ways to find a solution with a MCDA. As said above, a MCDA is inherently subjective. For this decision problem the choice was made to use a method that was based on some mathematics and not only on a subjective opinion. It would have been also possible to use a more economical approach by using a cost-benefit analysis, or a much quicker approach, which is more subjective, such as the pro-and-con analysis.

The main benefit of the AHP is its use of pairwise comparison. This means that each decision is simple, keeping the decision process clear. By using the consistency index an additional check is performed to see if the decision process makes sense.

However, there are also dangers. When performing a comparison the user already has a view of how the criteria or alternatives relate to each other. It is possible that this view is not matched by the outcome of the scoring system. This irregularity might prompt the user to change the score to more meet their view. This is an understandable reaction as in some cases filling in that each option is just a little bit better than the previous one leads to a score that does not represent that.

However, this problem is not solved by using another method. The more detailed and less subjective MCDA methods require information that is not available while the other methods are even more subjective.

Validity of the results

If research is conducted using a subjective method, the validity of the results is always questioned. In this report three scenarios are used to ensure that the solution found is valid in more than one situation. In the outcome it became clear that in the current market state and in an improving market state a modular vessel is the best solution.

However, since the scores are also based on subjective interpretations of investment strategy and market predictions there is always a danger that the solution is easily changed by making a small adaptation to the scores.

To ensure that this is not the case the sensitivity study is performed. This sensitivity study shows that changing the order of any two options is sometimes very easy. However, changing which alternative comes out on top is significantly more difficult and requires significant changes to either the criteria weights or the alternative scores. With a solid sensitivity study, as well as the same result for two market states it can be stated that the results of the decision process have been thoroughly tested.

6.3 Recommendations for further research

This report continues with a design based on the research that has been done. However, there are always elements that could be investigated further or options that have been discarded that could be looked at a second time.

As mentioned before, there might be interesting opportunities in other markets that have been discarded at the beginning of this project. Further research into these markets could wield some interesting results.

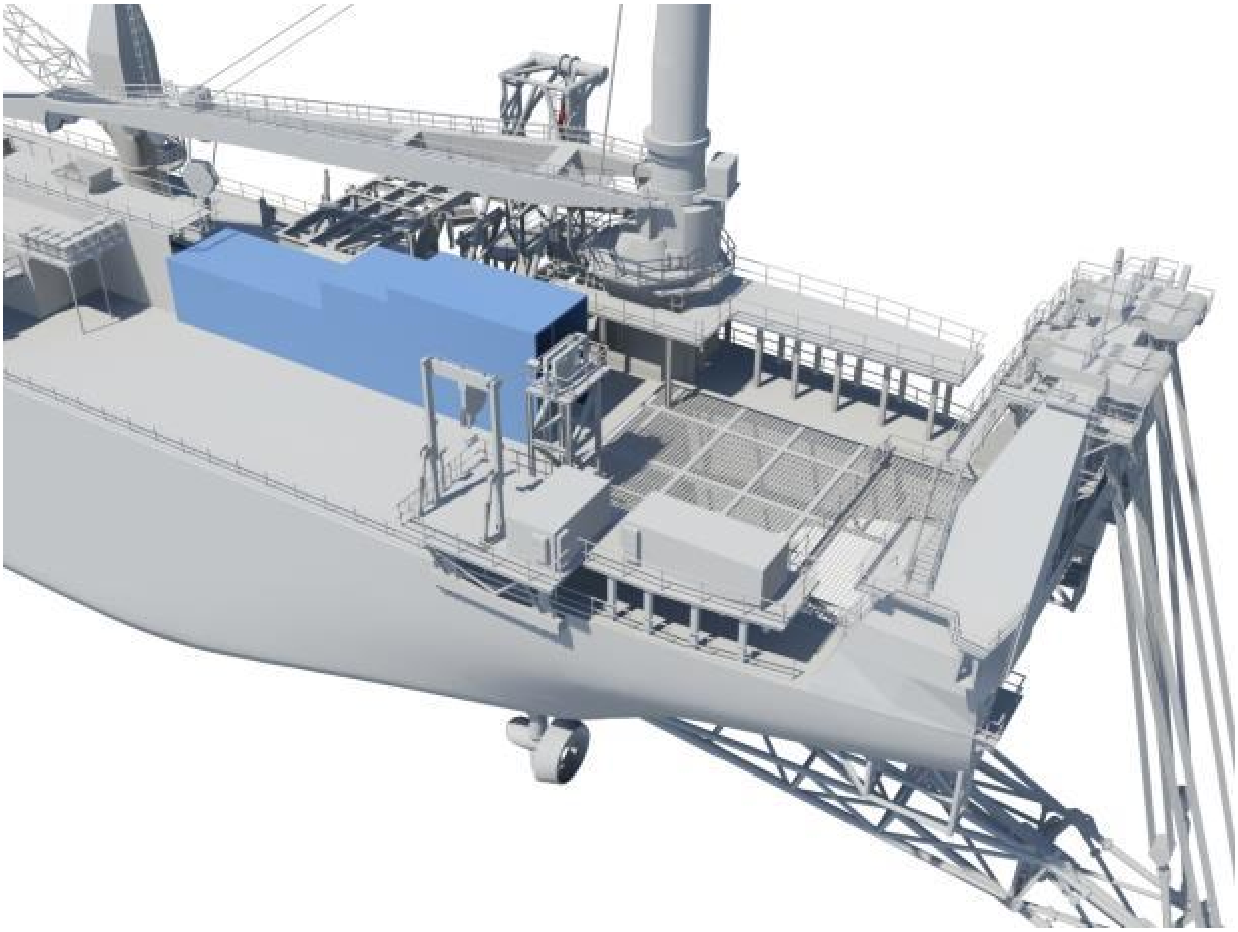
Since this research is focussed on the *Lorelay* some options have been eliminated because the *Lorelay* is not well suited to perform these tasks. However, should a new ship be build, it is possible to further investigate options such as choosing to use the reel-lay method over the S-lay method to add flexible pipes and cable laying as an additional option.

Another interesting concept, which was unfortunately created at such a late stage that it could no longer be investigated, is to convert the *Lorelay* in such a way that she can perform complete pipeline installation projects by herself. This would be an ideal solution for remote projects where it would be costly to work with multiple ships for longer periods of time.

This idea might work well with the modular concept but the need for such a vessel and its requirements have to be investigated.

With the changes in the energy market where offshore wind energy and other renewable energy sources are gaining popularity the oil and gas market is losing some of its popularity. The *Lorelay* is an old vessel, originally build in 1974 and converted to a PLV in 1986. It is likely that she can continue laying pipelines on the ocean floor for the remainder of her service lift. However, for new vessels a combination between laying pipelines and working in the renewable energy sector might be an idea worth investigating.

Part 2: Design



7.0 DESIGN PROBLEM DEFINITION

The first part of this report showed that the best solution for the redesign of the *Lorelay* is a modular option. In the second part of this report this option is expanded into a preliminary design. The first design step is to define the design problem. This means an investigation into the most important aspects of the design as well as narrowing the scope of the design. Next the goals for the design are defined. These goals can be used as a guide later on in the project to ensure that the design focusses on the right aspects. Lastly a concept idea is set up. This shows the main direction in which a solution is going to be found. This too helps in keeping the design process on track. [4]

7.1 Design scope

When redesigning a ship there are many elements that require attention and many different directions in which the design can be directed. Even within a chosen direction the focus can be placed on many different aspects.

The focus of this design is on the new design for the pipe laying configuration of the ship. Since this is the main function of the ship it is important that this is well designed.

To further increase the flexibility of the ship, the choice is made to enable the ship to remove its own modular equipment when it is not in use. This allows the ship to move its irrelevant equipment into its own hold or place it on land, without the need to rent a crane.

This means that only the part of the firing line that can be reached by the SPC can be redesigned as modular units. The SPC can reach all parts of the firing line up to tensioner three. The tensioner weighs 44 tonnes and is located just outside the range in which the crane can lift such a load. For this reason the tensioner shall remain on board. The crane curve in Appendix I shows that the crane cannot lift the tensioner.

If the units are left on board they can be stored in the hold of the vessel. Here they can serve as ballast for the ship. This is possible since the hold is not in use when the *Lorelay* is performing tasks other than pipe lying.

Leaving the units on land brings additional cost for the storage of the units as well as logistic challenges to ensure that the ship always has the right equipment on board. However, because the units do not have to be placed in the hold they have fewer size restrictions. This means they can be bigger which in turn means that there are fewer connection points that have to be designed and connected.

Figure 7-1 The Lorelay, the green circle shows the relevant part of the firing line

7.1.1 Boom rest

Another element of interest for determining the scope of the design, is the boom rest for the SPC. The boom rest is currently placed on top of the firing line. It is not the only boom rest that is available for this crane. The second boom rest, used during long transit and when the crane is not in use for longer periods of time, is located on the aft most point of the ship. There are two main reasons why the ship is equipped with a second boom rest. The first is speed; rotating the crane towards the back of the ship and lowering it completely is time consuming, especially if the crane is to be used again soon after. The second reason is that the forward boom rest allows for easy construction on the mast and hoist of the crane.

There are two options, either the boom rest is removed completely, leaving the ship with only the second boom rest when the firing line is not on the ship, or the boom rest remains on the ship, decreasing the space that is freed up.

Removing the boom rest and the housing of the firing line beneath it adds approximately 30 m^2 to the available deck space. This is not a very significant increase over an area of 800 m^2 which is freed up in total. The small increase in deck area does no weigh up against the negative impact the removal of the boom rest has on the way the crane is used on the ship.

Moving the boom rest is also considered. However, there is no equipment that the boom rest could be placed upon. This means that it would be supported on a specially build structure, taking up additional deck space that could not be used for any other purpose.

For these reasons the room rest remains on the ship as a fixed piece of equipment.

To summarise, Figure 7-2 shows which elements are removed from the ship and which remain.

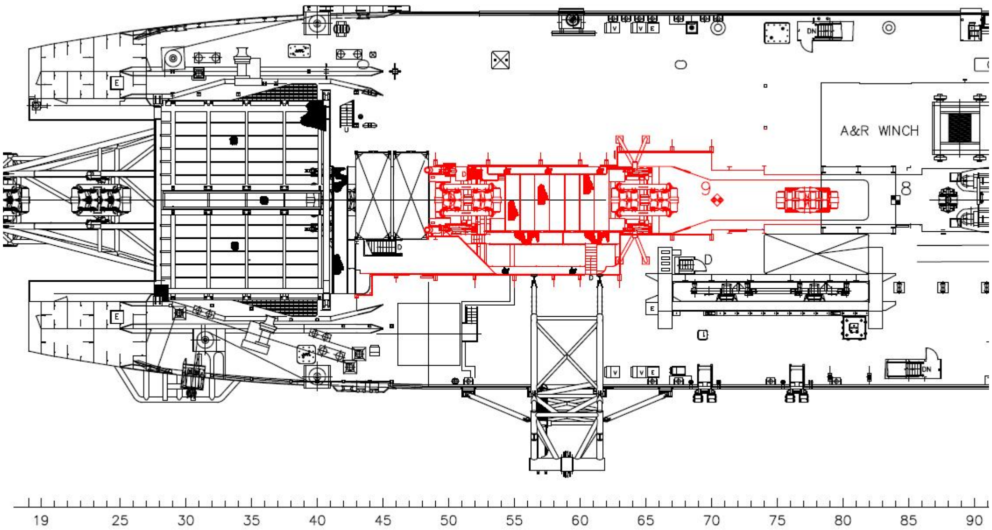


Figure 7-2 Visualisation of the area that is redesigned

7.2 Design goals

The design goals that are set up in this phase of the design form the foundation for all of the following design steps. The primary goal is to create a concept design of the firing line units. During the design process additional attention is payed to potential “showstoppers” that could break the design. At the end of the design a clear plan for the continuation of the design is given.

7.3 Concept idea

The next step in the design process is to define a general idea of what the conversion is going to look like. This idea serves as a guide in the following phases, ensuring that each of the steps taken helps to achieve the goals of the design. [4]

To enable the *Lorelay* to be used for more than only pipe laying the aft-most part of the firing line is rebuild using modular units. These units are installed and removed using the ships own 300t SPC. When the units are not in use they are placed in the hold of the ship via the container hatch where they serve as ballast for the ship or left behind on land.

The firing line is removed aft of the third tensioner and replaced by removable units. The units are connection to the ship and to each other.

Once the units are removed from the deck it leaves behind a large hole. Dependent on the project the choice can be made to build a temporary cover, made from a grate, or perhaps leaving the area open by surrounding the area by a fence or railing.

8.0 DETERMINATION OF THE DESIGN REQUIREMENTS

With the scope of the project known the next step is to perform a detailed investigation of the equipment and characteristics of the ship in the area of interest. This ensures that the key elements of the design, as well as possible restrictions are taken into account.

In order to provide a structured approach to the identification of said key elements, a functional analysis is performed. From there on a more in-depth look into each of these functions is used to identify the possibilities and limitations of the design.

The chapter ends with an overview of the requirements that must be met by the design.

8.1 Functional analysis

To determine what elements have to be investigated a functional analysis is performed. In this functional analysis the functions that the firing line units need to meet are defined. This then provides a structure to what elements are further investigated. [4] The functional analysis can be found in Figure 8-1.

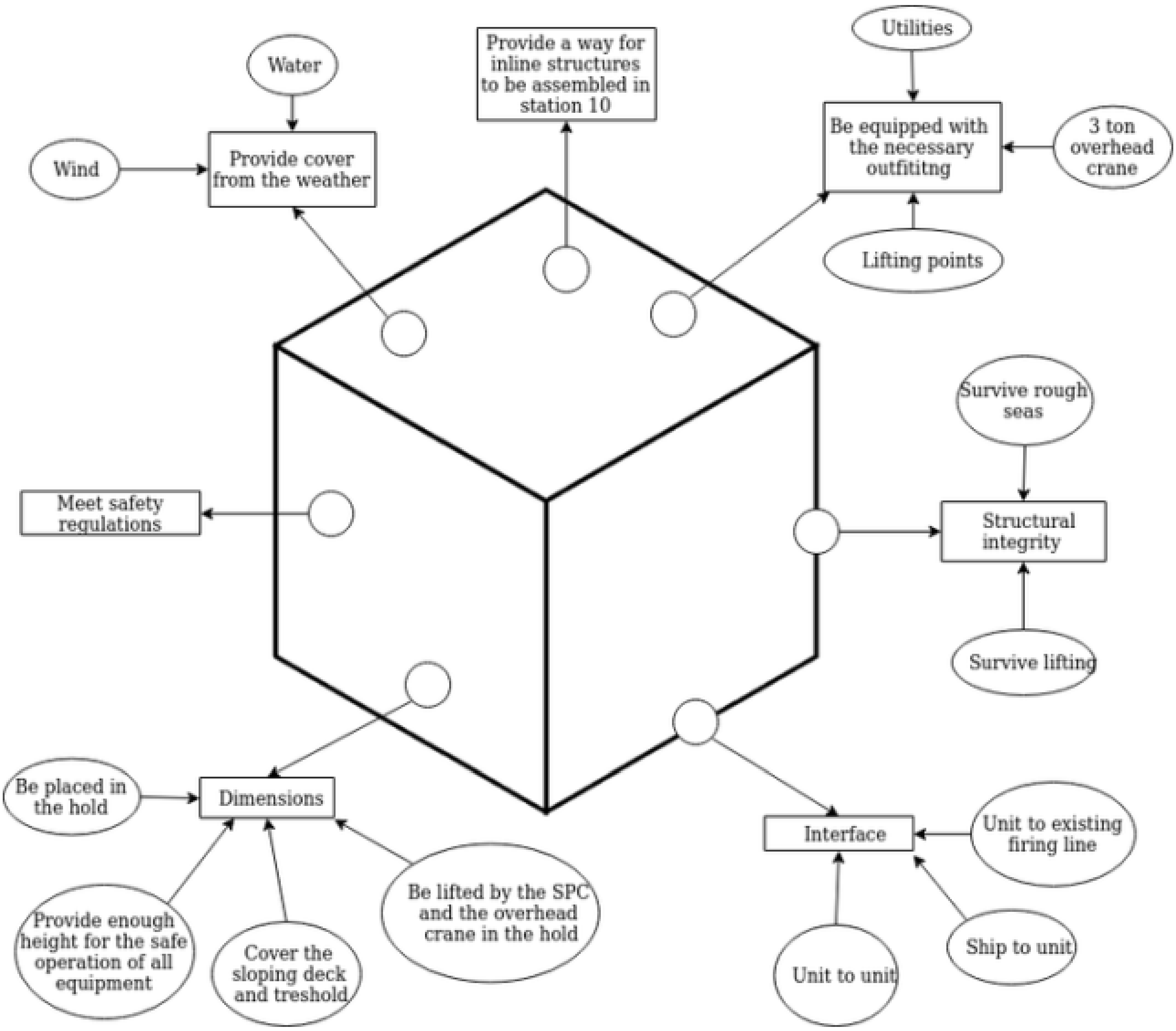


Figure 8-1 Analysis of the functions required for the firing line units

8.2 Equipment investigation

To find the limitations that the ship places on the design of the firing line units, the current general arrangement is investigated. Additionally it is important to know the details about the equipment that is currently located in the firing line. These details can assist in the determination of further requirements such as required space or utilities.

Figure 8-2 shows the relevant equipment in different colours and serves as a guide for the rest of the chapter.

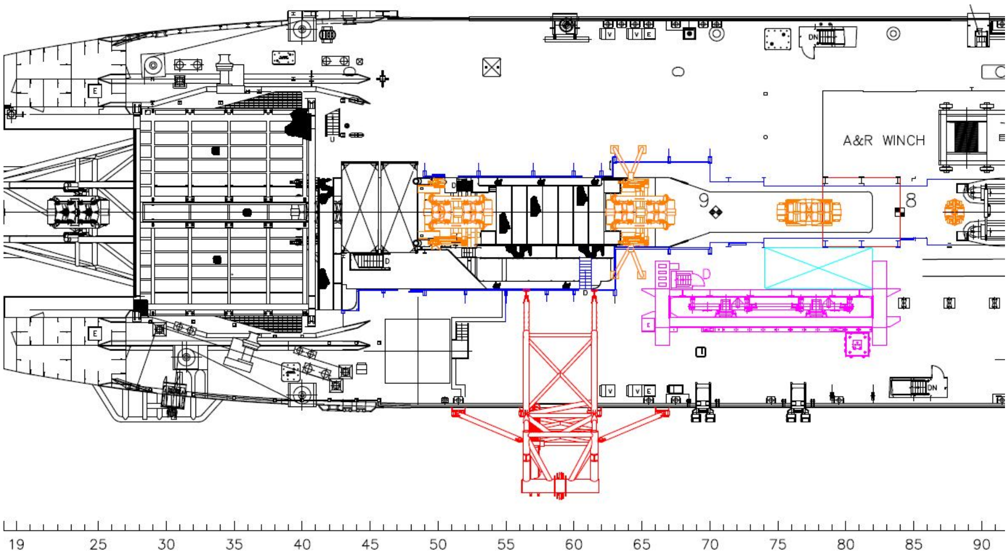


Figure 8-2 Visualisation of the main equipment on board

8.2.1 **Surrounding housing**

The dimensions of the housing surrounding the relevant part of the firing line are given in Figure 8-3. Currently the housing is completely integrated with the ship and with each other. To enable the modular units the housing needs to be rebuild and redesigned. The dimensions will remain similar however and as such these can serve as an indication of the required space.

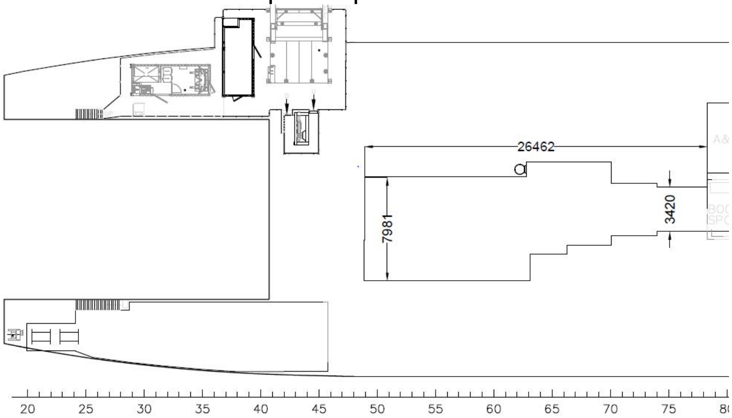


Figure 8-3 Dimensions [mm] of the firing line housing

8.2.2 **Sloping deck**

Under the whole area where the firing line is going to be redesigned, the deck slopes towards the waterline. In the narrow part of the sloping deck this process is gradual. At the front end of the slope the deck starts at a small depth of almost 20 cm. From there the deck slopes down at an angle of approximately 7 degrees, leading to a maximum depth below main deck of a little over 1.9 meters.. From there, in the wider part of the sloped deck, the floor drops down several meters, to form what is known as the threshold.

The widths of the different parts of the sloping deck are shown in Figure 8-4.

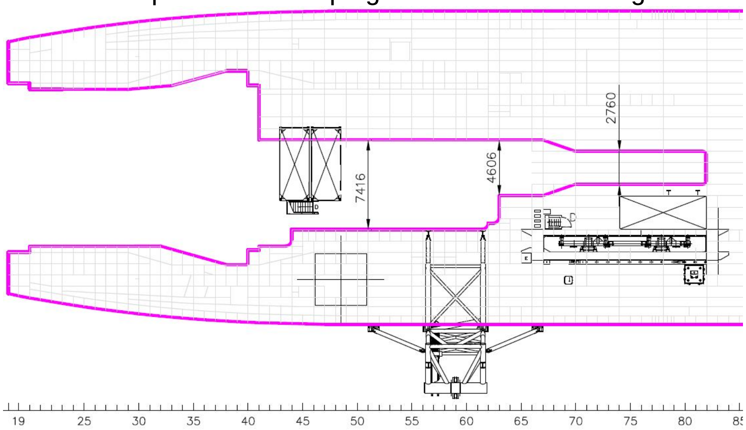


Figure 8-4 Outline of the aft ship and dimensions [mm] of the deck opening

8.2.3 **Firing line cross-section**

As mentioned in paragraph 8.2.1, the width of the firing line housing varies between different areas of the ship, dependent on the width of the sloping deck and other factors. This paragraph looks into the height of the firing line. The inner height of the firing line is dependent on the space needed for the installation of inline structures.

When an inline structure is installed, the installation takes place in the beadstall at the beginning of the firing line. To ensure that the structure can pass all other equipment on the firing line, such as the tensioners, elements that could cause a problem are removed. After the structure has passed all the tensioners the removed elements are reinstalled again. To this end a part of the current firing line cover, above station 9, has a removable roof. This allows the crew to use the SPC to lift the larger elements in place.

Figure 8-5 shows the minimum required space for an inline structure. As the picture shows the largest space required is approximately 2 meters wide and 2.4 meters above the bottom of the pipeline. On top of this minimum space for the inline structures some space is required for utilities such as lights and ventilation to be place overhead. In total a height between 3 and 3.5 meters is required above the highest position of the rollerbox.

In the case of frame 78, where the modular units start, an inner height of 4.1 meters is required. For later sections this is less due to the sloping deck.

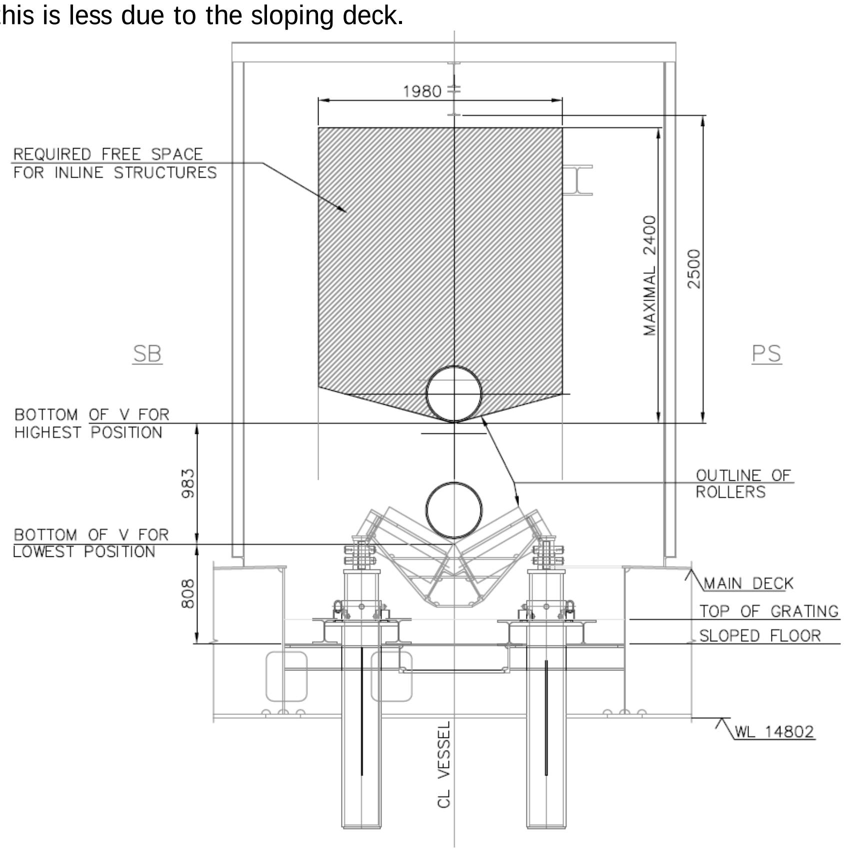


Figure 8-5 Cross section of frame 78, showing the minimum required height of the firing line [52]

8.2.4 **Threshold cover**

As the name suggests the threshold cover is the housing over the threshold. To allow for the placement of additional equipment for the pipe laying process, such as the fourth tensioner, an additional coating stations or the installation of inline structures, the threshold cover has three adjoining hatches on the roof which can be removed to allow access to the threshold. The threshold cover has a height of 5.6 meters.

The height is required for the placement of the fourth tensioner. This is a vertical tensioner, meaning that a lot of height is required. 0 shows a specially designed hatch cover has to be placed on top of the threshold cover to replace the standard on to allow for enough height above the tensioner. The walls have a height of approximately 5.6 meters. The hatch increases this height by 1.3 meters, leading to a tot outer height of 6.9 meters. Inside there is approximately 6.5 meters available.

Threshold shape
The threshold has an asymmetric shape, as seen in Figure 8-3, as part of an old design concept regarding the fourth tensioner. To save time it was decided that the fourth tensioner should remain on board at all times. When it was not in use and the space was required for other processes, skids where used to move the tensioner to the side. However, the weight of the tensioner, 75 tonnes, caused problems for the ship's capacity and stability. Therefore it was decided that it would be better to remove the tensioner form the ship when it was not in use. This means that this space is not used for anything at this point.

8.2.5 **Rollerboxes**
To guide the pipeline smoothly past all equipment and towards the stinger, rollerboxes are used. The rollerboxes are pictured in orange in Figure 8-2. There are three rollerboxes in the relevant area of the ship. The first one, denoted as rollerbox 4 in Figure 8-6, is a small rollerbox with limited possibilities for height adjustment. It has a footprint of about 7 m^2 and weighs about 10 tonnes. [53] This rollerbox is currently welded to the deck of the ship but it should be possible to adjust the securing system to allow for easier removal.

The other two rollerboxes are larger. Due to their position in the threshold, they play an integral role in guiding the pipeline downwards. The curve that the pipe makes depends on the stinger radius. This, in turn, determines the height of the rollerboxes on the ship. There is a significant height difference required to allow for the smallest and the largest stinger radius, used in respectively deep and shallow water.

To allow for this height difference, the rollerboxes can be adjusted using a hydraulic system. This hydraulic system is large and able to bridge a much greater height difference than is currently necessary. As can be seen in Figure 8-6 rollerboxes 6 and 7 and their hydraulic system reach above main deck.

The blue line shows the path of the bottom of the pipeline with the stinger in its lowest position, which requires the highest position of rollerbox 6 shown in blue. [54] In this situation the rollerbox extends above main deck. This means that the hydraulic system extends above main deck as well, causing a potential problem. However, company experts believe that it is possible to find solution for this problem relatively easy in a later stage of the design. Therefore this part of the design is left for a later stage.

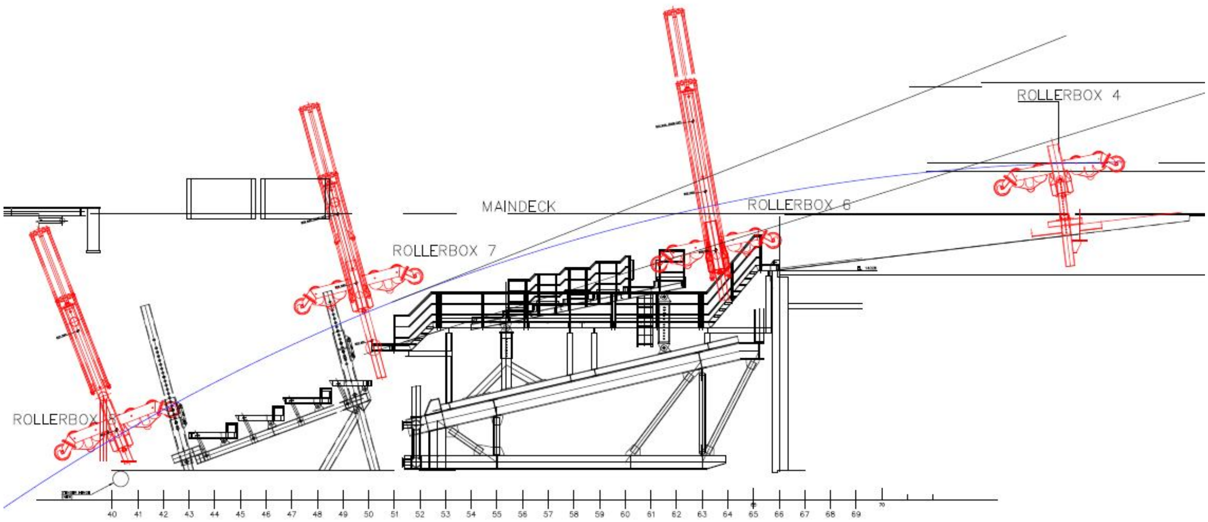


Figure 8-6 Cross section of the firing line in the threshold, showing the locations of the rollerboxes.

8.2.6 **Work stations**
There are two workstations that are of interest during this conversion. The first is the work station denoted by the number 9 in Figure 8-2. This station is exclusively used as part of the coating process. The coating equipment differs greatly from project to project. The equipment is all specifically designed and installed on the ship for each project. This means that there is no need to install special equipment permanently inside the units.

It is important to note that the coating equipment is mainly connected to the roof of the firing line. This means that the roof should be strong enough to carry the equipment.

The second workstation is workstation 10, not pictured in Figure 8-2, but located between the rollerbox 6 and 7. Station 10 is the extra station build for a fourth tensioner to increase capacity of the ship. It is also sporadically used as a coating station when the Injection Moulding Poly-Propylene (IMPP) technique is used for coating. Neither the tensioner or the IMPP moulding process requires additional equipment, they require only utilities which are discussed in paragraph 8.4.3.

8.2.7 **Pipe elevator**

The pipe elevator, pictured in pink in Figure 8-2, is used to transport pipes from the deck into the hold. It remains on the ship, independent of its configuration. Due to the layout of the machinery, as well as its location, between the portal frame and the container hatch it would serve little purpose to remove it from the ship as it would not free up any significant usable space.

8.2.8 **Portal frame**

The portal frame, pictured in red in Figure 8-2, is used for J-lay structure installations and remains on the ship as well. It is an extremely large structure that is not easily removed or placed somewhere else. Additionally, the portal frame is used for the installation of structures, which is one of the tasks that require an empty deck.

A second element to keep in mind is that there is very little space between the edge of the portal frame and the side of the threshold. In the current configuration the walls of the threshold cover are placed against the side of the threshold and the edge of the portal frame with no space left.

8.2.9 **Container hatch**

The container hatch, denoted in light blue in Figure 8-2, has an important role in the concept idea for the modular design. By being able to place the modular units below deck when they are not in use the ship gains a lot of freedom. In that case it would not be necessary to return to its home port to retrieve the missing units nor is it necessary to supply additional transport to bring the units to the ship. Currently the container hatch is made for TEUs which are 6.1 meters long.

It is possible to elongate the container hatch but increasing the width of the hatch is not possible due to the location of other equipment.

8.3 Relevant regulations

In the design of a ship there are always safety regulations to consider. Ship regulations range from the safety of the crew to structural requirements. For the safety of crew the most important conventions is the Safety Of Life At Sea (SOLAS) convention. This convention covers all aspects of safety, from fire safety to ship stability. [55]
With regards to the structural integrity of the ship the Lloyds regulations are followed as the *Lorelay* was built under their supervision.

8.3.1 **SOLAS**

There are two elements of the SOLAS regulations that are of interest for the design of the firing line units; fire safety and escape routes.

Fire safety

The fire safety regulations [55] state the following general regulations:

- The ship shall be equipped with a general emergency alarm that is audible throughout the accommodation and working stations
- All working stations shall be equipped with a fire detection system and fire alarm suitable for the nature of the space
- A sprinkler system shall be installed in areas where a fire might originate
- Fire extinguishers of the appropriate type shall be provided in service spaces and control stations
- Manually operated call points shall be placed effectively to ensure a readily available means of notification
- All working stations shall be equipped with a general information system (speaker) that allows the bridge to inform all crew of important information

In order to provide these safety provisions each unit has to be equipped with the utilities to provide them. In this case, this means electric power (220V), water for the sprinkler system and a phone connection to the bridge. This list of utilities is expanded later on in this chapter.

Escape routes

To provide a safe working environment for the crew and allow for quick escapes in case of an emergency SOLAS also gives several regulations about escape routes. [55] The relevant regulations are:

- Each work station shall provide a safe means of escape, larger areas shall have two exits
- All escape routes shall have a width of 70 cm and shall be clear of obstructions
- Dead-end corridors shall be avoided

Given that firing line is divided into two parts by the pipe line, doors on either side are required to provide a safe way to escape.

8.3.2 Structural regulations

Lloyd's regulations pertain to the ship's structural integrity. Since the units are not a permanent part of the ship they have no influence on the ship strength as a whole. However, if changes are made to the hull of the ship during the conversion, it is important to look into the relevant Lloyds rules.

This does not mean there are no structural requirements to follow with regards to the firing line units. The unit should still have the strength to hold its form while it is lifted off the deck or while the ship is in rough seas. Additionally it should have the strength to hold up the equipment and allow for the placement of other equipment on top.

8.4 Miscellaneous requirements

With regards to the design there are several other elements that need to be taken into account that cannot be placed in a specific category. These elements are mentioned below.

8.4.1 Support of the unit

When placing containers or other equipment on the deck of the ship it is important to take the deck strength into account. For the *Lorelay* the strength of the aft deck is 10 $\frac{t}{m^2}$. [56] However, containers and other units seldom have a completely straight underside. This means that the weight is not equally distributed across the deck but only placed on two, or four, points, causing problems for the deck construction. To this end containers are often supported, either by placing them on a supporting frame which can distribute the weight of the container equally, or by placing them on the frames of the deck. This allows the weight of the container to be distributed into the structural construction of the ship and not only the deck plates. [57]

In practice this means that either the units have to be sized in such a way that they terminate exactly at the either a longitudinal stiffener or a transverse stiffener or that a support frame for the units has to be devised.

8.4.2 General equipment

To assist with the pipe laying activities the whole firing line has several crane beams running along the roof. These cranes have a small lifting capacity of two or three tonnes. These cranes are also required in the new units.

8.4.3 Utilities

Besides the utilities defined above for the safety regulations and the general outfitting there are several other utilities that are required inside every unit.

The following utilities are required in one or more of the locations in the firing line:

- Ventilation, to allow for the removal of production fumes
- Fresh water, for production, for consumption and for the sprinkler system
- Electricity (220 V and 440 V), to power everything from lights to heavy equipment
- Hydraulics, for heavy equipment such as the rollerboxes
- Communication possibilities and internet, as prescribed by SOLAS regulations
- Data cables from the sensors to the computers

For the success of this concept it is important that it is easy to connect the different units to each other. If this process is complicated and takes a long time the advantages of a modular concept decrease quickly.

8.4.4 Interface between unit and deck or unit and unit

To allow for a quick removal of the units from the deck a simple system is required. There are multiple container lashing systems that can be of interest for this. In addition to working quickly, it is also important that the lashings can be completely removed to allow for a flat deck.

With regards to the unit to unit interface it is important that the units fit well together to keep the working area they cover watertight.

8.4.5 Interface with existing firing line

To allow the units to seamlessly interact with the existing firing line special attention has to be paid to the interface between the existing firing line and the modular units. If the interface is not approached properly problems ranging from utility interface to safety could become an issue.

8.5 Program of requirements

The analysis done above can be used to determine the program of requirements. An ideal program of requirements uses only a small number of requirements to cover the whole project. This is to simplify the decision making process when working on the design. More requirements mean more evaluation criteria which makes it harder to choose the best solution. However, the program of requirements should also cover the whole score of the project. [4]

Requirements are binary, either a concept meets the requirement or it does not. For example: "the unit has to have a minimal height of 5 meters". All concepts that do not reach that height are eliminated. To allow for a choice between two concepts that both meet all the requirements it is possible to also add non binary criteria, or wishes. An example of this is "the units weigh as little as possible".

General requirements

- The complete removal or installation of the firing line units shall not take more than two days to complete.
- The stability of the ship shall not be worse than the current situation.

Regulatory requirements

- The units shall meet all requirements set by both the IMO and Lloyds register which are relevant for this design.

Dimensional requirements

- The total length of the new firing line shall be the same as the total length of the current firing line.
- The units shall fit through the container hatch in order to be stored in the hold of the ship.
- The width of the units shall be enough to cover the sloping deck or the threshold.
- The height of the units shall be enough to allow inline structures to pass through them without problem and to allow for the installation of the fourth tensioner.

Structural requirements

- It shall be possible to lift the units using a crane, without the structural integrity of the unit being compromised.
- The units shall have enough structural integrity to provide a safe working environment in all sea conditions the *Lorelay* can sail and operate in.
- It shall be possible to place a load of 400 $\frac{kg}{m^2}$ on top of the units.

Equipment requirements

- The units shall be equipped with the utilities identified in paragraph 8.4.3.
    - It shall be possible to quickly and easily interface these utilities between the different units.
- The units shall be equipped with one or more small overhead cranes.
- There should be enough space for the installation of the fourth tensioner in the threshold.
- It shall be possible to install inline structures in station 10.

Interface requirements

- The units shall be supported on the deck in such a way that the unit's weight is distributed into the rest of the ship.
- A watertight and easily removable connection shall be made between the following elements
    - Unit and deck
    - Unit and unit
    - Unit and existing firing line

9.0 CONCEPT DESIGN

In the previous chapter, the main equipment was investigated and the main requirements for the new design were determined. In this chapter the next step of the design process, setting up a concept design, is performed. During the concept design phase different solutions are conceived to solve the design problem. This phase ends in one single solution which meets the design goals and all requirements defined in previous chapters.

In this chapter a decision is made whether the units are taken on board of the ship or left on shore. The next step is to determine the shape and size of the units. With the main dimensions known the weight of the changes can be determined. This in turn is used to estimate the effects these changes have on the stability of the ship. From there on the method of interfacing the units to the deck and to each other, as well as the interface of the required utilities is determined. The next step is to look to the hatch and overhead cranes that need to be present in the firing line. Lastly the requirements to the structural integrity of the units are investigated.

This chapter only discusses the final solutions that are chosen. The other options that were considered but were discarded can be found in 0.

9.1 Threshold

As stated in the concept idea in chapter 7.0, the removable units can either be placed in the hold of the ship or be left on land somewhere. If the units are kept on the ship they have to be placed inside the hold to free up deck space. To be placed in the hold the units have to be lowered through the container hatch. As mentioned in chapter 8.0, the container hatch is designed in such a way that 20 foot containers, 6.1 meters long and 2.44 meters wide, fit through. Additionally it was concluded that increasing the width of the hatch is not possible.

The threshold has a maximum width of 7.4 meters, more than 1 meter wider than the length of a container. This means that if the units fit across the threshold, they do not fit through the container hatch. Increasing the length of the hatch is possible, but would require opening up a larger part of the ship, lowering its structural integrity.

Leaving the units on land brings several logistical challenges. While the units can be bigger since there are no restrictions, storage and transport are required for them. Currently the ship returns to Rotterdam after each project but that is mostly due to the low workload. In busier times the *Lorelay* worked on back to back projects more than once. Should the ship work on two back to back projects, one pipe laying project and one where the units are not required, the transport of the units would have to be performed by another ship. Having the units on board would provide more freedom to the ship on when and where to switch from pipe laying mode to another mode. For this reason the choice is made that the units are taken on board.

To solve the issue of getting the units to fit through the container hold, the threshold width is reduced to 4.6 meters by closing off part of the threshold by a deck. The space that is going to be closed off, shown in Figure 9-2, is currently not in use. Therefore the decision to close off part of the threshold does not negatively impact the processes on board.

The space that is transformed into a deck is just wide enough for the placement of two additional container storage areas that can be used for storage. However, this might mean additional strength requirements and thus additional weight.

Since this deck is connected to the whole ship, it is subject to Lloyds rules. The structural changes are not expected to cause major problems for the ship. It is once again important to check the stability. An estimation of the ship stability is performed in paragraph 9.5, after the relevant weights are determined.

9.2 Unit shape

Before the dimensions and details of the units can be decided a choice for the shape of the units has to be determined. Modularity is not used much in shipping, only several naval ships, for example from the Danish and American navies, are equipped with modular units. [58], [59] In most cases this means that some elements can be swapped out for others, on specific locations on the ship. The Danish concept uses standardised units that can be placed in prebuild openings in the ship, as pictured in Figure 9-1. This allows for easy interface as well as a high level of flexibility. However, it is more suitable for new build than for a conversion. An opening of this size could limit the structural integrity of the *Lorelay* and cause torsional problems.

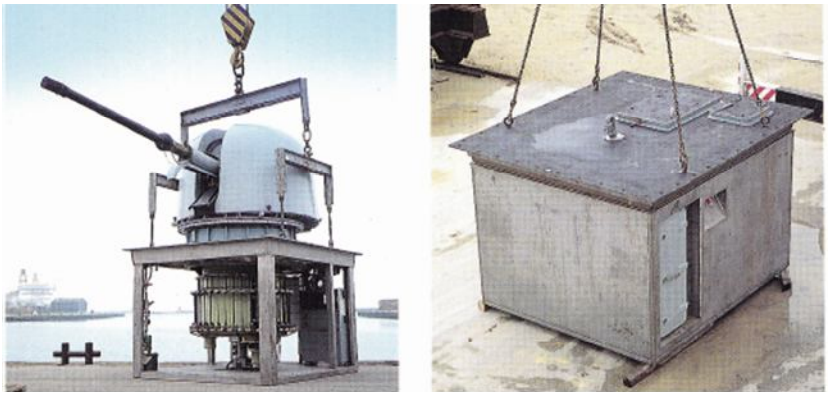


Figure 9-1 Gun unit and storage container for the Danish Standard Flex 300 ships [58]

Making use of modular structures is relatively common in the building of, for example, office buildings and apartment complexes. Modular buildings are used to speed up construction or create temporary buildings. There are two methods that are commonly used; the use of complete units or the use of prefab elements, side and roof panels that are pre-constructed and installed on location. Both of these options could be used on the ship.

Out of these two options using complete units shows the most promise for the *Lorelay*. The main reason for this is the number of connection points, which increases when using panels over complete units. Using complete units also allows for a larger part of the utilities to be pre-installed in the units, which also simplifies this interface process.

The shape of the unit is largely determined by the tasks that are going to be performed inside the unit. The unit does not have a bottom, to accommodate the equipment placed on the sloping deck and in the threshold. To allow for the passage of the pipeline and crew between the different units the transverse sides are also left open. This leaves an arch-shaped unit consisting of the two short sides and a roof. The general layout of the unit is pictured in Figure 9-2.

9.3 Unit size

With the shape of the threshold and the unit known, the dimensions of the units can be determined. In the problem definition it was stated that the units have to fit through the container hatch on the ship.

9.3.1 Unit width

The maximum width a unit can have is dependent on the width of the container hatch, as the containers are placed in transverse direction on the ship. The container hatch is optimised for TEUs, meaning that the maximum width a unit can have while still fitting through the container hatch is 2.44 meters. Together the units have to cover the same length as is removed from the ship, 26.5 meters.

Ideally a minimum number of units are used as fewer units means less time spent on installing and interfacing the units. This means that the firing line will consist of 11 units, each with a width of 2.4 meters.

9.3.2 Unit length

As mentioned previously, the threshold is closed off partly to reduce the required unit length. For the threshold this means that the minimum unit length that is required to bridge the threshold is 4.6 meters. Around the threshold no further covered deck space is necessary, since all equipment is already several meters beneath the deck, where walkways and platforms are available at working height. Making a unit that is wider than the threshold is useless.

Around the sloping deck this is different. The sloping deck is just wide enough for the firing line equipment, leaving no space for the crew to work. This means that here some parts of the deck have to be covered to provide space to work.

Ideally all the units have the same size. This simplifies the connecting process and helps with keeping the units watertight. Placing the same size units across the sloping deck as are placed across the threshold should allow for enough working space.

However, the units are most likely build up out of large I-profiles to help with the structural integrity. In the current firing line, I-profiles with a length of 40 cm are used. Assuming that these profiles are also used in the new units means that the total outside length of the units is 5,4 meters.

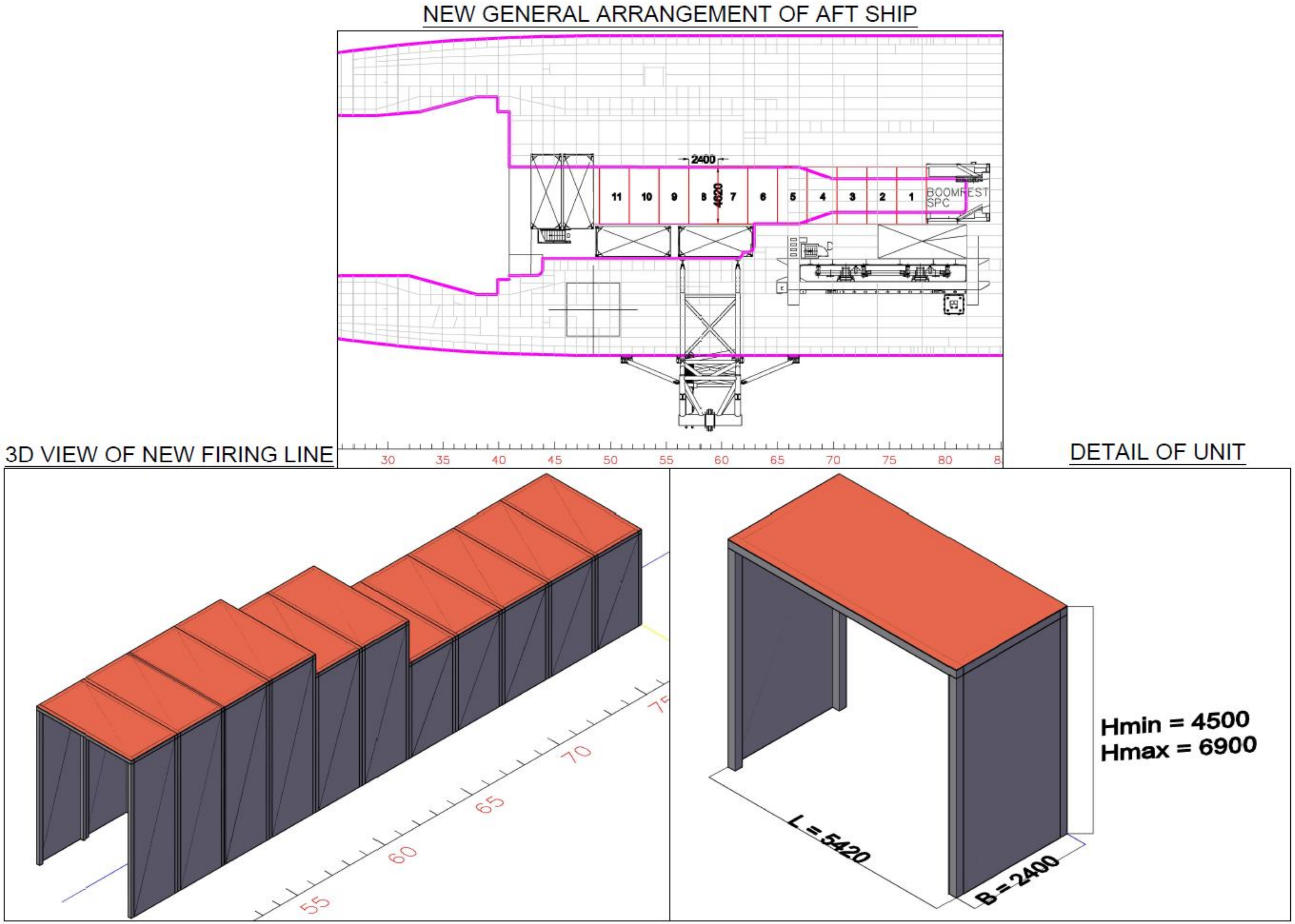


Figure 9-2 General arrangement and details of the new design

9.3.3 **Unit height**

The final dimension that has to be determined is the height of the unit. In an ideal case the height of the units would all be the same. However, that would mean that most of the units are unnecessarily heavy due to increased height. This clashes with the wish to each unit as light as possible.

As was explained in chapter 8.0 the fourth tensioner has to fit under the threshold cover. To allow for this a unit an inner height of 6.5 meters is required. Using the same logic as was used to determine the outside length of the units, the outside height of the units is 6.9 meters.

To minimise the weight of the units the choice is made to use different heights, dependent on the requirements of the locations. For this reason forwards part of the firing line is chosen to have the minimum height, 4.5 meters, the two next units have a height of 6 meters and the final units have a height of 6.9 meters. Figure 9-2 shows the height differences between the units.

The lowest units, placed between from the boomrest towards the threshold have an outside height of approximately 4.5 meters to accommodate an inner height of 4.1 meters. The highest units have an outside height of 6.9 meters to accommodate the height of the fourth tensioner. The other two units have a height of 6 meters to allow for a smoother connection between the lowest and highest units.

It is also possible to make the choice that the firing line consists of only low units when the fourth tensioner is not in use. However, this would increase the production cost as well as add to the logistical problem. Since the units that are not in used have to be placed on the ship, even in pipe laying mode. This would mean that the pipe carrying capacity of the ship decreases.

Figure 9-3 shows the units placed on the ship.

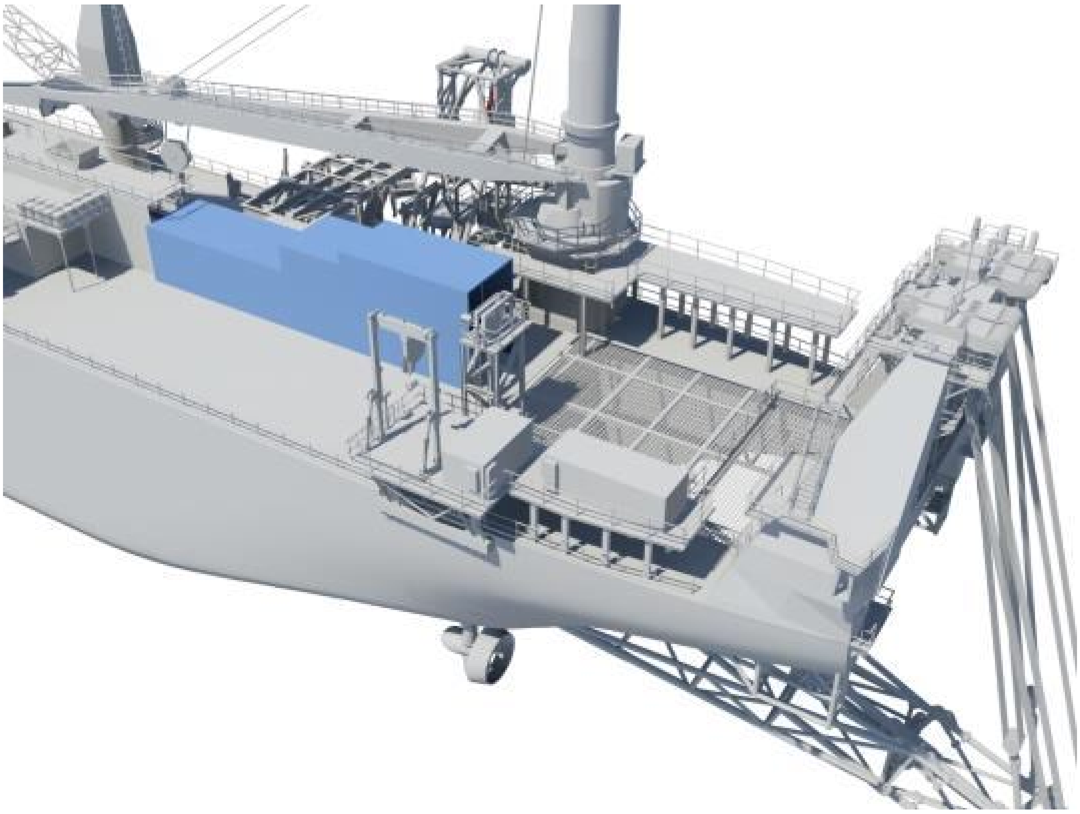


Figure 9-3 Placement of the units on the ship

9.4 Weight of the new elements

In this paragraph the weight of the units and the deck in the threshold are estimated. These weights are then used to estimate the changes to the stability of the ship.

9.4.1 **Unit weight**

With the decision to place the units in the hold of the vessel an additional weight requirement is placed on the units. Inside the hold the units are moved around by the overhead crane present there. This overhead crane has a capacity of 20 tonnes. [60] This means that, in order for this concept to work, the weight of the units has to be below 20 tonnes.

The weight of the units is estimated by assuming that the new units are built up out of the same materials as the current firing line. This means that the beams are made of an IPE-400 I profile and that the walls have a thickness of 10 mm. The additional steel weight for stiffeners and such is assumed to be 20% of the weight of the IPE-400 profiles and the plates. The total weight of the utilities and permanent equipment is assumed to be 80% of the weight of the IPE-400 profiles and the plates.

For the calculations the following values are assumed:

Weight of IPE-400 profile: $66.3\ \frac{kg}{m}$ [61]

Density steel: $7850\ \frac{kg}{m^3}$

The following weight estimation can be made for the units:

Table 9-1 Estimation of the weight of the units

	Low (4500 mm)	Medium (6000 mm)	High (6900 mm)
Unit Length [mm]	5420	5420	5420
Unit width [mm]	2400	2400	2400
Unit height [mm]	4500	6000	6900
IPE-400 weight [kg]	2549	2946	3185
Plate weight [kg]	2717	3282	3621
Subtotal	5266	6228	6806
Additional steel weight [kg] (20 % of subtotal)	1052	1246	1361
Total steel weight [kg]	6314	7474	8167
Total extra weight [kg] (80 % of subtotal)	4210	4982	5445
Total unit weight	10524	12456	13612

A comparison can be made with the known steel weight of the current threshold cover, which is approximately 45 tonnes. For the current design the weight of the threshold cover is estimated at 48 tonnes. This small difference in weight is to be expected. The new firing line is more narrow that the previous one, due to the partial closing of the threshold. On the other hand the units are expected to consist of more steel since each unit has to be capable of standing on its own, meaning it has more support than the current firing line

The total weight of the new firing line, including utilities and outfitting, is estimated at 132 tonnes. Unfortunately there is no known weight for the whole firing line as it is currently build. However, when assuming that the 6% weight increase over the threshold cover holds true for the rest of the firing line the current design is approximately 7 tonnes heavier than the old design.

9.4.2 Deck weight

The area of the threshold that is covered by the new deck is approximately 60 m^2. Assuming a weight of 100 $\frac{kg}{m^2}$ for the deck leads to a total weight of approximately 6 tonnes.

9.4.3 Ship weight

Since the weight of the new firing line is higher than that of the current firing line the pipe carrying capacity of the ship decreases slightly. This is due to the fact that the ship is loaded to capacity when it is laying pipe. Every ton that the ship is heavier in equipment is a ton that cannot be used for pipe storage. However, with a pipe carrying capacity of 8200 tonnes, a decrease of 15 tonnes, or 0.2%, is not significant. [60]

9.5 Ship stability

There are two elements of interest with regards to ship stability. The first is the influence of the new firing line on the stability of the ship when they are placed on deck and the second is the effect the units have when they are placed in the hold of the vessel. A simplified calculation can be performed to estimate the stability of the ship.

9.5.1 **Influence of unit weight on ship stability**

In paragraph 9.4 the weight of the units and the deck are estimated. These weights are further used to calculate the stability of the ship. The calculations, which are detailed in 0, show that the expected weight increase only does not affect the location of the CoG significantly. The increase in the location of the VCG (Vertical Centre of Gravity) is estimated at 0.4 centimetres.

In longitudinal direction the LCG (longitudinal Centre of Gravity) moves an estimated 20 centimetres backwards and the TCG (transverse Centre of Gravity) moves only 0.1 centimetre. None of these changes are deemed significant.

9.5.2 **Placement of the units in the hold of the vessel**

After the units are removed from the ship they are placed below deck in the hold. There is more than enough space, since the hold is empty when the ship is not laying pipe.

For the four highest units the possible placement is limited. As shown in Appendix L there is very little lifting height available for these units. The hold of the *Lorelay* is partly filled with concrete beams as additional ballast, with a height of 40 centimetres. This means lifting height becomes critical again. Therefor these two units are placed in the back of the hold where the additional ballast is not located.

The other units can be placed at any location in the hold. With regards to the trim of the ship, the best location for these units is in the middle of the ship. There they have the least influence, keeping the ship at the preferred trim angle.

It is also possible to use the units are movable ballast and use them to keep the ship level, for example, if a very heavy load is placed on the back of the ship, moving the units forwards in the hold can help counteract any trim changes to the ship.

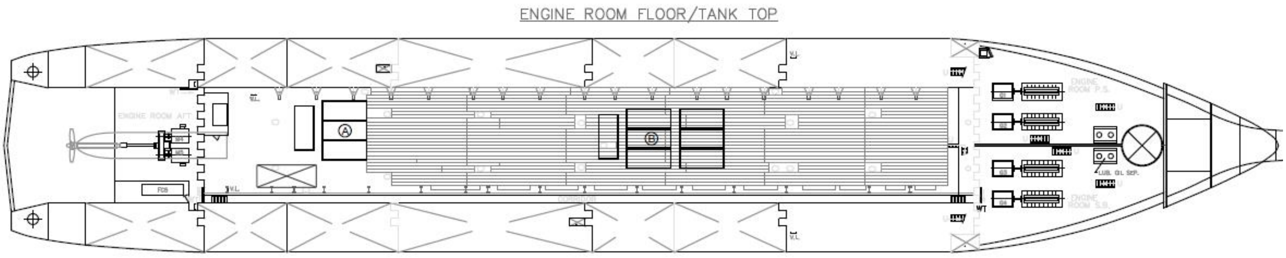


Figure 9-4 Potential placement of the 11 units in the hold

The units also affect the load that can be placed on deck without having a negative influence on the location of the CoG. Together the units weigh 132 tonnes and they are placed very low in the ship, well below the ship's CoG at 13 meters. This means that, by placing the units in the hold of the ship, on deck level an additional 362.9 tonnes of weight can be added without changing the total CoG of the ship.

The exact calculations that were performed to calculate this value can be found in 0.

9.6 Interface

The next element to look into, is the way the units are interfaced with each other, the ship and the existing firing line as well as how the utilities are connected. How well the units fit together is a crucial part of the success of a modular design. If there are problems with the installation that influence any of the primary functions of the units, the project cannot be completed.

9.6.1 **Unit to ship**

In general, when housing is placed on the deck of a ship it is bolted or welded into place. However, since the units are removable and they are subject to the requirement that this removal has to be quick, the securing of the units is approached as if they are cargo units.

There are many different ways of securing cargo on a ship, ranging from pulling a net over wood or other loose cargo, to using twistlocks to quickly secure containers to the deck. [62] Due to the unit's similarity to containers, the lashings used for containers show the most promise.

Most containers are secured to the deck using twistlocks. Twistlocks are rotatable, cone shaped, pins that lock to the underside of the container. They stop the container from moving across the deck and also stops the upwards motions. [63]

The units are comparable in size and weight to containers. Therefore it is assumed that they can be secured by twistlocks. However, the units have much more height than a regular container. For additional securing, lashing rods can also be applied to limit the movement of the upper part of the unit. Lashing rods are steel connectors that cross over the side of the containers. Their function is to limit the transverse container motions. Both securing methods are shown in Figure 9-5.

Figure 9-5 Left: Semi-automatic twistlock [64], Right: Containers supported by lashing rods [65]

9.6.2 **Unit to unit**

For the connection between two units not only an easily removable connection is required, but it also has to be watertight. The solution in this case is drawn from the way modular office buildings are build. There are two common methods that could both the used for the connection of the units.

The first potential method is using an H-shaped form to connect two corner profiles of the units to each other as shown in Figure 9-6. To keep the two units together tension rods at the top and bottom of the unit could be used.

To also ensure that the roof is also water tight a T-shaped profile could be placed between the roof panels. By sloping this part slightly the water is transported off the connection. To ensure that no water is left on the roof of the unit the top could have a slight convex shape to make sure the water falls of the side.

Another method that is used frequently in modular building is using a rubber strip to create a watertight seal between two units. [66] In this method the two units are placed close together and a rubber seal is inserted between them. The units are them pulled even closer using tension rods at the bottom and top of the units. This method creates a watertight seal between the sides and also between the roofs.

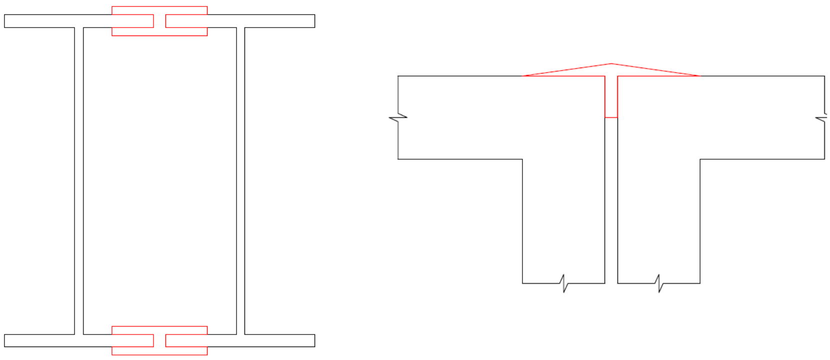


Figure 9-6 Left: H-shaped connection profile, right: T-shaped profile between two roof panels

Which of these two methods is the best solution is difficult to say. Each of them has both advantages and disadvantages. The H and T-shaped connections are a more secure way to connect the units but do add additional material that has to be stored somewhere. Additionally, the connection parts might get damaged or plastically deformed meaning that a replacement is necessary. This is not the case for the rubber strips. However, this installation method is more laborious because the rubber has to be inserted by hand and at significant height.

Furthermore an investigation is required into the manner in which the units of different height are going to be connected. It might be possible to close off the higher part of the unit and adding an additional longitudinal I-beam at the height of the lower unit. This would allow for an interface option. There might also be lighter options that could be considered such as a rubber “skirt”.

9.6.3 **Utility interface**

The utilities that need to be available in the unit are:

- Ventilation, to allow for the removal of production fumes
- Fresh water, for production, for consumption and for the sprinkler system
- Electricity (220 V and 440 V), to power everything from lights to heavy equipment
- Hydraulics, for heavy equipment such as the rollerboxes
- Communication possibilities and internet, as prescribed by SOLAS regulations

Figure 9-7 Detail of the firing line, utilities [Authors own collection]

The installation of the electricity cables is something that is relatively common when constructing modular offices. In these cases the units come with all the wiring, switches and conduits preinstalled. After the unit is placed on its required location, the only thing left to do is to plug the power source into the breaker box. When connecting multiple units simple connections are used that snap together and do not require an electrician to connect. [67]

Electricity cable has to advantage that they are flexible and thus easy to connect between the different units.

The same sort of system can be used for the other utilities. The main infrastructure per unit can be installed permanently and systematically in each unit. For the connection between each of the unit flexible connectors can be used to close the connections.

For this concept to be successful it is important that a detailed layout of the utilities is made and followed. Currently utilities are routed to the place where they are needed rather haphazardly. This results in a complicated layout of utilities going to different places and dead ends, left over from old projects. Figure 9-7 shows some of the utilities in the *Lorelay's* firing line and show the magnitude of the interface problem.

Detailed engineering is required to determine how much of each utility is required at which location. Then a design of how these utilities are routed to the units is needed. In this design the number of connections between the units should be limited.

9.6.4 **Unit to existing firing line**

Structurally, connecting the unit to the existing firing line is relatively easy. For the interface between the existing firing line and the new units the same method can be used as is used for the unit to unit interface. This might require some changes to the existing firing line to allow for these methods to be used.

Here the interfacing of the equipment is also going to be a challenge. The same problems that arise as at the interfacing of the utilities from unit to unit, and the same solution applies here too. The utilities have to be untangled to allow for a minimum of needed connections to the modular units.

9.7 General equipment

This paragraph discusses the implementation of the overhead crane and the overhead hatch in the units.

9.7.1 **Overhead crane**

To help with the movement of equipment each unit is equipped with at least one overhead crane, installed in the ships longitudinal direction. The main difficulty for outfitting the units with cranes is the manner in which this is done. The simplest solution would be to place a rail, with cart, in each unit. However, this would mean that in a workstation of 12 meters long the load would have to be transported from one crane to another several times, which would limit the working speed of the crew.

However, by connecting the rails of the overhead cranes a longer rail can be created allowing for a larger range of the cranes. This means that the complete firing line could be divided into three of four parts with regards to the overhead cranes. Three is the minimum number due to the height differences of the units.

9.7.2 Overhead hatch above threshold

To ensure that it is possible to install the removed elements of the inline structures, as mentioned in chapter 8.0, access has to be created. In the current configuration there are three larges hatches that also allow for the installation of the inline structures as well as the placement of the fourth tensioner. However, the requirements for both tasks are very different. The tensioner requires a large opening to fit through, while the parts of the inline structures are much smaller. For this reason the *Solitaire,* which has a similar design in its aft ship has a large hatch for placement of a tensioner and a smaller hatch of 2 by 2.8 meters for the installation of inline structures inside the bigger hatch. [68]

Using this idea, unit 9, as denoted in Figure 9-2, is equipped with a hatch of similar size. This hatch is used for the installation of inline structures. Should the fourth tensioner be required, the relevant units can be removed completely to create enough space for the installation. This is possible since the ship is docked for this installation. While the inline structures are installed, removal of units is not possible. With the ship in operation somewhere out at sea and the hold filled with pipes there is no place to put the units for a short while. Additionally the units are all connected via the utilities. This means that if a unit is removed from the middle, the utilities in half of the units are also removed, which could cause problems when the ship is in full operation.

This hatch means that additional attention has to be paid to the structural integrity of this specific unit since opening the roof means decreasing the integrity of the unit.

9.8 Structural integrity

The final element that is investigated is the structural integrity of the units. The program of requirements states that the units must have enough structural integrity to be used safely by the crew while working, as well as survive being lifted by a crane. In order to design a unit that can survive these conditions, the forces and accelerations on the unit must be determined. This report goes no further than identifying these forces and suggesting possible adaptations to the unit design.

9.8.1 Forces and accelerations while installed on the ship

While the unit is installed on the ship it is subjected to several different loads. The first is, as defined in the program of requirements, a load of 400 $\frac{kg}{m^2}$. This load is created by different objects such as spare parts or unused equipment. In Figure 9-8 this load is denoted by Fload.

The next load is a wind load. For design purposes the worst possible case is assumed, heavy winds on the largest possible area of the unit. This means quartering winds, coming in from the side at either 90 or 270 degrees. This wind load can be taken as 1 $\frac{kN}{m^2}$. [69]

Finally the structural integrity of the units is influenced by the ship motions. As the ship moves in waves it is accelerated in different directions simultaneously and repeatedly. These accelerations are also passed on to everything placed on the ship. How big these accelerations are is dependent on the location of the unit on the ship but for rough calculations the following assumptions can be made [69]:

- Yaw does not create accelerations that influence the units
- The accelerations caused by surge, along the ship's x-axis, are assumed to be 0.4g
- The accelerations caused by sway, along the ship's y-axis, are assumed to be 0.8g
- The accelerations caused by pitch, roll and heave, along the ship's z-axis, are assumed to be 1.0g

In which g is the gravitations acceleration at 9.81 $\frac{m}{s^2}$.

These accelerations can be recalculated into a force using Newton's second law: $F = m \cdot a$.

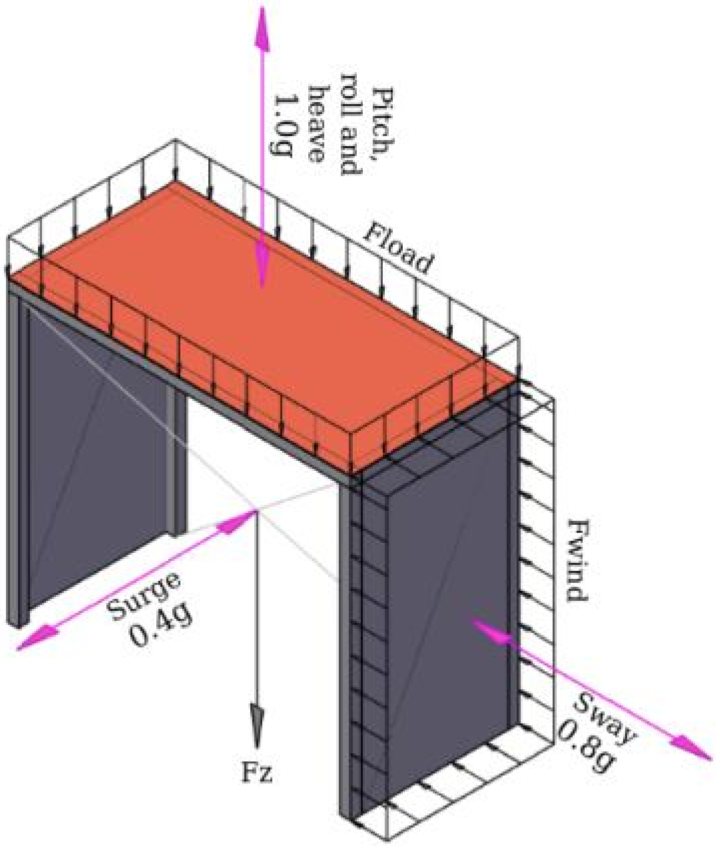


Figure 9-8 Forces and accelerations on the unit while sailing in bad weather

As pictured in Figure 9-8 the accelerations caused by sway are relatively high with 0.8g. This could result in the unit moving heavily from side to side, possibly damaging itself. To counter this movement support beams can be installed between the sides and the roof. This provides the unit with protection against collapse due to these movements. This is pictured in Figure 9-9.

In surge direction the forces are smaller and the movements are supported better since the walls also play a role. However, it might be a necessary to install additional supports in that direction as well. Possibilities of this are stiffeners along the wall and beams at the top and bottom of the wall. Both of these options are also shown in Figure 9-9.

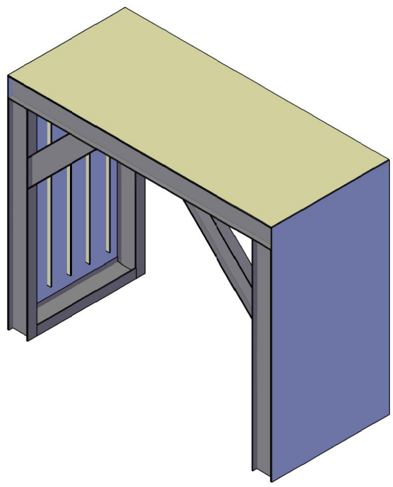


Figure 9-9 Example for the unit with additional stiffening to counteract the sway and surge motions

9.8.2 Forces and accelerations during lift

A second load case that has to be investigated is the case where the unit is lifted by the crane to be installed or stored.

Lifting methods

In general, when a load is lifted, lifting slings are connected to the load and it is hoisted up. To ease the lifting of the units pad-eyes are installed. These eyes make it easier to connect the lifting slings and often provide additional corner support.

There are two possible manners in which the units could be lifted, both based on ways containers are lifted. The simplest method is one where four lifting wires are connected to the corners of the unit. These are connected to the hook of the crane under an angle to the vertical between 30 and 45 degrees, where 30 degrees is preferred. The second method is using a spreader bar or clamp that ensures that the forces that are applied on the units are going upwards, instead of each of the corners being pulled towards the middle. Both of these lifting methods are pictured in Figure 9-10.

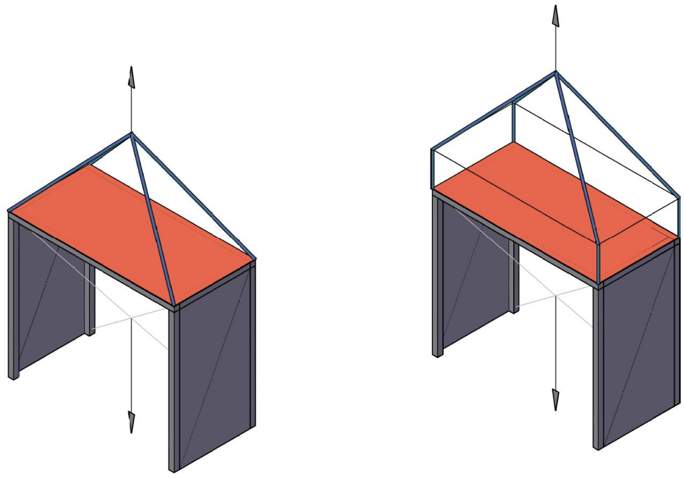


Figure 9-10 Left: Direct lifting, right: lifting with a spreader bar

Due to their design, the units are prone to buckling. Therefore additional care has to be taken when the units are lifted. This effect is bigger when the units are lifted directly in comparison to the units being lifted using a spreader bar, due to the direction of the forces. These forces might result in the sides of the unit being rotated outwards, making the placement of the legs on deck and interfacing between the units more difficult.

There is one big disadvantage to using a spreader bar: the height required for the lifting cables to come together is higher when using a spreader bar. This could be a problem when the units have to be lifted while in the hold.

Lifting the units in the hold

In the hold, the units are lifted by an overhead crane. Since the space below deck is limited the available height has to be checked to see if it is possible to lift the units in order to move them around the hold and place them in their position for transport. Inside the hold the, crane hook can reach a height of 9.2 meters above the ground. [70] Since this is the place where the slings meet this is the maximum available height for the unit plus its lifting slings. The largest unit has a height of 6.9 meters. For the direct lifting method 3.0 meters of height is required above the unit. This means that the total required height adds up to 9.9 meters, which is too high.

Figure 9-11 Container being lifted by a spreader [71]

There are two possible solutions to ensure that the units can still be lifted inside the hold. The first is to move the padeyes inwards. This is possible when the unit is equipped with the additional stiffening shown in Figure 9-9. For example, moving each padeye inwards one meter means that the hook has to be 2.1 meters above the unit. This means that lifting is now possible, but only just.

The second method is using a different type of spreader, shown in Figure 9-11. This type, generally used for lifting containers, connects to the twistlocks on top of the container. This means that the required height also decreases. A disadvantage of this method is that these spreaders are only available for standard ISO container sizes. [71] This means that, should this method be selected, a special spreader has to be built for these units.

Which lifting method is used is dependent on the final structural design of the unit. When a final design for the unit is created it, the decision can be made to either move the padeyes inwards or to use a spreader. Appendix L shows how much space is available when the largest unit is lifted in the hold using a spreader.

9.9 Design summary

To make the firing line removable the firing line is removed starting from the boomrest and going aft. The current firing line is replaced by eleven units, each with a length of 5.4 meters and a width of 2.4 meters. The height of the unit is dependent on its position on the firing line. It is estimated that each unit weighs between 10 and 14 tonnes.

The difference in weight between the current firing line and the new design is minimal. Basic stability estimations show that exchanging the firing line with modular units does not have a significant effect on the ships stability. The placement of the units is the hold of the ship does allow for an additional 362.9 tonnes of weight to be placed at deck level, without changing the VCG of the ship.

The units are connected to the ship by using twistlocks and lashing rods. To connect the unit to each other there are two possible solutions. The first is using an H-shaped profile in which the two ends of the units are secured by a tension rod. In the same fashion a T-shaped profile can be used to seal the roof. Another option is to use rubber strips which are placed between the units which are then tightened together with tension rods. Which of these methods is the preferred solution is unclear at this point.

To connect the unit to the existing firing line the same system can be used as is used for the interfacing of the units to each other. The biggest challenge in this respect is the manner in which the utilities are interfaced. It is necessary simplify the layout of the utilities so that they can be easily connected to the new modular units.

The utilities are installed in the units permanently as much as possible. This means that a detailed layout of the utilities is required. The number of connections is kept to a minimum and the connections are made using flexibles.

Additionally one of the units is equipped with a hatch to allow for the installation on inline structures. For the installation of the fourth tensioner the relevant units are removed from the ship to create enough space for the installation.

The units can be placed inside the hold. However, the highest units cannot be placed in every location due to the height restriction of the hold. The lower units can be placed at any location.

10.0 DESIGN EVALUATION

The final step of the design process is to evaluate how well the design meets the design criteria. Additionally the next steps in the design process are outlined, together with some of the other ideas that were not incorporated in the concept design but need further investigation to find out if they have merit.

10.1 Design evaluation

In chapter 8.0 each of the main requirements for the modular design of the *Lorelay* were investigated. For each of the practical requirements a solution was found and none of the requirements proved to be a showstopper. The only criterion that could not be checked was the general requirement which stated:

- The complete removal or installation of the firing line units shall not take more than two days to complete.

Without further calculations and a more detailed design it is impossible to say if this requirement can be met.

All other requirements are met. The solutions that were found, are based on existing ideas that are employed in other markets. However, the ideas are purely theoretical and have not been tested on a ship. Therefore further investigation could still prove that this concept does have problems. However, this concept design proves that technically it is possible to meet the design requirements stated in paragraph 8.5.

By converting part of the firing line into modular units the ship gains more flexibility in which tasks are performed. This is very beneficial in the subsea installation market as it is very volatile. In this market one day there are many cables to install and the next there are only pipe lines to install. To have a ship that can quickly adapt to the many different wishes within the subsea installation market can significantly improve its utilisation.

There is a significant risk involved with building a ship that is made for on purpose only. If that market crashes the ship is worthless. This risk is partly mitigated by enabling the ship to perform a multitude of tasks. This way the profit the ship makes increases compared to a ship that can only perform one task.

By making the choice to keep the units on the ship, many limitations are introduced, for example on the size and the weight of the units. Additionally it means that only a small part of the firing line can be removed to create more deck space. Relinquishing the requirement that the units stay on board and that they are lifted by the 300t SPC means that many new options become available. It would mean that a larger deck area could be cultivated, larger units could be used which would simplify the interface between them or other concepts for the units could be introduced as suggested in paragraph 10.2.

However, the benefit of opening up a larger deck would have to be investigated. The part of the firing line that is currently removed is at the edge of the crane reach. Removing more equipment means that it can only be used for tasks for which the SPC is not needed.

Additionally the question is if the space is very useful as there is a lot of equipment that cannot be moved from the ship such as the power unit for the tensioner or the workshops. This means that the space that is gained by removing the firing line does not cover the whole width of the ship.

10.1.1 Proposed changes to the design

As mentioned before the *Lorelay's* stability is always a critical point. Every ton of weight that in placed above her CoG negatively influences the ships stability. Therefore the modular units should be as light as possible to minimise the effect they have. In the design the units increase in height to allow for the installation of the fourth tensioner. The decision to have these higher units on board permanently means that the firing line is, at times, an estimated 16 tonnes heavier than it needs to be. Over the total ship weight this might not be significant but it is approximately 12% of the total estimated weight of the new firing line.

If further research is conducted into the layout of the units another solution might be found for adjusting the height of the units. That way the units could be in their light configuration when the fourth tensioner is not required and in a higher configuration if the fourth tensioner is in use.

10.1.2 Design implementation

The redesign of the *Lorelay* gives the ship more flexibility and opens up the possibility to work on more aspects of the subsea installation market and quite a lot of other projects. With the small units that fit in the hold of the ship the vessel has a lot of flexibility in regards to which projects can be accepted.

It is expected that the changes to the *Lorelay* however costly and large they are, can have a positive influence on the utilisation of the ship.

10.2 Other ideas

For each design aspect different solutions were investigated before the final decision was made. There are two ideas that were discarded for various reasons but could be further investigated to find out if they can be used anyway.

The first was a concept based on telescopic hangars used on naval ships. An example of such a hangar is shown in Figure 10-1. The idea was to use this concept to create enough space for the installation of inline structures and the fourth tensioner. However, the increase in both the width and the height of the construction created problems. Since the requirement of being able to remove the units was still in effect it was only possible to slide three units over each other to create space.

This was not a possibility either. Due to the limited space available on the ship the units be moved far and thus only a small amount of space, at an impractical location could be made available.

However, should this concept be used on another ship or a new pipe laying vessel be designed this concept might be worth investigating further. It is a quick way to provide a covered space that can be used for any activity. Investigating how this technology can be used for pipe laying might be worth the effort.


Figure 10-1 Telescopic hangar [72]

Another idea that could benefit from further investigation is using prefabricated side and roof panels instead of complete units. This idea was discarded due to the longer installation period but does have storage advantages. The plates can be stacked on top of each other in the hold of the vessel, decreasing the required space.

The other ideas, as considered per design step can be found in Appendix K.

10.3 Future design steps

The first thing to do when continuing with this design is to perform detailed structural calculations. These calculations, based on the forces and accelerations determined for the units and Lloyd's rules for the deck inside the threshold, will lead to much more detailed weight calculations. This includes both load cases for the units, in use on the ship and lifted by the cranes as well as the new deck in various situations and circumstances.

With this more detailed weight calculation the ship stability can be investigated. This is a short intermediate check to see if this design is still a possibility.

With the stability checked and the structural details determined and accepted the next step is to further complete the design of the units. This means looking at the interface of the units with each other, the ship and the existing firing line. The ideas suggested in the concept design should be calculated and worked out in more detail. This also goes for the locations of the padeyes and the points where the lashings are connected, all of which could require additional stiffening.

Subsequently attention has to be paid to the hatch in the unit above station 10. This hatch will lead to additional structural requirements which need to be taken into account.

Another element that requires further investigation is the way the step-wise height increase of the units is closed off. An additional interesting element is to look into the effect this part has on the structural integrity of the unit and checking to see if it could be made lighter because of it. While it might be easier to keep the structural layout of the units mostly the same it is important to keep looking for ways to save weight since a heavier firing line has a negative effect on two fronts, the stability of the ship decreases and the maximum pipe carrying capacity of the ship is also decreased.

Together these elements lead to a structurally sound unit that can withstand all load cases.

The next step is to look into the interface of the unit. Further investigation into the two different methods suggested for the interface of the unit to unit is required to find out which method is the best.

Another element that requires attention is the interfacing of the utilities. This starts by identifying what the requirements are per units. From there the next step is to determine where these utilities are going to come from. The interface of the utilities does not only require a detailed investigation into the where they are and where they go but also a redesign of the utility infrastructure in the current firing line. By simplifying and updating the existing utility system interfacing it with the units is more easily done.

The final step with regards to the units is to finish all the small details. This includes, for example, the placement of doors, general equipment and firefighting equipment.

This should result in a complete view of what the units are going to look like and how much their weight is going to be. This means that now it is possible to do the final strength and stability calculations to ensure that the units meet all the requirements. With the total weight of the unit known the iterative process of the weight and the strength of the units can be completed after which to stability of the ship, in its new configuration with units and the expanded deck, can be checked.

Subsequently the way the deck can be made into a usable space after the units are removed can be investigated. For example, there is a rollerbox that has to be removed from the deck. Additionally there are smaller elements, such as fences and railings, which also have to be removed. In this phase of the design it is important to map everything that has to be removed and to figure out if it is necessary in the new design. If the element is necessary it might need to be redesigned to make it removable. The final step is to make a storage plan for all these elements to ensure that all can be reinstalled easily when they are once again required.

There are also some additional projects that have to be done in order for this concept to be a success:

a) The new design of rollerbox 6 and 7, which sticks out from the deck. It was concluded that a redesign of this rollerbox is possible.
b) Further thought has to be given to the way by which the sloping deck and the threshold are closed off or covered when the firing line is removed. In some cases it might be possible to place a large structure over the hole but in other cases a grid might be required.
c) The logistics of the removal and installation have to be thought out. Questions such as; what is removed first, where are the smaller elements stored and how are the utilities closed off when they are not in use, have to be answered.

10.4 Modularity on a new pipe lay vessel

This report focusses on the redesign of the *Lorelay* as a modular vessel. Redesigning a vessel brings specific challenges, as the location of equipment and the shape of the ship influence the design. The *Lorelay* is an old vessel and will at some point in the future be replaced. In order to once again have a large work field for the new vessel, modularity should be considered.

In a new vessel the whole design can be optimised to allow for the modular units to be placed and removed from the ship. For a new ship some of the design parameters are the same. For example, carrying the units on board of the vessel still provides the ship with improved flexibility. However, with the new design a different approach could be chosen to allow for the placement of the units on the ship. For example the hatch into the hold could be increased in size or the telescopic firing line concept could be revisited.

Designing a new vessel for modular use will be a lot of work but with the benefits being what they are it is deemed a feasible option.

WORKS CITED

[1] Douglas Westwood, “World Subsea Hardware Market Forecast 2016-2020,” Douglas Westwood, N/A, 2016.

[2] M. Loffman, “Global Subsea Hardware Market Forecast To Total USD 117 Billion From 2014 to 2018,” Douglas Westwood, N/A, 2014.

[3] Allseas Engineering Proposals Department, “Proposal Summary sheets,” Allseas Engineering, Delft, 2015 - 2016.

[4] N. Roozenburg and J. Eekels, Productontwerpen, structuur en methoden, Utrecht: Uitgeverij Lemma BV, 2001.

[5] Allseas, “Lorelay,” N/A N/A N/A. [Online]. Available: http://allseas.com/equipment/lorelay/. [Accessed 09 09 2016].

[6] Allseas, “Introduction file,” Allseas, Delft, 2007.

[7] S. Thorsen, “Conceptual design and review of open PLET system,” University of Stavanger, Stavanger, Norway, 2012.

[8] Oil and Gas technologies, “Subsea PLEM and PLET,” 08 08 2012. [Online]. Available: https://oilandgastechnologies.wordpress.com/2012/08/08/subsea-plem-and-plet/. [Accessed 16 09 2016].

[9] Allseas, Director, *405530 Enbridge-Heidelberg J-Mode PLEM GC515 Installation.* [Film]. N/A.

[10] J. G. Speight, Handbook of offshore oil and gas operations, Laramie, Wyoming, USA: Gulf Professional Printing, 2015.

[11] W. J. Vlasblom, Dredging and offshore engineering - Lecture notes, Delft: TU Delft, 2003.

[12] Scottisch Enterprise and The Crown Estate, “A Guide to UK Offshore Wind Operations and Maintenance,” Scottisch Enterprise and the Crwon Estate, London and Glasgow, 2013.

[13] J. Greenburg, “New jackup rigs are more robust,” *offshore-mag.com,* 2011.

[14] EWEA, “Deep water - the next step for offshore wind energy,” EWEA, N/A, 2013.

[15] Wind Europe, “The European offshore wind industry - Key trends and statistics 1st half 2016,” Wind Europe, Brussels, 2016.

[16] Siemens Energy, “Fathoming news depths with service vessels,” N/A N/A 2016. [Online]. Available: http://www.energy.siemens.com/hq/en/energy-topics/energy-stories/sov.htm. [Accessed 19 09 2016].

[17] T. Alabi and A. Olatunji, “Pipeline shore approach construction - 48" Bonnypipeline,” Offshore West Africa Conference; Shell Petroleum Development Company Nigeria, Accra; Abuja, 2014.

[18] Allseas, *News & Announcements - Purchase of a DP Construction Support Vessel,* Delft: Allseas, 2016.

[19] Y. Bai and Q. Bai, Subsea Engineering Handbook, Waltham, USA: Gulf Professional Publishing, 2010.

[20] Geophysical Services Offshore, “Cable & Pipelay Support Operations,” N/A N/A 2011. [Online]. Available: http://www.gsobv.com/our-expertise/pipe-cable-lay-support-operations.html. [Accessed 13 10 2016].

[21] I. Frazer, D. Perinet and O. Vennemann, “Technology required for the installation of Production Facilities in 10000 ft of Water,” in *Offshore Technology Conference*, Houston, 2005.

[22] B. Baker and L. McClure, “Reel Method speeds lay of pipe-in-pipe,” 01 08 2002. [Online]. Available: http://www.offshore-mag.com/articles/print/volume-62/issue-8/news/reel-method-speeds-lay-of-pipe-in-pipe.html. [Accessed 21 11 2016].

[23] Rigzone, “Training: How Does Offshore Pipeline Installation Work?,” N/A. [Online]. Available: http://www.rigzone.com/training/insight.asp?insight_id=311.

[24] Technip, “Ridig Pipe Technologies,” 2016. [Online]. Available: http://www.technip.com/en/our-business/subsea/rigid-pipe-technologies.

[25] Minerals Management Service Gulf of Mexico OCS Region, Proposed Use of Floating Production Storage and Offloading Systems on the Gulf of Mexico Outer COntinental Shelf - Western and Central Planning Areas - Final Environmental Impact Statement, New Orleans: Department of the Interior, 2001.

[26] Deep down Inc, “Carousels,” N/A. [Online]. Available: http://www.deepdowninc.com/products/carousels. [Accessed 04 11 2016].

[27] Drammen Yard, “home,” N/A. [Online]. Available: http://www.drammenyard.no/. [Accessed 04 11 2016].

[28] Intec Sea, “Above water midline tie-in operation,” Intec Sea, N/A, 2009.

[29] International Marine Contractors Association (IMCA), “Diver and ROV Based Concrete Mattress Handling, Deployment, Installation, Repositioning and Decommissioning,” IMCA, 2011.

[30] Y. Bai and Q. Bai, Subsea pipelines and risers, San Diego: Elsevier, 2005.

[31] Subcon, “Groutbags,” N/A. [Online]. Available: http://www.subcon.com/product/grout-bags/. [Accessed 14 10 2016].

[32] ULO systems, “Fabric Formwork, Grouting, Structural Grouting and Concrete Mattresses,” ULO Systems, Sharjah, UAE, 2012.

[33] G. Boyun, S. Song, A. Ghalambor and T. R. Lin, Offshore pipelines; design, installation and maintenance, Gulf Professional Publishing, 2014, pp. 135-146.

[34] Offshore Energy, “Pre-Commissioning Overview: Pipelines,” Offshore Energy, Tyne and Wear, 2013.

[35] D. Baker, D. Bridges, R. Hunter, G. Johnson, J. Krupa, J. Murphy and K. Sorenson, “Guidebook to Decision-Making Methods,” US Department of Energy, N/A, 2001.

[36] Allseas Engineering, “Vessel Management System: Volume VI - Appendix 3 Stability and Ballast manual,” Allseas Engineering, Delft, 2011.

[37] Allseas Engineering Drawing Department, *WS-01-02E,* Delft, 2010.

[38] Subsea 7, “Vessel Datasheets,” 2016. [Online]. Available: http://www.subsea7.com/en/media-centre/datasheets/vessel-datasheets.html. [Accessed 14 12 2016].

[39] Drammen Yard, “Drammen Yard Brochure,” 2016. [Online]. Available: http://www.drammenyard.no/filarkiv/File/folder-DrammenYard-rev10C-skjerm.pdf. [Accessed 22 11 2016].

[40] Drammen Yard, Director, *Drammen Yard Offshore Cable Carousel.* [Film]. 2016.

[41] Ampelmann, “Safe and efficient people transfer - about the A-type,” N/A. [Online]. Available: http://www.ampelmann.nl/systems/a-type. [Accessed 23 11 2016].

[42] A. Ishizaka and P. Nemery, Multi-criteria Decision Analysis - Methods and Software, Chichester: John Wiley & Sons, Ltd, 2013.

[43] F. A. Lootsma, Multi-criteria decision analysis via ratio and difference judgement, Dordrecht: Kluwer Academic Publishers, 1999.

[44] T. k. Dijkstra, “On the extraction of weights from pairwise comparison matrices,” Rijks Universiteit Groningen, Groningen, 2010.

[45] B. Mareschal, “What is a correct value for a preference threshold (p)?,” 22 12 2011. [Online]. Available: http://www.promethee-gaia.net/faq-pro/?action=article&cat_id=003002&id=6&lang=. [Accessed 24 11 2016].

[46] T. Saaty, The Analytic Hierarchy Process, New York: McGraw Hill, 1980.

[47] R. Saaty, “The analytical Hierarchy Process - What it is and how it is used,” *Math Modelling,* pp. 161 - 176, 1987.

[48] T. Saaty and L. G. Vargas, Models, methods, concept & applications of the analytic hierarchy process, New York: Springer, 2012.

[49] J. A. Alonsol and T. Lamata, “Consistency in the Analytic Hierarchy Process - A new approach,” *International Journal of Uncertainty,* pp. 445-459, 2006.

[50] E. Thiantaphyllou and A. Sánchez, “A sensitivity analysis approach for some deterministic multi-criteria decision making methods,” *Decision sciences,* pp. 151-194, 1997.

[51] Nasdaq, “Crude oil Brent - Latest price & chart for crude oil Brent,” 09 12 2016. [Online]. Available: http://www.nasdaq.com/markets/crude-oil-brent.aspx?timeframe=5y. [Accessed 09 12 2016].

[52] Allseas Engineering Drawing Department, *Arrangement Grit Blaster and Heat Coat Machine Woek Area on Lorelay - Sections,* 2005.

[53] J. Regelink, *Weights of installed station 10 and 11 equipment,* Delft, 2009.

[54] Allseas Engineering Drawing Department, *Stinger and Rollerbox Settings Lorelay 70m Radius, 73m Stinger,* Delft, N/A.

[55] IMO, *SOLAS - International Convention for the Safety of Life at Sea - Chapter II-2 - Construction - Fire protection, fire detection and fire extinction,* IMO, 2017.

[56] Allseas Engineering Drawing Department, *Permissible deck loads and stowage plan,* 2014.

[57] UK P&I Club, “Carefully to Carry - Lashing and securing deck cargoes,” UK P&I Club, N/A, 2016.

[58] S. T. Petersen and K. Borck, “Standard Flex 300 - The True Multi-role Ship,” Danyard; CelciusTech; TERMA Elektronik AS, Aarhus, Danmark, 1992.

[59] K. M. B. P. J. M. J. M. S. John F. Schankm Scott Savitz, “Designing Adaptable Ships - Modularity and Flexibility in Future Ship Deisgns,” RAND Corporation, Santa Monica, California, USA, 2016.

[60] Allseas Engineering TD, “Vessel specification - Dynamically positioned pipelay vessel Lorelay,” Allseas Engineering, Delft, 2015.

[61] Staalhandelstaphorst.nl, N/A. [Online]. Available: http://www.joostdevree.nl/bouwkunde2/jpgi/i-profiel_5_draagkracht_en_afmetingen_ipe_profielen_www_staalhandelstaphorst_nl.pdf. [Accessed 28 03 2017].

[62] DNV, “Cargo Securing Model Manual,” Det Norske Veritas, Horvik, 2004.

[63] E. Murdoch and D. Tozer, “Noord Nederlands P&I Club - A master's guide to: container securing,” The Standard, N/A.

[64] Mjr Corporations, “Container and cargo Securing Product,” [Online]. Available: http://www.mjrcorporation.com/container-securing-product.html. [Accessed 29 03 2017].

[65] Pacific Marine & Industrical.net, “How do container ships work,” [Online]. Available: http://www.pacificmarine.net/marine-deck/cargo-securing/how-do-container-ships-work.htm. [Accessed 29 03 2017].

[66] Ark Prefab, Director, *Assembly Linking KIT of ARK Flatpack Office COntainer/Cabin.* [Film]. 2010.

[67] Portafab, “Electrical & Lighting,” [Online]. Available: www.prefab.com/electrical-and-lighting. [Accessed 30 03 2017].

[68] Allseas Engineering Drawing Department, *Solitaire General Arrangement,* N/A.

[69] GDV, Container Handbook, GDV, 2017.

[70] Kenz Figee, *GA-Gantry Crane,* N/A.

[71] Nautic expo, “RAM Spreaders,” 2017. [Online]. Available: http://www.nauticexpo.com/prod/ram-spreaders/product-30630-190076.html. [Accessed 28 03 2017].

[72] Curtiss-Wright, “Telescopic Helicopter Hangars,” [Online]. Available: https://www.curtisswrightds.com/products/naval-systems/hangars-doors/telescopic-helicopter-hangars.html. [Accessed 31 03 2017].

[73] Pattarozzi, Leffler and Steeling, Deep water petroleum exploration and production - a nontechnical guide, Tulsa, USA: TennWell Corporation, 2011.

[74] E. Hovland, “Evaluation of vessel concepts for subsea operations in nothern seas,” University of Stavanger, Stavanger, Norway, 2007.

[75] L. Sun and Y. Kang, “Installation Strength Analysis of Subsea Flowline Jumpers,” *Journal of marine Science and Application,* pp. 316 - 326, 2015.

[76] C. Braithwaite, *Flowlines & Risers,* Newcastle upon Tyne, UK: Wellstream International Limited, N/A.

[77] R. Yasseri, S. Yasseri and B. Wang, “Integrety of subsea control umbilical,” in *International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, 2014.

[78] Allseas, Director, *405530 Enbridge-Heidelberg J-Mode PLEM GC515 Installation.* [Film]. N/A.

[79] Nord Stream, “The Nord Stream Report for Consultation under the Espoo Convention,” Nord Stream, N/A, 2009.

[80] S. Parker Musarra, “Concrete Mattresses offer more than just pipeline protection,” *Offshore Engineer Digital,* p. N/A, 2013.

[81] Jee Ltd, “Mattress Solutions - Prepared by Jee Ltd. on behalf of Zero Waste Scotland and Decom North Sea,” Decom North Sea, Aberdeen, 2015.

[82] Offshore Magazine, “Subsea Production Systems Collection,” N/A. [Online]. Available: http://www.offshore-mag.com/learning-center/subsea/subsea-production-systems/subsea-flying-lead-installation.html. [Accessed 08 11 2016].

[83] ULO Systems, “ROV installed,” 2016. [Online]. Available: http://www.ulosystems.com/products/fabric-formwork/rov-installed/. [Accessed 28 10 2016].

[84] Circor Energy, “Pig Launchers & recievers,” 2016. [Online]. Available: http://www.circorenergy.com/pipeline-solutions/pig-launchers-and-receivers.php. [Accessed 3 11 2016].

[85] Allseas engineering, “Sable decommissioning project,” Allseas Engineering, Delft, 2016.

[86] McDermott International, Inc., “Fleet,” 2016. [Online]. Available: https://www.mcdermott.com/fleet/. [Accessed 14 12 2016].

[87] Technip, “The Technip Fleet,” 2016. [Online]. Available: http://www.technip.com/en/about-us/technip-fleet. [Accessed 14 12 2016].

[88] Saipem, “Vessels,” 2016. [Online]. Available: http://www.saipem.com/sites/SAIPEM_en_IT/filtrato/ACTIVITIES-saipem-activities-offshore-vessel-off-vessels.page. [Accessed 14 12 2016].

[89] D. Russel, “Pigging in pipeline pre-commissioning,” Pigging Products and Services Association, N/A, 2005.

APPENDICES

Appendix A Introduction to offshore structures

In addition to the pipelines that are mentioned in paragraph 2.2, which are export pipelines or flowlines, many more structures and pipelines are used to transport the oil or gas from the well to the platform and then to shore. This appendix introduces some of these structures that are of interest.

Figure A-1 gives a schematic overview of some of the possible subsea structures, flowlines and umbilicals. Some of these structures can also be installed by Allseas' ships, but others require different equipment than is currently installed on their ships.

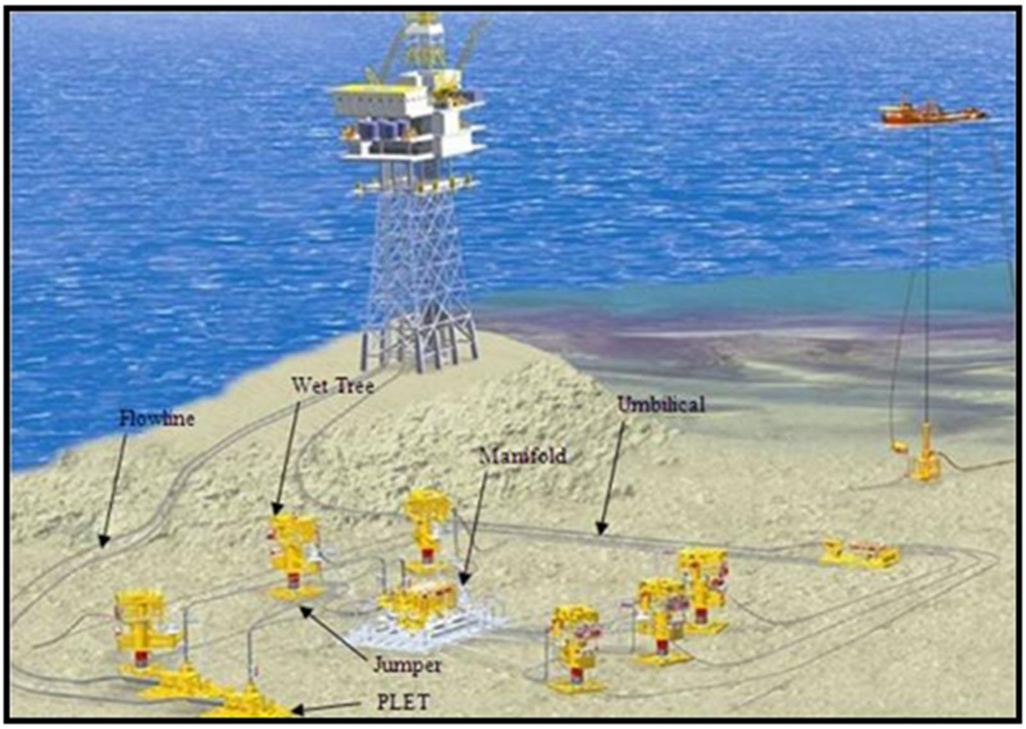


Figure A-1 Architecture of a subsea production system [19]

Subsea trees

Subsea trees are constructions that are placed directly on the well head. Trees determine the flow path of the fluids coming out of the well and provide a first line of defence in case of a blowout. A tree consists of multiple connection ports for the attachment of pipelines and umbilicals. These connections are made by an ROV. This is taken into account when the connections are designed. [73]

A subsea tree is mostly be installed by either an Installation Repair and Maintenance (IRM) vessel or a construction vessel. [74]

Jumpers and spools

A jumper is a collective name for short (<40 m) connection pipes between two subsea structures. It could for example be used to connect the tree to a nearby manifold.

A jumper can be a (semi) rigid construction made from steel or a flexible pipe made from composite materials. Their shape is dependent on the distance and the connection that is made, commonly used shapes are an inverted U-shape, and M-shape or a 3 dimensional Z-shape. [75]

Jumpers are installed vertically while spools are installed horizontally. [30]

Flowlines

Flowlines are basically pipelines. The only difference between export pipelines and flowlines is the product they transfer. Flowlines transport the rough materials from the well to the topside. Pipelines transport the processed materials from the topside to the shore.

Flowlines can be either rigid or flexible and can be installed using any of the pipe installation methods. [76]

Manifolds and sleds
A manifold is a collection station where different risers and flowlines come together. From here the streams are combined into another flowline that transports the fluid towards the riser. Dependent on the requirements manifolds can be relatively simple structures that collect fluids from different sources and send them on or they can be complex structures that control different flows. [73]

Sleds are another type of connection node that connects a gathering line or a flowline to a manifold or well. Sleds too can range from simple to complicated depending on their function. [73]

Umbilicals and flying leads
An umbilical is a line that supplies all the necessary flows to subsea structures. This can include, but is not limited to, chemicals, electricity and hydraulics. These lines run from the topside to umbilical termination assemblies (UTA). The UTA can be a standalone construction or be integrated in a manifold.

Umbilicals can either provide a single service or provide multiple, saving on installation time. All umbilicals are equipped with an electrical wire that supplies commands from the topside. The construction of umbilicals makes them vulnerable thus requiring special care during the installation process. [19] Umbilicals are a standard part of every offshore field. Their length as well as their composition varies between fields. Some umbilicals have a length of only a few kilometres while others can have a length of up to 200 kilometres. [77]

Simply said, flying leads are subsea extension cords. They connect the UTA to other subsea structures. [19]

Risers
The final connection between the seabed and the platform or FPSO is the riser. Usually two are in use, one going up with the raw materials and one going down towards shore. Risers exist in many shapes and sizes, each form suitable for a different type of topside or different type of environment.

In their book deep water petroleum exploration and production Pattarozzi, Leffler and Steeling identified six riser types [73]:

a) Attached risers; risers that are attached to the outside of the topside. This method is used for fixed platforms but isn't suitable for floating structures as the movement are too large.
b) Pull tubes; in this case the pipeline or flowline is pulled up towards the topside and becomes the riser. This method is a good choice for a fixed structure but is not a good solution for floating structures due to the movement of the vessel.
c) Steel catenary risers (SCR); are free hanging steel risers that is only connected at the seabed and the topside. They can handle some movement and can thus be applied for floating and fixed structures.
d) Top tensioned risers; risers that go straight down from the platform towards a riser base directly beneath the platform. This method can only be used by a Tension Leg Platform (TLP) or spar topside.
e) Riser tower; a tower starting from the seabed which has one or more risers installed inside. The tower stops well beneath the water surface and from there flowlines are used to connect the riser tower to the topside. This method is preferred for deep water as the tension on the risers attached to the topside is limited. This method is only used for FPSOs.
f) Flexible risers; these riser types are comparable to SCR only made from a flexible material and thus more easily bend into the preferred shape. This method can be used for all topside.

The most common riser types are the SCR and the flexible risers. In principle a riser is just a piece of pipeline with additional rules with regards to the fatigue life. Since the riser is floating in the sea and in some cases is attached to a moving construction the riser has to endure many fatigue stresses. That means that the regulations for the welds and the material are much higher than those for an export pipeline or flowline.

Appendix B Further details about installation techniques

This appendix gives some more information on the installation of different subsea elements that are discussed in chapter 4.0.

Jumper and spool installation

Sun and Kang [75] designed and analysed a method that is similar to the method Allseas will use for the Rota 3 project in Brazil. They identified three stages of installation together with the critical aspects for each phase.

The process starts above the water where the spool or jumper has to be transported to the location where it is going to be installed. This can be done by transporting the jumper or spool on the installation vessel or by using a barge. Each method has both advantages and disadvantages. Which method is chosen depends on many elements such as the location of the installation, the weather and sea conditions and the shape of the structure to be installed. In this first phase analysed by Sun and Kang the jumper or spool is picked up by the crane from either the ship itself or a barge.

If the structure is picked up from the barge there is a risk of it hitting the deck of the barge or the spreader bar due to relative motions. To reduce the chance of the jumper hitting the deck of the barge a crane with AHC can be used. This ensures that the load in the crane does not move in the waves, decreasing the chances of damaging the jumper or spool.

If the structure is transported by the ship there is no chance of hitting the deck during the first lift since the crane and the structure have no relative motions. However, transport on deck means that space has to be found for storage. Due to the irregular shape of the jumpers and spools and its size it is difficult to find enough space. A jumper can be as long as 40 to 50 meters. [21] This size leads to some problems when trying to place it on a ship. The main problem with is that it is very difficult to place and remove due to the location of the other equipment such as the pipe transfer crane and the portal frame. A possible solution for this could be to place the structure on the outside of the ship, as is done for the Rota 3 project. Once again the possibility of this depends strongly on the shape of the structure as some are known to have a three dimensional shape.

After the jumper or spool is picked up it is moved overboard using the crane. If the whole jumper is free from the ship it is lowered towards the "splash zone" or waterline.

From there the jumper is lowered further into the water. Some vessels, such as the *Lorelay,* are equipped with a limited cable length a winch must take over in deeper waters. This requires an underwater "handshake" where the tension in the cable is transferred from the crane to the A&R winch and the crane cable is released by an ROV. [78]

The next phase is the landing phase. This phase requires the use of one or two ROVs. For the Rota 3 project Allseas will use one ROV which first oversees the placement of one end and then the placement of the second. This is achieved by lowering the jumper into the water while at a slight angle. This means that one end reaches the installation point first, followed by the second. For the installation of spools two ROVs are preferable to ensure that both ends are connected correctly at the same time as gravity is not helpful in this case as it is with jumper installations. To have a decent workability an AHC winch is needed for this part as well. [75]

Mattress installation

Crossings are used as protection for existing pipelines and cables against stresses and loads caused by the installation of a new pipeline crossing the existing pipeline. A minimum distance between the new pipeline and the existing cable or pipeline is required. [79] This can be achieved using several methods. In case of a cable a trench could be dug that is deep enough to protect the cable without further support. This is usually not possible for pipelines and most cables are not placed in a trench this deep. This means that another solution has to be found. The most common method is using several mattresses placed on the existing pipeline or cable.

Additionally mattresses are used to protect pipelines and cables in busy shipping routes from anchors, fishing nets or other falling objects.

Since crossings can happen at any depth mattresses have to be installed up to around 3000 meters as well as in near shore areas. [80]

In many cases multiple types of mattresses are used during one project which are preferably all accessible at the same time. This means that there should be enough space on deck for several stacks of mattresses. Most mattresses come in one size, 6000 x 3000 mm, with a variable standardised height of 150, 300 or 450 mm. The density of the concrete used can also be varied which leads to a mattress weight between 5 and 20 ton. [81]

Trenching

Trenching is another protection method for pipelines and cables. In this case the pipeline is not protected by mattresses but it is placed into a trench especially dug on the seabed. The pipeline is then covered again with the sediment on the seabed.

Allseas does this by using their special build *Digging Donald* which is installed on the *CJ.* Additionally the Oceanic will be equipped with a modular trencher which can be removed from the ship if necessary.

The trenching process is started by lowering the trencher on top of the pipeline. The trencher cuts away the seabed, opening up a trench. Behind the trencher it pipeline lowers into the newly dug hole and is slowly covered with the removed debris from the seabed. How long this process takes depends on the type of underground the trench is dug.

Installation of a flying lead

The installation of a flying lead in done by lowering a construction down with the flying lead placed on it in such a way that it does not tangle if removed by an ROV. The next step is for the ROV to connect the flying leads to the connection ports. [82]

Free span rectification

Divers can only work in shallow waters. They can dive down towards the pipeline and install the bags under the pipeline by hand. After the bags are secured in place the diver can attach the grout line, also lowered from the ship, and fill the bags. When the bags are filled completely the diver disconnects the nozzle and closes off the bag. For this installation method diver support equipment is required, as well as a system that can deliver the grout to the seabed and storage for the grout on board. [32]

In case of an ROV installation the bags are lowered down on a frame build for this occasion. In addition to the grout bags this frame also holds the umbilical for the grout injection. The ROV picks up the bag from the frame and drags it under the pipeline. The ROV controls and checks the location of the bag in relation to the pipe that is to be supported. When the bag is in place the ROV is used to open the valve to fill the bag with grout. If the bag is filled the ROV cuts of the grout line and close it off to ensure that the grout remains in the bag. [83]

FGT

Before the start of the FGT process the ROV connects the hose to the connection port on the PLET or PLEM. The pigs used for cleaning and gauging are usually already installed in the pig launcher of the structure or can be installed by an ROV. At the end of the process the pigs can be removed from the pig receiver at the other end of the pipeline. [84]

The subsea system is advantageous if the available deck space is limited or if the working depths regularly exceed 300 meters. The unit can be seen as a portable filter, chemical injection and flow control system, all of which are installed on the ship when a on board system is used. The subsea unit is prepared on deck and deployed to the seabed close to the connection point of the pipeline. An ROV is used to connect the unit to the connection point. For the first part of the process the unit requires no outside control or assistance, flow is created using the pressure difference between the pipeline and the surrounding sea. If necessary the ROV is used to power the unit to keep the flow at a high enough rate.

Using the ROV's power is also used for hydro testing. [34]

Topside removal preparations

Preparing to remove a topside means ensuring that the platform is safe to lift when the *PS* arrives. Prior to removal some elements might have to be secured to the platform while others have to be removed because they might cause problems during the lift. For the securing of structures a crane is required to install the materials on the topside. For the removal of structures, which range from cranes to bridges to other appendages, a crane with a large reach is required. It is assumed that the crane installed on the *Lorelay* cannot reach high enough for the removal of some of these structures. A crane with a larger boom might be required so that equipment can be removed from the top of the platform.

In addition to these tasks lift points might also be needed. These have to be welded to strategic points on the platform. These lifting points can weigh up to 80 tons. [85]

The final task that can be done to prepare the topside for lifting is cutting the legs. This can be done long before the removal of the topside, the construction can remain upright even with cut legs. The legs are cut using specialised cutting tools that have to be brought on board by the support vessel. For the removal of the Yme platform these cutting tools had a weight of around 20 tons each.

Jacket removal and installation

How a jacket is removed depends on which system is going to be used. Currently the *PS* is in the process of being equipped with a large 5000t crane. This crane can be used to remove the jacket in pieces. In that case a ship is needed that installs cutting tools under water to cut the jacket into smaller pieces that can be lifted with the crane.

There are also plans to install a jacket lift system on the *PS.* In this case the jacket is lifted from the seabed in one piece. In this case a support vessel is needed to cut the piles beneath the jacket to remove it.

For the installation of a jacket the jacket lift system is required. The jacket is put into place and a support vessel installs the piles to secure the jacket to the seabed.

Appendix C Overview of required equipment

	Current	Jumpers and spools	Structures	Umbilicals and cables	Riser installation	Mattresses		Span rectification		Precommissioning			Heavy lift support		
						MIF	SIF	Diver	ROV	FGT vessel	FGT subsea	Dewatering	Topside	Jacket	Accommodation
Crane															
Capacity	300	50	300	300	300	25	35	0	50	0	20	0	100	200	50
Heave compensation	PHC	PHC	PHC	PHC	PHC	AHC	PHC	N/A	PHC	N/A	PHC	N/A	PHC	AHC	PHC
Winch															
Cable length	3000	3000	3000	3000	3000	3000	0	0	3000	0	3000	0	0	0	0
Heave compensation	AHC	AHC	PHC	PHC	PHC	AHC	0	N/A	PHC	N/A	PHC	N/A	N/A	N/A	N/A
ROV															
Number of ROVs	1	1 or 2	1	1	1	1	0	0	1	1	1	1	0	1	0
Required space															
Deck space	limited	some	a lot	some	none	some	some	some	some	some	some	some	A lot	some	Some
Additional features															
Portal frame	X														
Upending frame	X														
Dewatering infrastructure	X														
Jumper transport frame	X	X													
Small carousel				X											
Large carousel															
Chute				X											
Cable tensioner				X											
Riser welding stations															
Flex lay installation (reel)															
Mattress installation frame						X									
SIF + storage and support							X								
Mattress lashings						X	X								
Diving equipment								X							

	Current	Jumpers and spools	Structures	Umbilicals and cables	Riser installation	Mattresses		Span rectification		Precommissioning			Heavy lift support		
						MIF	SIF	Diver	ROV	FGT vessel	FGT subsea	Dewatering	Topside	Jacket	Accommodation
Grout tank								X	X						
Grout pump and line								X	X						
Grout bag frame									X						
Storage tank chemicals										X	X				
Pumps + power units										X		X			
hose reel										X		X			
Subsea FGT unit											X				
Crew transfer															X
Hydraulic gangway															X
Accommodation													X	X	
Optional improvements															
Increased crane capacity			X		X										
Additional power to ROV											X				
Additional crane height													X		
Additional accommodation															X

Appendix D Alternative scoring

This appendix covers the scoring of each scenario as well as the scoring of each alternative on each of the four criteria that were set up in chapter 5.0. Each set of alternatives is discussed separately and scored in pairwise comparison on the four criteria. A short explanation about the scores is also provided.

After all the sets of alternatives are scored, the best solutions are determined. The best alternatives per group, are combined for a final comparison that leads to the final best solution per scenario.

This appendix covers the scoring tables for each of the alternatives for each criteria as well as the final outcome for all three scenarios. It is important to keep in mind that the alternatives are only scored with regards to the alternatives within the same comparison. If two alternatives of different groups both score a 3 with regards to doing nothing, they are by no means the same.

With the scores for each criteria and scenario known the total scores for each of the alternatives can be determined to find which alternatives are to be evaluated to make a final decision.

Scenarios

Here the scoring tables for each of the scenarios are given. In chapter 5.0 the explanation for these scores is given.

Scenario 1: current market state

Table D-1 Scoring table for scenario 1: current market state, CR = 0.008

	Size of refit (Time)	Size of refit (Cost)	Market size	Competitiveness	Normalised total score
Size of refit (Time)	1	$\frac{1}{4}$	$\frac{1}{7}$	$\frac{1}{6}$	0.05
Size of refit (Cost)	4	1	$\frac{1}{2}$	$\frac{1}{2}$	0.2
Market size	7	2	1	$\frac{3}{2}$	0.42
Competitiveness	6	2	$\frac{2}{3}$	1	0.33

Scenario 2: Improving market

Table D-2 Scoring table for scenario 2: Improving market, CR = 0.010

	Size of refit (Time)	Size of refit (Cost)	Market size	Competitiveness	Normalised total score
Size of refit (Time)	1	5	1	$\frac{3}{4}$	0.28
Size of refit (Cost)	$\frac{1}{5}$	1	$\frac{1}{5}$	$\frac{1}{6}$	0.06
Market size	1	5	1	$\frac{1}{2}$	0.25
Competitiveness	$\frac{4}{3}$	6	2	1	0.41

Scenario 3: Further decreasing market

Table D-3 Scoring table for scenario 3: further decreasing market, CR = 0.039

	Size of refit (Time)	Size of refit (Cost)	Market size	Competitiveness	Normalised total score
Size of refit (Time)	1	$\frac{1}{8}$	$\frac{1}{6}$	$\frac{1}{3}$	0.05
Size of refit (Cost)	8	1	3	6	0.58
Market size	6	$\frac{1}{3}$	1	3	0.26
Competitiveness	3	$\frac{1}{6}$	$\frac{1}{3}$	1	0.11

Installation of jumpers, spools and structures
This alternative is divided into either a small or a large refit, each with several further additions:

a) Mattress installation
b) Span rectification
c) A combination of mattress installation and span rectification

To keep the alternatives comparable a dichotomy is made between the smaller refit and the refit that includes the use of a larger crane, in the rest of this appendix denoted by 'large refit'.

Installing structures is a task that the *Lorelay* can already perform. In this case the refit is based on improvement not on adding capabilities.

A large improvement in structure installation can be made by placing the AHC winch in the crane instead of using it as an A&R winch as is done at this moment. This significantly improves the manner in which structures are currently installed.

<u>Size of the refit</u>
The size of the refit is determined by the amount and size of changes as well as the required equipment for the change. It is important to remember that in this case a small refit is a good thing.

There is a large difference between the changes that have to be made for the small refit and the changes requires to facilitate a larger crane while adding either mattress installation or span rectification requires only a small change. Using the estimated changes that have to be made to the ship, leads to the scoring table below.
Table D-4 Scoring table: Installation vessel (small refit) - Size of the refit, CR = 0.014

	Small refit	+ mattress installation	+ span rectification	+ mattress installation and span rectification	Do nothing	Normalised score vector
Small refit	1	3	3	5	$\frac{1}{2}$	0.30
+ mattress installation	$\frac{1}{3}$	1	1	2	$\frac{1}{3}$	0.12
+ span rectification	$\frac{1}{3}$	1	1	2	$\frac{1}{3}$	0.12
+ mattress installation and span rectification	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{1}{2}$	1	$\frac{1}{5}$	0.06
Do nothing	2	3	3	5	1	0.40

Table D-5 Scoring table: Installation vessel (large refit) - Size of the refit, CR = 0.02

	Large refit	+ mattress installation	+ span rectification	+ mattress installation and span rectification	Do nothing	Normalised score vector
Large refit	1	3	3	5	$\frac{1}{2}$	0.22
+mattress installation	$\frac{1}{3}$	1	1	2	$\frac{1}{3}$	0.09
+ span rectification	$\frac{1}{3}$	1	1	2	$\frac{1}{3}$	0.09
+ mattress installation and span rectification	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{1}{2}$	1	$\frac{1}{5}$	0.05
Do nothing	2	3	3	5	1	0.56

Market size
Creating more deck space by removing part of the firing line does not lead to more contracts when compared to doing nothing as it has always been possible to transport the structures using a support vessel. Adding mattress installation or span rectification leads to a small increase in the possible contracts that can be performed by the ship.

Adding a larger crane is expected to have a positive effect on the number of contracts as it is be possible to install larger structures or structures at a greater depth.

Table D-6 Scoring table: Installation vessel (small refit) - Market size, CR = 0.0278

	Small refit	+ mattress installation	+ and span rectification	+ mattress installation and span rectification	Do nothing	Normalised score vector
Small refit	1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{5}$	3	0.09
+ mattress installation	3	1	1	$\frac{1}{2}$	4	0.23
+ span rectification	3	1	1	$\frac{1}{2}$	4	0.23
+ mattress installation and span rectification	5	2	2	1	5	0.4
Do nothing	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{5}$	1	0.05

Table D-7 Scoring table: Installation vessel (large refit) - Market size, CR =0.028

	Large refit	+ mattress installation	+ and span rectification	+ mattress installation and span rectification	Do nothing	Normalised score vector
Large refit	1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{5}$	3	0.09
+ mattress installation	3	1	1	$\frac{1}{2}$	4	0.23
+ and span rectification	3	1	1	$\frac{1}{2}$	4	0.23
+ mattress installation and span rectification	5	2	2	1	5	0.4
Do nothing	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{5}$	1	0.05

Competitiveness
The main dimensions of the ship, the deck area and permissible deck loads as well as the crane capacity from 31 ships from 4 main competitors were collected. [86], [87], [38], [88].

When compared to other vessels the deck area that can be made available for the transport of structures is limited. This is partly due to the smaller breadth of the vessel compared to others. On the other hand, the deck strength per square meter is relatively high in comparison. [56]

With regards to the crane the *Lorelay* has a more competitive position. Around 70% of the reference ships have a crane smaller than the *Lorelay*. With increase crane capacity this is even 80%.

It is unclear if these vessels are capable of performing either mattress installation or span rectification so it is difficult to determine the competitiveness with regards to other vessels. It is possible to compare the mattress installation capabilities with those of Allseas' *CJ.* This ship can install mattresses quickly with its large frame and in deep water using a smaller frame, its only downside is that the mattresses can only be accessed one pile at the time. With the placement of the mattresses on deck this problem would be taken away.

The *Lorelay* has a good market position and is capable of installing structures if required. By removing a small part of the firing line the competitiveness of the *Lorelay* does not improve. It simply makes it more affordable to transport structures.

The same goes for the addition of mattress installation or span rectification. The *Lorelay* cannot compete with more specialised vessels which are faster and more versatile in their selected strengths. However, the addition of these tasks does not have a negative effect on the pipe laying or structure installation capabilities of the *Lorelay.*

The increased crane capacity causes a slight improvement in comparison to the small refit.

Table D-8 Scoring table: Installation vessel (small refit) – Competitiveness, CR = 0.002

	Small refit	+ mattress installation	+ and span rectification	+ mattress installation and span rectification	Do nothing	Normalised score vector
Small refit	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	2	0.14
+ mattress installation	2	1	1	1	3	0.26
+ span rectification	2	1	1	1	3	0.26
+ mattress installation and span rectification	2	1	1	1	3	0.26
Do nothing	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1	0.08

Table D-9 Scoring table: Installation vessel (large refit) - Competitiveness, CR = 0.002

	Large refit	+ mattress installation	+ span rectification	+ mattress installation and span rectification	Do nothing	Normalised score vector
Large refit	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	2	0.14
+ mattress installation	2	1	1	1	3	0.26
+ span rectification	2	1	1	1	3	0.26
+ mattress installation and span rectification	2	1	1	1	3	0.26
Do nothing	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1	0.08

<u>Total scores</u>

Table D-10 Final scores: Installation vessel (small refit)

	Scenario 1	Scenario 2	Scenario 3
Small refit	0.16	0.18	0.23
+ mattress installation	0.21	0.20	0.16
+ span rectification	0.21	0.20	0.16
+ mattress installation and span rectification	**0.27**	**0.23**	0.17
Do nothing	0.15	0.18	**0.27**

Table D-11 Final scores: Installation vessel (large refit)

	Scenario 1	Scenario 2	Scenario 3
Large refit	0.14	0.15	0.18
+ mattress installation	0.20	0.19	0.14
+ span rectification	0.20	0.19	0.14
+ mattress installation and span rectification	**0.27**	0.22	0.16
Do nothing	0.19	**0.24**	**0.37**

Flex lay

There are two options for converting the *Lorelay* into a reel-lay vessel:

a) Converting the ship to a reel-lay vessel
b) Combining reel-lay with jumper, spool and structure installation

Most of the competitors of the *Lorelay* are reel laid vessels. Both S-lay and reel-lay are viable options for installing smaller diameter pipelines. S-lay vessels can normally lay a larger diameter pipe which can be concrete covered while reel-lay vessels achieve a higher laying speed and can also install flexible pipelines and cables.

The reel-lay vessels need to return to shore or meet with another vessel nearby during the pipe laying process to refill their empty reels. When using the S-lay method the resupplying is done during the pipe laying process. Some vessels can install the reel in sheltered water but most need to return to shore to pick up a new reel. If the pipeline is located near a spool base this is no big problem but if the location is remote an S-lay vessel, which can pick up pipes while placing them on the seabed, is the better choice. This is the largest advantage that the *Lorelay* has over her competitors, she is not bound to a specific location.

Size of the refit

The amount of work required to convert the *Lorelay* to a reel-lay ship is significant. There is no difference between only using the vessel as a reel laid ship and also introducing the capability to install jumpers, spools and structures.

Table D-12 Scoring table: Flex lay - Size of the refit, CR = 0

	Flex lay	+ structure installation	Do nothing	Normalised score vector
Flex lay	1	1	$\frac{1}{7}$	0.11
+ structure installation	1	1	$\frac{1}{7}$	0.11
Do nothing	7	7	1	0.78

Market size

There are differences between the S-lay method and the reel-lay method which result in changes to the pipe laying capabilities of the ship. The maximum pipe diameter that can be installed decreases and the ability to install concrete covered pipes disappears. On the other hand the laying speed increases and the ability to install flexible pipes and cables is gained.
It is assumed that there is no discernible difference between the market size for an S-lay vessel or a reel-lay vessel. There are too many factors that influence who gets the contracts and for what reason.

Table D-13 Scoring table: Flex lay – Market size, CR = 0

	Flex lay	+ structure installation	Do nothing	Normalised score vector
Flex lay	1	1	1	0.33
+ structure installation	1	1	1	0.33
Do nothing	1	1	1	0.33

Competitiveness

The *Lorelay* is the only S-lay vessel of its size, meaning she operates in a small niche market in which she is the optimal choice and can also compete with the reel-lay vessels in that market segment. If the *Lorelay* is converted to a reel-lay vessel as proposed her capabilities lay well within the average capabilities of the competitors. However, since Allseas does not have the infrastructure to support a reel-lay vessel at this moment it would put them at a disadvantage compared to its competitors. This probably remains the case for some time as building a spool base infrastructure.

Being able to install structures would increase the competitiveness of the vessel somewhat as not all vessels have space available on deck to transport structures.

Table D-14 Scoring table: Flex lay – Competitiveness, CR = 0.021

	Flex lay	+ structure installation	Do nothing	Normalised score vector
Flex lay	1	$\frac{1}{2}$	$\frac{1}{5}$	0.12
+ structure installation	2	1	$\frac{1}{4}$	0.2
Do nothing	5	4	1	0.68

Total score

Table D-15 Final scores: Flex Lay

	Scenario 1	Scenario 2	Scenario 3
Flex lay	0.21	0.17	0.17
+ structure installation	0.23	0.20	0.18
Do nothing	**0.56**	**0.63**	**0.65**

Precommissioning

With regards to precommissioning there are three options, as well two combinations that are compared to each other.

a) Vessel based FGT
b) Subsea based FGT
c) Dewatering
d) Vessel based FGT and dewatering
e) Subsea based FGT and dewatering

Size of the refit

Subsea units require fewer changes to the ship but are ultimately more costly that a vessel based system due to the investment cost. Dewatering requires a lot of equipment and is therefore costly.

Table D-16 Scoring table: Precommissioning - Size of the refit, CR = 0.026

	Vessel based FGT	Subsea FGT	Dewatering	Vessel based FGT and dewatering	Subsea FGT and dewatering	Do nothing	Normalised score vector
Vessel based FGT	1	2	3	4	5	$\frac{1}{3}$	0.22
Subsea FGT	$\frac{1}{2}$	1	2	3	4	$\frac{1}{4}$	0.14
Dewatering	$\frac{1}{3}$	$\frac{1}{2}$	1	2	3	$\frac{1}{5}$	0.09
Vessel based FGT and dewatering	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2}$	1	2	$\frac{1}{6}$	0.06
Subsea FGT and dewatering	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2}$	1	$\frac{1}{7}$	0.04
Do nothing	3	4	5	6	7	1	0.44

Market size

It is assumed that the market size for subsea FGT and vessel based FGT are the same size. The market for dewatering is assumed to be slightly larger, as FGT is in most cases part of the pipe laying scope and dewatering is done when the pipeline is taken into operation. This means that there are some stand-alone contracts available for pipes that have been laid on the seabed but have not yet been taken into operation.

Table D-17 Scoring table: Precommissioning - Market size, CR = 0.007

	Vessel based FGT	Subsea FGT	Dewatering	Vessel based FGT and dewatering	Subsea FGT and dewatering	Do nothing	Normalised score vector
Vessel based FGT	1	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	2	0.10
Subsea FGT	1	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	2	0.10
Dewatering	2	2	1	$\frac{1}{2}$	$\frac{1}{2}$	3	0.17
Vessel based FGT and dewatering	3	3	2	1	1	4	0.29
Subsea FGT and dewatering	3	3	2	1	1	4	0.29
Do nothing	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{4}$	1	0.06

Competitiveness

Due to the larger reach of the subsea FGT unit the *Lorelay* compares better to its competitors than when equipped with a vessel based unit. The addition of dewatering to either of these options causes an additional improvement by adding an extra part of the project scope to the possibilities.

Dewatering alone also improves the competitiveness of the *Lorelay* but only slightly. FGT operations are executed at the end of every pipe laying project whereas dewatering can be performed a long time after the end of a project. In that case a smaller vessel, with a lower cost due to lower operational cost, might be a better option. [89]

Table D-18 Scoring table: Precommissioning - Competitiveness, CR = 0.043

	Vessel based FGT	Subsea FGT	Dewatering	Vessel based FGT and dewatering	Subsea FGT and dewatering	Do nothing	Normalised score vector
Vessel based FGT	1	$\frac{1}{5}$	2	$\frac{1}{3}$	$\frac{1}{7}$	3	0.07
Subsea FGT	5	1	6	3	$\frac{1}{3}$	7	0.26
Dewatering	$\frac{1}{2}$	$\frac{1}{6}$	1	$\frac{1}{4}$	$\frac{1}{8}$	2	0.04
Vessel based FGT and dewatering	3	$\frac{1}{3}$	4	1	$\frac{1}{5}$	5	0.13
Subsea FGT and dewatering	7	3	8	5	1	9	0.47
Do nothing	$\frac{1}{3}$	$\frac{1}{7}$	$\frac{1}{2}$	$\frac{1}{5}$	$\frac{1}{9}$	1	0.03

Total score

Table D-19 Final score: Precommissioning

	Scenario 1	Scenario 2	Scenario 3
Vessel based FGT	0.19	0.13	0.17
Subsea FGT	0.16	0.18	0.14
Dewatering	0.11	0.09	0.11
Vessel based FGT and dewatering	0.18	0.15	0.13
Subsea FGT and dewatering	**0.29**	**0.28**	0.15
Do nothing	0.15	0.18	**0.30**

Heavy lift support

The *Lorelay* can also assist the *PS* with heavy lift operations. This task can be performed without making any changes to the ship but can be optimised by making changes or additions to the ship.

Size of the refit

The scores for the refit size are based on the changes suggested in chapter5.0.

Table D-20 Scoring table: Heavy lift support - Size of the refit, CR 0.052

	Heavy lift support	+ installation	Increased crane capacity	Increased crane capacity and installation	Do nothing	Normalised score vector
Heavy lift support	1	3	7	8	$\frac{1}{3}$	0.28
+ installation	$\frac{1}{3}$	1	4	5	$\frac{1}{5}$	0.13
Increased crane capacity	$\frac{1}{7}$	$\frac{1}{4}$	1	2	$\frac{1}{8}$	0.05
Increased crane capacity and installation	$\frac{1}{8}$	$\frac{1}{5}$	$\frac{1}{2}$	1	$\frac{1}{9}$	0.03
Do nothing	3	5	8	9	1	0.51

Market size

As a support vessel for the *PS* the market isn't very large. The *PS* is designed with the idea of it performing only a handful of lifts every year. Adding the possibility to install structures, which requires no additional changes to the ship opens up a small part of the market, but does not have a large effect. Increasing the crane capacity for heavy lift support work does not lead to any more heavy lift projects, it only leads to more options in the execution of the projects.

Table D-21 Scoring table: Heavy lift support - Market size, CR = 0.004

	Heavy lift support	+ installation	Increased crane capacity	Increased crane capacity + installation	Do nothing	Normalised score vector
Heavy lift support	1	$\frac{1}{3}$	1	$\frac{1}{4}$	1	0.10
+ installation	3	1	3	$\frac{1}{2}$	3	0.27
Increased crane capacity	1	$\frac{1}{3}$	1	$\frac{1}{4}$	1	0.10
Increased crane capacity and installation	4	2	4	1	4	0.43
Do nothing	1	$\frac{1}{3}$	1	$\frac{1}{4}$	1	0.10

<u>Competitiveness</u>
For the heavy lift support work the *Lorelay* has two main competitors. The first is Allseas' new vessel the *Oceanic* which is also capable of performing heavy lift operations, the second is a vessel hired specifically for this task. The biggest advantage of the *Lorelay* over the *Oceanic* is that with its larger crane she has a larger reach. On the other hand the *Oceanic* has a large empty deck area, around 1650 m^2, a faster crane and cheaper in use due to the smaller crew and the fact that it is a newer vessel. [18] Using a different vessel, by renting it, is also a possibility but as stated before Allseas prefers to work with its own vessels. A hired vessel would only be used if neither the *Lorelay* nor the *Oceanic* would be available or if their capabilities are severely lacking. Looking at the method statement for a decommissioning project and internal research done into the vessel requirements for heavy lift assist work, it assumed that this is not a common occurrence.

Table D-22 Scoring table: Heavy lift support – Competitiveness, CR = 0.018

	Heavy lift support	Heavy lift support and installation	Increased crane capacity	Increased crane capacity + installation	Do nothing	Normalised score vector
Heavy lift support	1	$\frac{1}{3}$	1	$\frac{1}{5}$	2	0.10
+ installation	3	1	3	$\frac{1}{3}$	4	0.24
Increased crane capacity	1	$\frac{1}{3}$	1	$\frac{1}{5}$	2	0.10
Increased crane capacity and installation	5	3	5	1	6	0.50
Do nothing	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{6}$	1	0.06

Total score

Table D-23 Final scores: Heavy lift support

	Scenario 1	Scenario 2	Scenario 3
Heavy lift	0.14	0.16	0.21
+ installation	0.23	0.21	0.18
Heavy lift with increased crane capacity	0.09	0.08	0.07
Heavy lift with increased crane capacity and structure installation	**0.35**	**0.32**	0.19
Do nothing	0.19	0.22	**0.35**

Combining the best concepts

Size of the refit – Scenario 1

Table D-24 Scoring matrix: Final determination for scenario 1 – Size of the refit, CR = 0.032

	Small refit, mattress installation and span rectification	Subsea FGT and dewatering	Large refit, mattress installation and span rectification	Cable laying	Combination of all options	Heavy lift support and structure installation	Norm. score vector
Small refit, mattress installation and span rectification	1	2	9	3	6	5	0.40
Subsea FGT and dewatering	$\frac{1}{2}$	1	8	2	5	4	0.27
Large refit, mattress installation and span rectification	$\frac{1}{9}$	$\frac{1}{8}$	1	$\frac{1}{6}$	$\frac{1}{4}$	$\frac{1}{5}$	0.03
Cable laying	$\frac{1}{3}$	$\frac{1}{2}$	6	1	3	2	0.16
Combination of all options	$\frac{1}{6}$	$\frac{1}{5}$	4	$\frac{1}{3}$	1	$\frac{1}{2}$	0.06
Heavy lift support and structure installation	$\frac{1}{5}$	$\frac{1}{4}$	5	$\frac{1}{2}$	2	1	0.09

Table D-25 Scoring matrix: Final determination for scenario 2 - Size of the refit, CR = 0.0395

	Small refit, mattress installation and span rectification	Subsea FGT and dewatering	Do nothing	Cable laying	Combination of all options	Heavy lift support and structure installation	Normalised score vector
Small refit, mattress installation and span rectification	1	2	1/2	3	9	5	0.26
Subsea FGT and dewatering	1/2	1	1/3	2	8	4	0.17
Do nothing	2	3	1	4	9	6	0.38
Cable laying	1/3	1/2	2	1	6	2	0.10
Combination of all options	1/9	1/8	4	1/6	1	1/5	0.02
Heavy lift support and structure installation	1/5	1/4	1/2	1/2	5	1	0.06

Market size

Table D-26 Scoring matrix: Final determination for scenario 1 - Market size, CR =0.012

	Small refit, mattress installation and span rectification	Subsea FGT and dewatering	Large refit, mattress installation and span rectification	Cable laying	Combination of all options	Heavy lift support and structure installation	Norm. score vector
Small refit, mattress installation and span rectification	1	1/2	1/3	1/4	1/7	1/2	0.05
Subsea FGT and dewatering	2	1	1/2	1/3	1/6	1	0.08
Large refit, mattress installation and span rectification	3	2	1	1/2	1/4	2	0.13
Cable laying	4	3	2	1	1/3	3	0.21
Combination of all options	7	6	4	3	1	6	0.46
Heavy lift support and structure installation	2	1	1/2	1/3	1/6	1	0.08

Table D-27 Scoring matrix: Final determination for scenario 2 - Market size, CR =0.012

	Small refit, mattress installation and span rectification	Subsea FGT and dewatering	Do nothing	Cable laying	Combination of all options	Heavy lift support and structure installation	Normalised score vector
Small refit, mattress installation and span rectification	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{7}$	$\frac{1}{2}$	0.05
Subsea FGT and dewatering	2	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$	1	0.08
Do nothing	3	2	1	$\frac{1}{3}$	$\frac{1}{4}$	2	0.13
Cable laying	4	3	2	1	$\frac{1}{3}$	3	0.21
Combination of all options	7	6	4	3	1	6	0.46
Heavy lift support and structure installation	2	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$	1	0.08

<u>Competitiveness</u>

Table D-28 Scoring matrix: Final determination for scenario 1 - Competitiveness, CR =0.0432

	Small refit, mattress installation and span rectification	Subsea FGT and dewatering	Large refit, mattress installation and span rectification	Cable laying	Combination of all options	Heavy lift support and structure installation	Norm. score vector
Small refit, mattress installation and span rectification	1	3	$\frac{1}{3}$	5	$\frac{1}{5}$	$\frac{1}{4}$	0.09
Subsea FGT and dewatering	$\frac{1}{3}$	1	$\frac{1}{5}$	3	$\frac{1}{7}$	$\frac{1}{6}$	0.05
Large refit, mattress installation and span rectification	3	5	1	7	$\frac{1}{3}$	$\frac{1}{2}$	0.18
Cable laying	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{7}$	1	$\frac{1}{9}$	$\frac{1}{8}$	0.03
Combination of all options	5	7	3	9	1	2	0.39
Heavy lift support and structure installation	4	6	2	8	$\frac{1}{2}$	1	0.27

Table D-29 Scoring matrix: Final determination for scenario 2 - Competitiveness, CR =0.0432

	Small refit, mattress installation and span rectification	Subsea FGT and dewatering	Do nothing	Cable laying	Combination of all options	Heavy lift support and structure installation	Normalised score vector
Small refit, mattress installation and span rectification	1	3	$\frac{1}{3}$	5	$\frac{1}{5}$	$\frac{1}{4}$	0.09
Subsea FGT and dewatering	$\frac{1}{3}$	1	$\frac{1}{5}$	3	$\frac{1}{7}$	$\frac{1}{6}$	0.05
Do nothing	3	5	1	7	$\frac{1}{3}$	$\frac{1}{2}$	0.18
Cable laying	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{7}$	1	$\frac{1}{9}$	$\frac{1}{8}$	0.03
Combination of all options	5	7	3	9	1	2	0.39
Heavy lift support and structure installation	4	6	2	8	$\frac{1}{2}$	1	0.27

Final score

Table D-30 Summary of the final score

Alternative	Score scenario 1	Score scenario 2
Small refit, mattress installation and span rectification.	0.15	0.14
Large refit, mattress installation and span rectification	0.11	-
Subsea FGT and dewatering	0.12	0.10
Cable laying	0.13	0.10
Combination of all options	**0.34**	**0.29**
Heavy lift support and structure installation	0.14	0.15
Do nothing	-	0.24

Appendix E Results of the sensitivity study

This appendix gives the full results of the sensitivity study. In the whole chapter the bold values are the percent any values and the underlined values are the percent top values.

Jumpers, spools and structures (Small refit)

1A Small refit
1B Small refit + mattress
1C Small refit + Span
1D Small refit + mattress + span Best solution scenario 1 and 2
1E Do nothing Best solution scenario 3

Table E-1 Sensitivity of the criteria weights, Scenario 1: Installation vessel (small refit)

		C1	C2	C3	C4
1A	**1B**	-523.1	-145.3	91.1	0.0
1A	**1C**	-523.1	-145.3	91.1	0.0
1A	**1D**	-854.0	-237.2	85.4	0.0
1A	**1E**	-208.5	**-57.9**	66.0	59.1
1B	**1C**	0.0	0.0	0.0	0.0
1B	**1D**	-1941.1	-539.2	<u>80.8</u>	0.0
1B	**1E**	-414.1	-115.0	85.4	0.0
1C	**1D**	-1941.1	-539.2	<u>80.8</u>	0.0
1C	**1E**	-414.1	-115.0	85.4	0.0
1D	**1E**	-667.5	-185.4	83.1	0.0

Table E-2 Sensitivity of the criteria weights, Scenario 2: Installation vessel (small refit)

		C1	C2	C3	C4
1A	**1B**	-43.9	-213.6	65.1	45.2
1A	**1C**	-43.9	-213.6	65.1	45.2
1A	**1D**	-71.2	-346.7	60.7	95.7
1A	**1E**	**-0.2**	-0.9	0.5	0.2
1B	**1C**	0.0	0.0	0.0	0.0
1B	**1D**	-161.0	-784.0	57.2	0.0
1B	**1E**	-28.7	-139.9	50.5	31.1
1C	**1D**	-161.0	-784.0	57.2	0.0
1C	**1E**	-28.7	-139.9	50.5	31.1
1D	**1E**	-50.7	-246.8	<u>53.8</u>	65.7

These tables have to be read as follows: An 80.8% change to the score of criteria 3 would change the best solution from concept D to either concept B or C.

Table E-3 Sensitivity of the criteria weights, Scenario 3: Installation vessel (small refit)

		C1	C2	C3	C4
1A	**1B**	0.0	62.2	-184.8	-499.5
1A	**1C**	0.0	62.2	-184.8	-499.5
1A	**1D**	0.0	40.1	-68.4	-420.2
1A	**1E**	0.0	79.1	-426.8	-736.3
1B	**1C**	0.0	0.0	0.0	0.0
1B	**1D**	-389.1	-32.4	**23.0**	0.0
1B	**1E**	0.0	68.1	-239.5	-573.8
1C	**1D**	-389.1	-32.4	**23.0**	0.0
1C	**1E**	0.0	68.1	-239.5	-573.8
1D	**1E**	0.0	<u>51.4</u>	-109.2	-519.4

The following tables show the sensitivity of the alternative scores. The tables have to be read as follows: in scenario in, see Table E-4, a change of 51.4% is required to the alternative score between alternatives 1A and 1E to swap the positions of concept 1A and 1E.

Table E-4 Sensitivity of the alternative scores, Scenario 1: Installation vessel (small refit)

Alt.	C1	C2	C3	C4	Swap with
1A	0.0	-157.7	-131.4	-117.7	**1B**
1A	0.0	-157.7	-131.4	-117.7	**1C**
1A	0.0	-919.1	-271.0	-306.7	**1D**
1A	51.4	**16.1**	28.5	24.6	**1E**
1B	0.0	0.0	54.7	58.2	**1A**
1B	0.0	0.0	0.0	0.0	**1C**
1B	0.0	-384.9	-59.1	-82.6	**1D**
1B	0.0	0.0	67.2	72.1	**1E**
1C	0.0	0.0	54.7	58.2	**1A**
1C	0.0	0.0	0.0	0.0	**1B**
1C	0.0	-384.9	-59.1	-82.6	**1D**
1C	0.0	0.0	67.2	72.1	**1E**
1D	0.0	0.0	68.7	0.0	**1A**
1D	0.0	0.0	<u>36.0</u>	57.8	**1B**
1D	0.0	0.0	<u>36.0</u>	57.8	**1C**
1D	0.0	0.0	76.6	0.0	**1E**
1E	-71.7	-16.5	-48.2	-39.5	**1A**
1E	0.0	-199.1	-273.4	-234.3	**1B**
1E	0.0	-199.1	-273.4	-234.3	**1C**
1E	0.0	-3026.8	-512.0	-551.4	**1D**

Table E-5 Sensitivity of the alternative scores, Scenario 2: Installation vessel (small refit)

Alt.	C1	C2	C3	C4	Swap with
1A	-35.8	-298.1	-90.8	-37.6	**1B**
1A	-35.8	-298.1	-90.8	-37.6	**1C**
1A	-94.0	0.0	-179.6	-84.5	**1D**
1A	0.1	0.3	0.2	0.1	**1E**
1B	52.8	0.0	40.6	22.8	**1A**
1B	0.0	0.0	0.0	0.0	**1C**
1B	-86.9	-707.2	-40.2	-25.3	**1D**
1B	49.2	0.0	42.4	24.3	**1E**
1C	52.8	0.0	40.6	22.8	**1A**
1C	0.0	0.0	0.0	0.0	**1B**
1C	-86.9	-707.2	-40.2	-25.3	**1D**
1C	49.2	0.0	42.4	24.3	**1E**
1D	0.0	0.0	53.0	45.2	**1A**
1D	0.0	0.0	26.6	22.4	**1B**
1D	0.0	0.0	26.6	22.4	**1C**
1D	0.0	0.0	55.6	48.0	**1E**
1E	**-0.1**	-0.2	-0.4	-0.1	**1A**
1E	-31.2	-292.0	-152.7	-60.3	**1B**
1E	-31.2	-292.0	-152.7	-60.3	**1C**
1E	-85.1	0.0	-302.5	-134.9	**1D**

Table E-6 Sensitivity of the alternative scores, Scenario 3: Installation vessel (small refit)

Alt.	C1	C2	C3	C4	Swap with
1A	0.0	40.3	0.0	0.0	**1B**
1A	0.0	40.3	0.0	0.0	**1C**
1A	0.0	36.8	0.0	0.0	**1D**
1A	-1639.6	-24.8	-229.2	-561.2	**1E**
1B	0.0	-88.4	-178.2	-881.6	**1A**
1B	0.0	0.0	0.0	0.0	**1C**
1B	-246.3	-16.2	-15.4	-41.3	**1D**
1B	0.0	-145.2	-449.8	0.0	**1E**
1C	0.0	-88.4	-178.2	-881.6	**1A**
1C	0.0	0.0	0.0	0.0	**1B**
1C	-246.3	-16.2	-15.4	-41.3	**1D**
1C	0.0	-145.2	-449.8	0.0	**1E**
1D	$-2 \cdot 10^4$	-129.4	-108.8	-543.9	**1A**
1D	0.0	26.0	**11.4**	34.0	**1B**
1D	0.0	26.0	**11.4**	34.0	**1C**
1D	0.0	-229.0	-343.2	0.0	**1E**
1E	0.0	19.5	0.0	0.0	**1A**
1E	0.0	52.2	0.0	0.0	**1B**
1E	0.0	52.2	0.0	0.0	**1C**
1E	0.0	51.4	0.0	0.0	**1D**

Flex lay

2A	Flex lay	
2B	Flex lay + structures	
2C	Do nothing	Best solution scenario 1,2 and 3

Table E-7 Sensitivity of the criteria weights, Scenario 1 and 2: Flex lay

		C1	C2	C3	C4
2A	**2B**	0	0	0	0
2A	**2C**	0	0	0	0
2B	**2C**	0	0	0	0

Table E-8 Sensitivity of the criteria weights, Scenario 3: Flex lay

		C1	C2	C3	C4
2A	**2B**	0	0	0	**100**
2A	**2C**	0	0	0	0
2B	**2C**	0	0	0	0

Table E-9 Sensitivity of the alternative scores, Scenario 1: Flex lay

Alt.	C1	C2	C3	C4	Swap with
2A	-908	-145.9	-20.9	-71.0	**2B**
2A	0.0	0.0	-1610	-1861	**2C**
2B	0.0	0.0	**18.4**	41.5	**2A**
2B	0.0	-9E4	-1050	-1004	**2C**
2C	0.0	0.0	0.0	0.0	**2A**
2C	0.0	0.0	0.0	96.2	**2B**

Table E-10 Sensitivity of the alternative scores, Scenario 2: Flex lay

Alt.	C1	C2	C3	C4	Swap with
2A	-121.8	-1246	-45.6	-71.0	**2B**
2A	-3E4	0.0	0.0	-2185	**2C**
2B	95.9	0.0	**35.0**	41.5	**2A**
2B	-8010	0.0	0.0	-1184	**2C**
2C	0.0	0.0	0.0	0.0	**2A**
2C	0.0	0.0	0.0	97.9	**2B**

Table E-11 Sensitivity of the alternative scores, Scenario 3: Flex lay

Alt.	C1	C2	C3	C4	Swap with
2A	-202.4	-14.0	-10.5	-71.0	**2B**
2A	0.0	-885.8	0.0	0.0	**2C**
2B	0.0	13.6	**9.8**	41.5	**2A**
2B	0.0	-853.9	0.0	0.0	**2C**
2C	0.0	91.6	0.0	0.0	**2A**
2C	0.0	91.1	0.0	0.0	**2B**

Precommissioning

3A	Vessel based FGT	
3B	Subsea based FGT	
3C	Dewatering	
3D	Vessel FGT + dewatering	
3E	Subsea FGT + dewatering	Best solution scenario 1 and 2
3F	Do nothing	Best solution scenario 3

Table E-12 Sensitivity of the criteria weights, Scenario 1: Precommissioning

		C1	C2	C3	C4
3A	**3B**	-1034.2	-287.3	0.0	69.2
3A	**3C**	0.0	38.0	-32.3	0.0
3A	**3D**	-687.5	-191.0	76.7	0.0
3A	**3E**	-1672.6	-464.6	0.0	0.0
3A	**3F**	0.0	62.9	-166.0	-232.2
3B	**3C**	0.0	0.0	-178.2	76.0
3B	**3D**	-371.1	-103.1	**21.6**	-42.0
3B	**3E**	-2145.3	-595.9	0.0	0.0
3B	**3F**	-102.2	-28.4	0.0	22.2
3C	**3D**	-3945.0	-1095.8	0.0	0.0
3C	**3E**	-6140.9	-1705.7	0.0	0.0
3C	**3F**	0.0	53.6	-79.5	-802.7
3D	**3E**	-9799.5	-2721.9	0.0	95.5
3D	**3F**	-162.0	-45.0	35.3	99.6
3E	**3F**	-634.0	-176.1	0.0	96.5

Table E-13 Sensitivity of the criteria weights, Scenario 2: Precommissioning

		C1	C2	C3	C4
3A	**3B**	-234.2	-1140.3	0.0	66.0
3A	**3C**	94.7	0.0	-190.7	0.0
3A	**3D**	-44.1	-214.9	42.0	74.1
3A	**3E**	-289.6	-1410.3	0.0	91.5
3A	**3F**	81.4	0.0	-509.5	-352.1
3B	**3C**	0.0	0.0	-472.5	99.5
3B	**3D**	0.0	0.0	-64.3	61.6
3B	**3E**	-330.7	-1610.3	0.0	0.0
3B	**3F**	-0.8	-4.0	6.9	**0.7**
3C	**3D**	-592.8	-2886.8	0.0	0.0
3C	**3E**	-1238.7	-6032.3	0.0	0.0
3C	**3F**	86.3	0.0	-303.2	-1512.3
3D	**3E**	-2314.7	-11272.8	0.0	95.1
3D	**3F**	28.1	0.0	-52.1	-72.8
3E	**3F**	-86.7	-422.1	0.0	55.6

Table E-14 Sensitivity of the criteria weights, Scenario 3: Precommissioning

		C1	C2	C3	C4
3A	3B	0.0	62.8	7E4	-138.0
3A	3C	0.0	86.6	-348.5	0.0
3A	3D	0.0	48.1	-91.5	-630.0
3A	3E	0.0	20.8	-44.5	-51.3
3A	3F	0.0	97.4	-1219	-3281
3B	3C	0.0	0.0	-197.3	0.0
3B	3D	0.0	34.7	-34.5	0.0
3B	3E	-122.8	**-10.2**	12.5	27.7
3B	3F	0.0	88.4	-1496	-628.6
3C	3D	-1245	-103.8	64.0	0.0
3C	3E	-1697	-141.4	0.0	95.3
3C	3F	0.0	93.4	-655.7	-12741.2
3D	3E	-2450	-204.2	0.0	65.3
3D	3F	0.0	76.4	-283.9	-1543.6
3E	3F	0.0	62.7	-244.8	-313.2

Table E-15 Sensitivity of the alternative scores, Scenario 1: Precommissioning

Alt	C1	C2	C3	C4	Swap with
3A	-3124.2	-144.3	-119.3	-191.4	**3B**
3A	76.6	24.2	21.6	44.5	**3C**
3A	0.0	-267.4	-142.5	-320.1	**3D**
3A	0.0	0.0	-512.3	-858.6	**3E**
3A	-312.3	-57.8	-74.0	-142.7	**3F**
3B	0.0	0.0	96.7	54.8	**3A**
3B	0.0	0.0	0.0	66.4	**3C**
3B	-367.5	-73.8	-36.6	-24.7	**3D**
3B	0.0	-1622	-333.5	-172.4	**3E**
3B	0.0	42.5	40.5	23.8	**3F**
3C	-203.8	-49.9	**-15.1**	-67.4	**3A**
3C	-2E4	-381.8	-94.1	-350.9	**3B**
3C	0.0	-649.4	-104.9	-557.9	**3D**
3C	0.0	-2E4	-355.5	-1366	**3E**
3C	-1097	-176.3	-64.8	-291.1	**3F**
3D	0.0	0.0	53.0	0.0	**3A**
3D	0.0	0.0	16.8	33.4	**3B**
3D	0.0	0.0	55.8	0.0	**3C**
3D	0.0	-2072	-116.8	-236.8	**3E**
3D	0.0	0.0	32.9	77.2	**3F**
3E	0.0	0.0	0.0	97.9	**3A**
3E	0.0	0.0	92.2	68.4	**3B**
3E	0.0	0.0	0.0	0.0	**3C**
3E	0.0	0.0	69.8	69.4	**3D**
3E	0.0	0.0	0.0	91.7	**3F**
3F	88.2	34.1	0.0	0.0	**3A**
3F	-174.4	-31.1	-67.5	-142.5	**3B**
3F	0.0	50.8	0.0	0.0	**3C**
3F	0.0	-88.1	-119.7	-341.6	**3D**
3F	0.0	0.0	-631.0	-1385	**3E**

Table E-16 Sensitivity of the alternative scores, Scenario 2: Precommissioning

Alt	C1	C2	C3	C4	Swap with
3A	-111.0	-1E4	-258.5	-181.5	**3B**
3A	55.9	0.0	0.0	0.0	**3C**
3A	-42.4	-325.2	-73.4	-75.1	**3D**
3A	-833.0	0.0	-994.3	-543.4	**3E**
3A	-77.8	-1146	-267.3	-227.3	**3F**
3B	0.0	0.0	0.0	52.7	**3A**
3B	0.0	0.0	0.0	82.6	**3C**
3B	74.6	0.0	95.1	31.3	**3D**
3B	-440.7	0.0	-488.6	-96.9	**3E**
3B	1.3	6.3	2.9	0.9	**3F**
3C	-133.4	-1236	-101.8	-208.3	**3A**
3C	-445.9	0.0	-338.6	-482.6	**3B**
3C	-275.7	-7E4	-141.5	-323.9	**3D**
3C	-2425	0.0	-1081	-1065	**3E**
3C	-315.1	0.0	-358.0	-618.5	**3F**
3D	99.0	0.0	31.1	38.3	**3A**
3D	-192.1	-1665	-61.7	-55.0	**3B**
3D	0.0	0.0	68.4	97.5	**3C**
3D	-1490	0.0	-357.4	-235.3	**3E**
3D	-143.5	-1038	-63.7	-68.6	**3F**
3E	0.0	0.0	0.0	81.5	**3A**
3E	0.0	0.0	0.0	50.1	**3B**
3E	0.0	0.0	0.0	94.2	**3C**
3E	0.0	0.0	0.0	69.2	**3D**
3E	0.0	0.0	0.0	64.6	**3F**
3F	42.3	0.0	0.0	0.0	**3A**
3F	**-0.8**	-3.9	-4.4	-4.6	**3B**
3F	71.9	0.0	0.0	0.0	**3C**
3F	33.7	0.0	0.0	0.0	**3D**
3F	-322.0	0.0	-784.0	-677.8	**3E**

Table E-17 Sensitivity of the alternative scores, Scenario 3: Precommissioning

Alt	C1	C2	C3	C4	Swap with
3A	0.0	22.7	99.9	0.0	**3B**
3A	0.0	51.7	0.0	0.0	**3C**
3A	0.0	38.6	0.0	0.0	**3D**
3A	0.0	20.1	67.7	0.0	**3E**
3A	0.0	-96.3	-1005	0.0	**3F**
3B	-829.7	-33.0	-124.1	-189.7	**3A**
3B	0.0	43.8	0.0	0.0	**3C**
3B	0.0	21.8	53.4	60.2	**3D**
3B	-117.0	**-8.4**	-20.9	-19.6	**3E**
3B	0.0	-176.9	-1589	0.0	**3F**
3C	0.0	-120.6	-217.1	-3388	**3A**
3C	-2918.4	-70.3	-106.0	-906.1	**3B**
3C	-803.2	-39.9	-42.9	-466.0	**3D**
3C	-2E4	-93.1	-102.3	-900.7	**3E**
3C	0.0	-348.9	-2629	0.0	**3F**
3D	-7276.4	-123.0	-95.0	-631.6	**3A**
3D	-827.9	-47.7	-30.6	-125.1	**3B**
3D	0.0	54.4	27.5	0.0	**3C**
3D	-1663.2	-73.0	-34.1	-147.3	**3E**
3D	0.0	-457.4	-1879	0.0	**3F**
3E	-1615.1	-85.2	-40.5	-113.3	**3A**
3E	0.0	24.7	9.9	14.7	**3B**
3E	0.0	0.0	54.8	88.1	**3C**
3E	0.0	97.5	28.5	52.9	**3D**
3E	0.0	-562.9	-928.9	0.0	**3F**
3F	0.0	48.8	0.0	0.0	**3A**
3F	0.0	61.7	0.0	0.0	**3B**
3F	0.0	75.8	0.0	0.0	**3C**
3F	0.0	72.9	0.0	0.0	**3D**
3F	0.0	67.3	0.0	0.0	**3E**

Heavy lift

4A Heavy lift
4B heavy lift + structures
4C increased crane capacity
4D increased crane capacity + structures — Best solution for scenario 1 and 2
4E Do nothing — Best solution for scenario 3

Table E-18 Sensitivity of the criteria weights, Scenario 1: Heavy lift

		C1	C2	C3	C4
4A	**4B**	-1046.7	-290.7	0.0	0.0
4A	**4C**	0.0	0.0	65535.0	65535.0
4A	**4D**	-1563.4	-434.2	0.0	0.0
4A	**4E**	0.0	98.4	0.0	-335.5
4B	**4C**	0.0	0.0	0.0	0.0
4B	**4D**	-2332.6	-647.9	0.0	0.0
4B	**4E**	-198.6	-55.2	**55.0**	66.7
4C	**4D**	-3E4	-9020.5	0.0	0.0
4C	**4E**	0.0	0.0	0.0	-781.0
4D	**4E**	-645.8	-179.4	0.0	0.0

Table E-19 Sensitivity of the criteria weights, Scenario 2: Heavy lift

		C1	C2	C3	C4
4A	4B	-127.2	-619.6	0.0	90.6
4A	4C	0.0	0.0	65535.0	65535.0
4A	4D	-235.5	-1147.0	0.0	0.0
4A	4E	95.5	0.0	0.0	-380.7
4B	4C	0.0	0.0	0.0	0.0
4B	4D	-396.8	-1932.3	0.0	0.0
4B	4E	**7.6**	36.9	-17.9	-10.7
4C	4D	-5675.3	-3E4	0.0	0.0
4C	4E	0.0	0.0	0.0	-872.5
4D	4E	-77.2	-375.8	0.0	57.4

Table E-20 Sensitivity of the criteria weights, Scenario 3: Heavy lift

		C1	C2	C3	C4
4A	4B	0.0	36.7	-68.4	-203.4
4A	4C	0.0	0.0	65535.0	65535.0
4A	4D	0.0	17.6	-29.0	-58.3
4A	4E	0.0	0.0	0.0	-3266.6
4B	4C	0.0	0.0	0.0	0.0
4B	4D	-130.3	**-10.9**	15.3	22.6
4B	4E	0.0	78.1	-369.0	-861.6
4C	4D	-2E4	-1369.0	0.0	0.0
4C	4E	0.0	0.0	0.0	-6711.0
4D	4E	0.0	59.5	-188.1	-344.6

Table E-21 Sensitivity of the alternative scores, Scenario 1: Heavy lift

Alt	C1	C2	C3	C4	Swap with
4A	0.0	-360.5	-207.3	-290.2	**4B**
4A	0.0	99.2	0.0	0.0	**4C**
4A	0.0	0.0	-607.3	-840.7	**4D**
4A	-672.5	-79.2	-117.1	-161.8	**4E**
4B	0.0	0.0	71.3	94.5	**4A**
4B	0.0	0.0	0.0	0.0	**4C**
4B	0.0	-1859	-127.7	-179.1	**4D**
4B	0.0	98.4	**38.1**	53.7	**4E**
4C	-1E4	-648.2	-161.7	-215.9	**4A**
4C	0.0	-4124.4	-408.0	-610.9	**4B**
4C	0.0	0.0	-929.2	-1392	**4D**
4C	0.0	-1132	-322.2	-477.9	**4E**
4D	0.0	0.0	99.5	0.0	**4A**
4D	0.0	0.0	61.0	67.8	**4B**
4D	0.0	0.0	0.0	0.0	**4C**
4D	0.0	0.0	86.5	94.7	**4E**
4E	0.0	44.1	95.1	0.0	**4A**
4E	0.0	-96.7	-90.1	-194.7	**4B**
4E	0.0	96.5	0.0	0.0	**4C**
4E	0.0	0.0	-427.5	-905.9	**4D**

Table E-22 Sensitivity of the alternative scores, Scenario 2: Heavy lift

Alt	C1	C2	C3	C4	Swap with
4A	-100.7	0.0	-216.6	-130.4	**4B**
4A	95.1	0.0	0.0	0.0	**4C**
4A	-1192	0.0	-941.5	-409.5	**4D**
4A	-76.3	-2134	-316.6	-187.6	**4E**
4B	0.0	0.0	73.3	54.5	**4A**
4B	0.0	0.0	0.0	0.0	**4C**
4B	-582.5	0.0	-220.0	-114.3	**4D**
4B	-15.8	-84.0	-14.4	-10.2	**4E**
4C	-600.7	0.0	-450.2	-243.7	**4A**
4C	-1549	0.0	-790.2	-400.8	**4B**
4C	-1^{E}4	0.0	-2523	-752.1	**4D**
4C	-1054	0.0	-1219	-565.1	**4E**
4D	0.0	0.0	0.0	80.5	**4A**
4D	0.0	0.0	79.1	53.7	**4B**
4D	0.0	0.0	0.0	0.0	**4D**
4D	0.0	0.0	87.5	62.3	**4E**
4E	43.1	0.0	0.0	0.0	**4A**
4E	**8.5**	35.6	26.2	27.6	**4B**
4E	94.2	0.0	0.0	0.0	**4C**

Table E-23 Sensitivity of the alternative scores, Scenario 3: Heavy lift

Alt	C1	C2	C3	C4	Swap with
4A	0.0	21.3	93.3	0.0	4B
4A	0.0	87.8	0.0	0.0	4C
4A	0.0	19.4	67.8	0.0	4D
4A	0.0	-85.9	-1119	0.0	4E
4B	-980.2	-37.3	-61.9	-214.3	4a
4B	0.0	0.0	0.0	0.0	4C
4B	-126.0	-9.1	-7.7	-20.0	4D
4B	0.0	-203.4	-1307	0.0	4E
4C	0.0	-524.4	-1255	0.0	4A
4C	0.0	-454.5	-593.0	-1E4	4B
4C	0.0	-546.9	-531.0	-4069	4D
4C	0.0	-1034	0.0	0.0	4E
4D	-2129	-107.2	-38.9	-128.9	4A
4D	0.0	28.9	**6.4**	14.5	4B
4D	0.0	0.0	94.6	0.0	4C
4D	0.0	-702.3	-2988	0.0	4E
4E	0.0	46.4	0.0	0.0	4A
4E	0.0	62.8	0.0	0.0	4B
4E	0.0	93.6	0.0	0.0	4C
4E	0.0	68.7	0.0	0.0	4D

Jumper, spool and structure installation (Large refit)

5A Large refit
5B Large refit + mattress
5C Large refit + span
5D Large refit + mattress + span
5E Do nothing Best solution for scenario 1,2 and 3

Table E-24 Sensitivity of the criteria weights, Scenario 1: Installation vessel (large refit)

		C1	C2	C3	C4
5A	**5B**	-1046	-290.5	0.0	0.0
5A	**5C**	-1046	-290.5	0.0	0.0
5A	**5D**	-1567	-434.6	0.0	0.0
5A	**5E**	0.0	76.1	-271.8	-322.2
5B	**5C**	0.0	0.0	0.0	0.0
5B	**5D**	-3339.6	-927.6	87.9	0.0
5B	**5E**	-28.9	**-8.0**	10.3	13.8
5C	**5D**	-3340	-927.6	87.9	0.0
5C	**5E**	-28.9	**-8.0**	10.3	13.8
5D	**5E**	-237.0	-65.8	47.3	0.0

Table E-25 Sensitivity of the criteria weights, Scenario 2: Installation vessel (large refit)

		C1	C2	C3	C4
5A	**5B**	-131.1	-638.4	0.0	88.4
5A	**5C**	-131.1	-638.4	0.0	88.4
5A	**5D**	-174.9	-851.9	96.8	0.0
5A	**5E**	88.5	0.0	-748.6	-438.4
5B	**5C**	0.0	0.0	0.0	0.0
5B	**5D**	-325.0	-1582.5	72.9	0.0
5B	**5E**	38.1	0.0	-116.1	-76.8
5C	**5D**	-325.0	-1582.5	72.9	0.0
5C	**5E**	38.1	0.0	-116.1	-76.8
5D	**5E**	**15.3**	74.4	-26.0	-32.9

Table E-26 Sensitivity of the criteria weights, Scenario 3: Installation vessel (large refit)

		C1	C2	C3	C4
5A	**5B**	0.0	37.6	-72.9	-197.8
5A	**5C**	0.0	37.6	-72.9	-197.8
5A	**5D**	39.1	**3.3**	-3.6	-22.1
5A	**5E**	0.0	99.8	-1688.6	-3852.6
5B	**5C**	0.0	0.0	0.0	0.0
5B	**5D**	-1373	-114.4	51.4	0.0
5B	**5E**	0.0	85.6	-521.3	-1344.0
5C	**5D**	-1373	-114.4	51.4	0.0
5C	**5E**	0.0	85.6	-521.3	-1344.0
5D	**5E**	0.0	73.0	-248.4	-1223.4

Table E-27 Sensitivity of the alternative scores, Scenario 1: Installation vessel (large refit)

	C1	C2	C3	C4	
5A	0.0	-323.2	-173.9	-162.0	5B
5A	0.0	-323.2	-173.9	-162.0	5C
5A	0.0	-1854	-329.2	-395.6	5D
5A	-1789	-139.4	-184.9	-171.2	5E
5B	0.0	0.0	68.1	72.7	5A
5B	0.0	0.0	0.0	0.0	5C
5B	0.0	-624.5	-63.8	-90.8	5D
5B	0.0	33.3	**10.1**	11.2	5E
5C	0.0	0.0	68.1	72.7	5A
5C	0.0	0.0	0.0	0.0	5C
5C	0.0	-624.5	-63.8	-90.8	5D
5C	0.0	33.3	**10.1**	11.2	5E
5D	0.0	0.0	77.1	0.0	5A
5D	0.0	0.0	38.2	61.7	5B
5D	0.0	0.0	38.2	61.7	5C
5D	0.0	0.0	52.1	79.9	5E
5E	0.0	56.1	0.0	0.0	5A
5E	-74.9	-15.7	-38.7	-26.1	5B
5E	-74.9	-15.7	-38.7	-26.1	5C
5E	0.0	-707.4	-332.7	-273.8	5D

Table E-28 Sensitivity of the alternative scores, Scenario 2: Installation vessel (large refit)

	C1	C2	C3	C4	
5A	-107.9	-3063.3	-188.1	-77.4	**5B**
5A	-107.9	-3063.3	-188.1	-77.4	**5C**
5A	-233.3	0.0	-309.4	-144	**5D**
5A	-169.7	0.0	-735.8	-254	**5E**
5B	0.0	0.0	72.0	42.2	**5A**
5B	0.0	0.0	0.0	0.0	**5C**
5B	-165.2	-1644.9	-51.7	-32.7	**5D**
5B	-186.6	-2149.6	-159.0	-76.9	**5E**
5C	0.0	0.0	72.0	42.2	**5A**
5C	0.0	0.0	0.0	0.0	**5B**
5C	-165.2	-1644.9	-51.7	-32.7	**5D**
5C	-186.6	-2149.6	-159.0	-76.9	**5E**
5D	0.0	0.0	74.6	67.4	**5A**
5D	0.0	0.0	32.6	27.9	**5B**
5D	0.0	0.0	32.6	27.9	**5C**
5D	-126.9	-794.3	-42.4	-29.5	**5E**
5E	61.9	0.0	0.0	0.0	**5A**
5E	48.5	0.0	0.0	0.0	**5B**
5E	48.5	0.0	0.0	0.0	**5C**
5E	**26.5**	80.1	0.0	57.9	**5D**

Table E-29 Sensitivity of the alternative scores, Scenario 3: Installation vessel (large refit)

	C1	C2	C3	C4	
5A	0.0	24.3	84.3	0.0	**5B**
5A	0.0	24.3	84.3	0.0	**5C**
5A	33.3	**3.0**	8.8	17.1	**5D**
5A	0.0	-200.0	-13494.3	0.0	**5E**
5B	-1149.8	-52.0	-56.0	-146.4	**5A**
5B	0.0	0.0	0.0	0.0	**5C**
5B	-1215.4	-53.6	-35.1	-105.2	**5D**
5B	0.0	-514.6	0.0	0.0	**5E**
5C	-1149.8	-52.0	-56.0	-146.4	**5A**
5C	0.0	0.0	0.0	0.0	**5B**
5C	-1215.4	-53.6	-35.1	-105.2	**5D**
5C	0.0	-514.6	0.0	0.0	**5E**
5D	-121.2	-9.6	-4.0	-12.2	**5A**
5D	0.0	81.5	23.8	68.0	**5B**
5D	0.0	81.5	23.8	68.0	**5C**
5D	0.0	-773.4	0.0	0.0	**5E**
5E	0.0	66.7	0.0	0.0	**5A**
5E	0.0	80.1	0.0	0.0	**5B**
5E	0.0	80.1	0.0	0.0	**5C**
5E	0.0	79.2	0.0	0.0	**5D**

Total score: Scenario 1

A1	Small refit + mattress + span	
A2	Subsea FGT + dewatering	
A3	Large refit + mattress + structures	
A4	Cable laying	
A5	Combination of all options	Best option for scenario 1
A6	Heavy lift + structures	

Table E-30 Sensitivity of the criteria weights, Scenario 1: Total score

		C1	C2	C3	C4
A1	**A2**	0.0	0.0	-275.3	0.0
A1	**A3**	0.0	37.6	-77.3	-90.9
A1	**A4**	0.0	28.6	-19.9	64.5
A1	**A5**	-1051.8	-292.2	0.0	0.0
A1	**A6**	29.3	**8.1**	-39.7	-8.2
A2	**A3**	-47.5	-13.2	27.2	14.3
A2	**A4**	-326.4	-90.7	36.4	-297.3
A2	**A5**	-1990.1	-552.8	0.0	0.0
A2	**A6**	-297.9	-82.7	0.0	39.3
A3	**A4**	0.0	54.3	43.1	-27.2
A3	**A5**	0.0	0.0	0.0	0.0
A3	**A6**	0.0	0.0	-97.1	77.3
A4	**A5**	-3987.8	-1107.7	0.0	0.0
A4	**A6**	-247.3	-68.7	-15.6	10.8
A5	**A6**	-11857.3	-3293.5	0.0	0.0

Table E-31 Sensitivity of the alternative scores, Scenario 1: Total score

	C1	C2	C3	C4	
A1	0.0	41.5	0.0	0.0	**A2**
A1	0.0	45.8	0.0	79.8	**A3**
A1	62.0	21.0	58.1	47.2	**A4**
A1	0.0	0.0	-1026.4	-909.4	**A5**
A1	28.7	8.7	24.0	13.9	**A6**
A2	-451.1	-66.7	-119.3	-237.0	**A1**
A2	-67.1	-16.5	-19.1	-37.5	**A3**
A2	-266.6	-48.8	-58.8	-145.6	**A4**
A2	0.0	0.0	-835.8	-2253.6	**A5**
A2	-669.4	-80.8	-97.7	-168.1	**A6**
A3	-2267.1	-444.1	-58.6	-55.9	**A1**
A3	0.0	98.7	12.0	12.0	**A2**
A3	-1140.3	-261.7	-24.2	-29.1	**A4**
A3	0.0	0.0	-492.3	-674.6	**A5**
A3	-2479.8	-472.7	-46.0	-37.2	**A6**
A4	-160.0	-37.7	-19.2	-158.7	**A1**
A4	0.0	54.3	25.3	0.0	**A2**
A4	0.0	48.3	16.7	0.0	**A3**
A4	0.0	0.0	-307.1	-3319.1	**A5**
A4	-130.8	-31.7	-11.7	-85.4	**A6**
A5	0.0	0.0	94.7	0.0	**A1**
A5	0.0	0.0	0.0	0.0	**A2**
A5	0.0	0.0	94.6	0.0	**A3**
A5	0.0	0.0	85.5	0.0	**A4**
A5	0.0	0.0	93.4	0.0	**A6**
A6	-79.9	-21.1	-16.0	**-6.8**	**A1**
A6	0.0	0.0	85.1	37.7	**A2**
A6	0.0	0.0	64.1	26.0	**A3**
A6	0.0	43.3	23.6	12.5	**A4**
A6	0.0	0.0	-674.7	-421.5	**A5**

Total score: Scenario 2

A1	Small refit + mattress + span
A2	Subsea FGT + dewatering
A3	Do nothing
A4	Cable laying
A5	Combination of all options — Best option for scenario 2
A6	Heavy lift + structures

Table E-32 Sensitivity of the criteria scores, Scenario 2: Total score

		C1	C2	C3	C4
A1	**A2**	0.0	0.0	-546.9	0.0
A1	**A3**	0.0	0.0	0.0	0.0
A1	**A4**	86.2	0.0	-93.9	0.0
A1	**A5**	-219.9	-1071	0.0	0.0
A1	**A6**	-20.9	-101.9	0.0	16.3
A2	**A3**	0.0	0.0	0.0	0.0
A2	**A4**	-10.5	-51.1	**6.0**	-24.3
A2	**A5**	-449.6	-2189	0.0	0.0
A2	**A6**	-167.9	-817.8	0.0	58.2
A3	**A4**	0.0	0.0	-704.2	0.0
A3	**A5**	-48.6	-236.6	57.8	57.1
A3	**A6**	96.6	0.0	0.0	-244
A4	**A5**	-822.4	-4005	0.0	0.0
A4	**A6**	-422.6	-2058	-149.9	51.2
A5	**A6**	-1263.9	-6155	0.0	0.0

Table E-33 Sensitivity of the alternative scores, Scenario 2: Total score

	C1	C2	C3	C4	
A1	52.2	0.0	0.0	0.0	**A2**
A1	-175.1	0.0	-1208.7	-326.3	**A3**
A1	53.5	0.0	0.0	0.0	**A4**
A1	-858.0	0.0	-1503.7	-440.7	**A5**
A1	-21.2	-131.7	-102.2	-28.7	**A6**
A2	-88.8	-1051	-260.1	-232.1	**A1**
A2	-405.0	0.0	-1434.9	-954.6	**A3**
A2	-4.5	-22.8	-9.4	-11.2	**A4**
A2	-2164.0	0.0	-1518.1	-1156.9	**A5**
A2	-154.4	0.0	-343.5	-258.6	**A6**
A3	74.9	0.0	0.0	0.0	**A1**
A3	0.0	0.0	0.0	0.0	**A2**
A3	0.0	0.0	0.0	0.0	**A4**
A3	-98.1	0.0	-129.5	-61.9	**A5**
A3	82.1	0.0	0.0	91.9	**A6**
A4	-130.1	-1314	-106.1	-390.1	**A1**
A4	6.5	30.8	**4.4**	19.4	**A2**
A4	-601.1	0.0	-681.1	-1655.8	**A3**
A4	-2513.3	0.0	-675.7	-2020.9	**A5**
A4	-223.1	-9744	-142.3	-441.5	**A6**
A5	0.0	0.0	0.0	87.8	**A1**
A5	0.0	0.0	0.0	0.0	**A2**
A5	0.0	0.0	48.4	34.0	**A3**
A5	0.0	0.0	0.0	0.0	**A4**
A5	0.0	0.0	0.0	70.8	**A6**
A6	55.8	0.0	60.6	12.8	**A1**
A6	0.0	0.0	0.0	53.2	**A2**
A6	-505.6	0.0	-637.5	-115.4	**A3**
A6	0.0	0.0	0.0	52.6	**A4**
A6	-1673.7	0.0	-832.2	-159.6	**A5**

Appendix F Matlab code for AHP calculations

This appendix shows the Matlab code used for the AHP calculations in the research part of the report. This code works by taking and placing data in an Excel file, of which pictures are included in Excel sheet used for AHP calculations.

Consistency Check

```
% Consistency check matrix
% This script is run independently from the others before the total score is
% calculated

% Read in the matrix from excel
filename = 'Consistencycheck.xlsx';
n = xlsread('Consistencycheck.xlsx',1,'B1');

% Define the range from which to take the matrix
firstrow = 3;
firstcol = 'B';
lastrow = firstrow + (n - 1);
lastcol = char(double(firstcol + n - 1));
xlRange = [firstcol,num2str(firstrow),':',lastcol,num2str(lastrow)];
A = xlsread(filename,1,xlRange);

% Define the random index
RIm = [0 0 0.58 0.9 1.12 1.24 1.32 1.41 1.45 1.49];
RI = RIm(n);

% calculate the geomean and weight/score vector
GM = geomean(A,2);
Sum = sum(GM);
WF = GM/Sum; % normalised GM

Labda = eig(A);
L = max(Labda);
CI = (L-n)/(n-1);
CR = CI/RI

if CR > 0.1
    disp('Matrix INCONSISTENT')
end
mat = zeros((2^(n-2)),5);
if CR > 0.1
count = 1;
store = 0;
for i = 1:(n-1)
    for j = 2:(n-1)
        for k = 2:n
            if i < j
                if j < k
                   B = A(i,j)*A(j,k);
                   C = A(i,k);
                   Ex = [i j k B C];
                   mat(count,:) = Ex;
                   dif = abs(mat(count,4)-mat(count,5));
                   if dif > store
                       store = dif;
                       loc = [i j k];
                   end
                   count = count + 1;
                end
            end
        end
    end
end
```

```
exp = [loc store];
disp('Change this cell');
disp(exp);
end
```

Total score calculation

```
% Calculate the total score for everything
clear;

% General
RIm = [0 0 0.58 0.9 1.12 1.24 1.32 1.41 1.45 1.49];
filename = 'InputAHP.xlsx';
m = xlsread(filename,1,'K2'); % number of scenarios
n = xlsread(filename,1,'K1'); % number of criteria
o = xlsread(filename,1,'K3'); % number of active sheets

% Run the scenario calculations to determine the weight vectors
Scenario_Calculation_Compact;

% Run the Alternatives calculations to determine their score vectors
Alternatives_score_vector;
```

Scenario calculation

```
% General information
sheet = 1;
RI = RIm(1,n);

% Define flexible excel range
firstrow = 2;
lastrow = 50;
firstcol = 'B';
lastcol = char((double(firstcol))+(n-1));
cellRange = [firstcol,num2str(firstrow),':',lastcol,num2str(lastrow)];

%Import all data
xlRange = cellRange;
B = xlsread(filename,xlRange);

% Define the starting row
row = 0;

% pre create matrices to fill with output from for loop
D = zeros(n,m);
R = zeros(n,n);

% Create matrix for sizing A
for i = 1:n
    row = row + 1;
    R(i) = row;
end

%define where the data input starts
firstrow = 2;

for i = 1:m
    % check consistency
    A = B(R(1):R(n),1:n);
    Labda = eig(A);
    L = max(Labda);
    CI = (L-n)/(n-1);
    CR = CI/RI;
    if CR > 0.10
        disp(i);
```

```
        str = 'CR is %% %1.2f. Subjective evaluation is NOT consistent!!!';
        str=sprintf(str,CR);
        disp(str);
    end

    R = R + 7;

    % calculate GM and WF
    GM = geomean(A,2);
    Sum = sum(GM);
    WF = GM/Sum;

    % write this into excel
    lastrow = firstrow -1 + n;
    firstcol = char((double('A') + n + 1));
    cellRange = [firstcol,num2str(firstrow),':',firstcol,num2str(lastrow)];
    xlswrite(filename,WF,cellRange);
    firstrow = firstrow + 7;

    % Store weight factors in matrix for later use
    D(:,i) = WF;
End
```

Score vector for the alternatives

```
  % This script allows for each different input sheet to be calculated
  % concurrently instead of running them all by hand.
  % General information - define the range of sheets that has to be evaluated
firstsheet = 2;
lastsheet = firstsheet+(o-1);
TOTMat = zeros(8,8,9);

for i = firstsheet:lastsheet
    sheet = i;

    %run the file for the calculation of one set of alternatives
    Alternative_calculation_per_sheet;
end
```

Alternative calculation

```
sheet = i;
p = xlsread(filename,sheet,'I1'); % number of alternatives

%predefine S for speed
S = zeros(p,n);
normC = zeros(p,p,n);

%define where the data input starts
firstrow = 4;

for j = 1:n
 % Define range for B
    lastrow = firstrow + p - 1;
    firstcol = 'B';
    lastcol = char(double('B')+ p - 1);
    cellRange = [firstcol,num2str(firstrow),':',lastcol,num2str(lastrow)];
    B = xlsread(filename,sheet,cellRange);
    b = sum(B);
    C = bsxfun(@rdivide, B, b);
    C(isnan(C)) = 0;
    normC(:,:,j) = C;

 %Determine GM and SV
    GM = geomean(B,2);
```

```
    Sum = sum(GM);
    SV = GM/Sum;
    S(:,j) = SV;

 %Place the scores in excel
    col = char((double('B') + p ));
    ansRange = [col,num2str(firstrow),':',col,num2str(lastrow)];
    xlswrite(filename,SV,sheet,ansRange);

   % move the first row to post the next matrix in excel
    firstrow = firstrow + 10;
 end

TOT = zeros(p,m);
T = zeros(1,m);

% calculate the Total score for each alternative and for each scenario
for j = 1:p
    for i = 1:m
        TS = S(j,:)*D(:,i);
        T(i) = TS;
    end
    TOT(j,:) = T;
end

xlswrite(filename,TOT,sheet,'M12:O17');

% Perform a sensitivity study on the results
Sensitivity_study;
```

Sensitivity study

```
% Sensitivity study
% Done for each scenario, for each criteria

% Predefine range for data dump in excel
firstcol = 'C';
firstrow = 51;
startrow = 51;
startcol = 'Q';

% Part 1 - Determine which criteria is the most sensitive

% Determine the number of comparisons that have to be made. Is used later
% on to define the excel range
t = 0;
for i = 1:(p-1)
    t = t + i;
end

% predefine matrices for speed
Sens = zeros(t,n,m);
SP = zeros(t,n,m);
tmat = zeros((p-1),n,p);
% Determine the minimal percentual change of the criteria weights required to
swith two alternatives in the ranking
for z = 1:m % For each scenario
    for x = 1:n % For each criteria
        w = 0; % Count for alternative combination
        for i = 1:p % For each combination of alternatives
            for j = (i+1):p
                w = w + 1;
                % Calculate the required change in score to achieve a switch
                % in ranking between the alternatives
```

```
                delta = (TOT(j,z)-TOT(i,z))/(S(j,x)-S(i,x));
                % Delta has to be smaller than the criteria weight as
                % having a score higher than 1 is not possible due to the
                % normalisation process
                if delta < D(x,z)
                    Sens(w,x,z) = delta;
                else
                   Sens(w,x,z) = 0;
                end
            end
        end
    end
    % Change the absolute values into percentages of the weight factor
    for y = 1:n
        SP(:,y,z) = (Sens(:,y,z)/D(y,z))*100;
    end
end

% place in excel
for z = 1:m
    A = SP(:,:,z);
    lastcol = char((double(firstcol) + m ));
    lastrow = firstrow + t - 1;
    xlRange = [firstcol,num2str(firstrow),':',lastcol,num2str(lastrow)];
    xlswrite(filename,A,sheet,xlRange);
    firstrow = lastrow + 4;
end

% Part 2 - Determine which alternative score is the most sensitive
% define starting range for data dump
firstcol = 'J';
firstrow = 51;
% determine the percentual change needed to swith two alternatives in the
% scoring process. For each scenario
for l = 1:m
    % Predefined values
    r = 1;
    M = zeros(p,n);
    % For each alternative
    for j = 1:p
        % Calculate for each criteria
        for i = 1:n
        % t with comparison to every other criteria
            for k = 1:p
                if k ~= j
                    t = ((TOT(j,l)-TOT(k,l))/(TOT(j,l)-TOT(k,l)+
D(i,l)*(S(k,i)-S(j,i)+1)))*100/S(j,i);
                    if t > 100
                        tmat(k,i,j) = 0;
                    else
                        tmat(k,i,j) = t;
                    end
                end
            end
        end

        % Place this in excel
        C = tmat(:,:,j);
        lastcol = char((double(firstcol) + m ));
        lastrow = firstrow + p - 1;
        xlRange = [firstcol,num2str(firstrow),':',lastcol,num2str(lastrow)];
        xlswrite(filename,C,sheet,xlRange);
        firstrow = lastrow + 1;
```

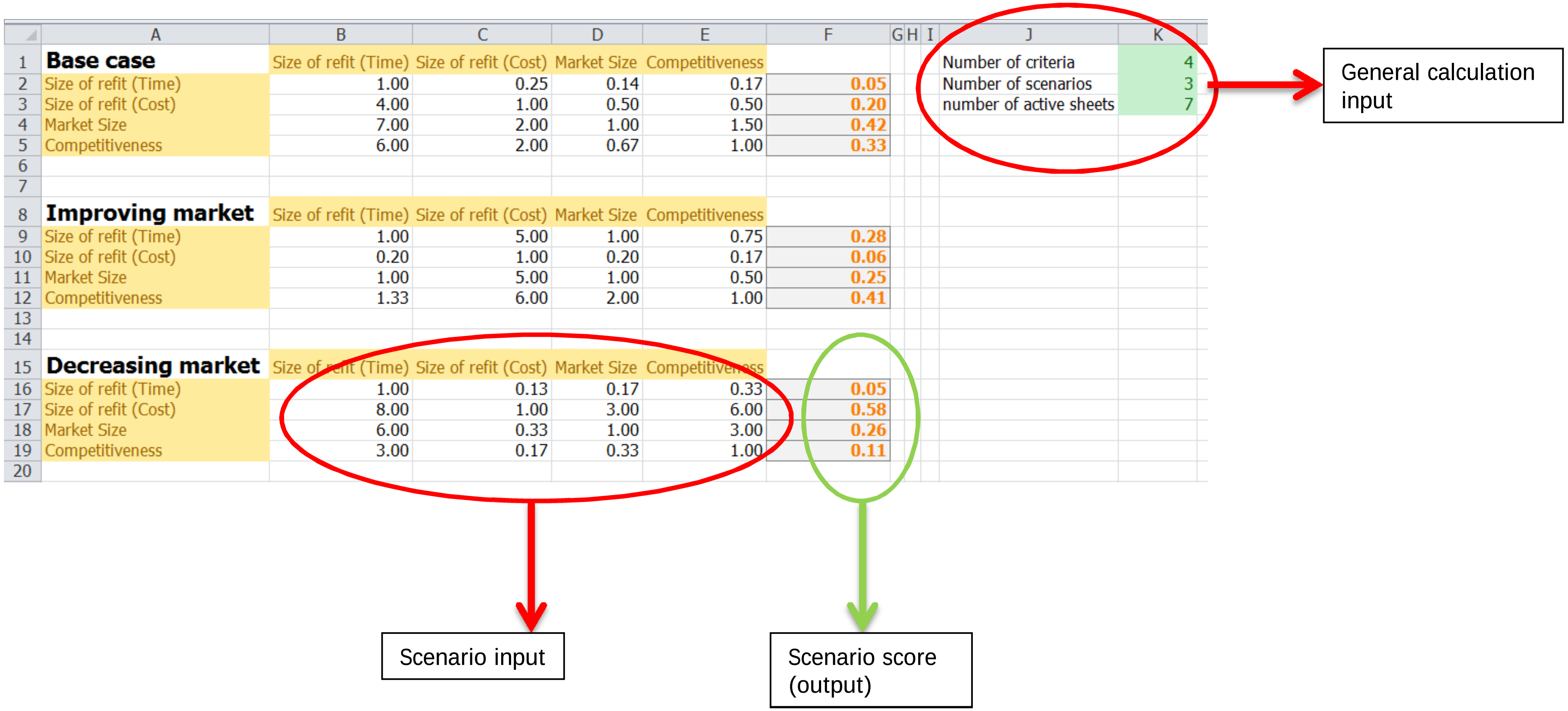
```
        %Create matrix with the absolute smallest non zero values as final
        %result

        for i = 1:n
            W = C(:,i);
            W = abs(W);
            if sum(W) > 0
                mn = min(W(W>0));
            else
                mn = 0;
            end
            M(r,i) = mn;
        end
        r = r + 1;
    end
    % Dump the data for the next scenario lower in excel
    firstrow = lastrow+4;

    % Place matrix M in excel
    endrow = startrow + p - 1;
    endcol = 'T';
    RangeXL = [startcol,num2str(startrow),':',endcol,num2str(endrow)];
    xlswrite(filename,M,sheet,RangeXL);
    startrow = endrow + 5;
end
```

Appendix G Excel sheet used for AHP calculations

This appendix gives a short overview of the layout and input and output of the Excel sheet used in combination with the Matlab code presented in the previous appendix.

Scenario input

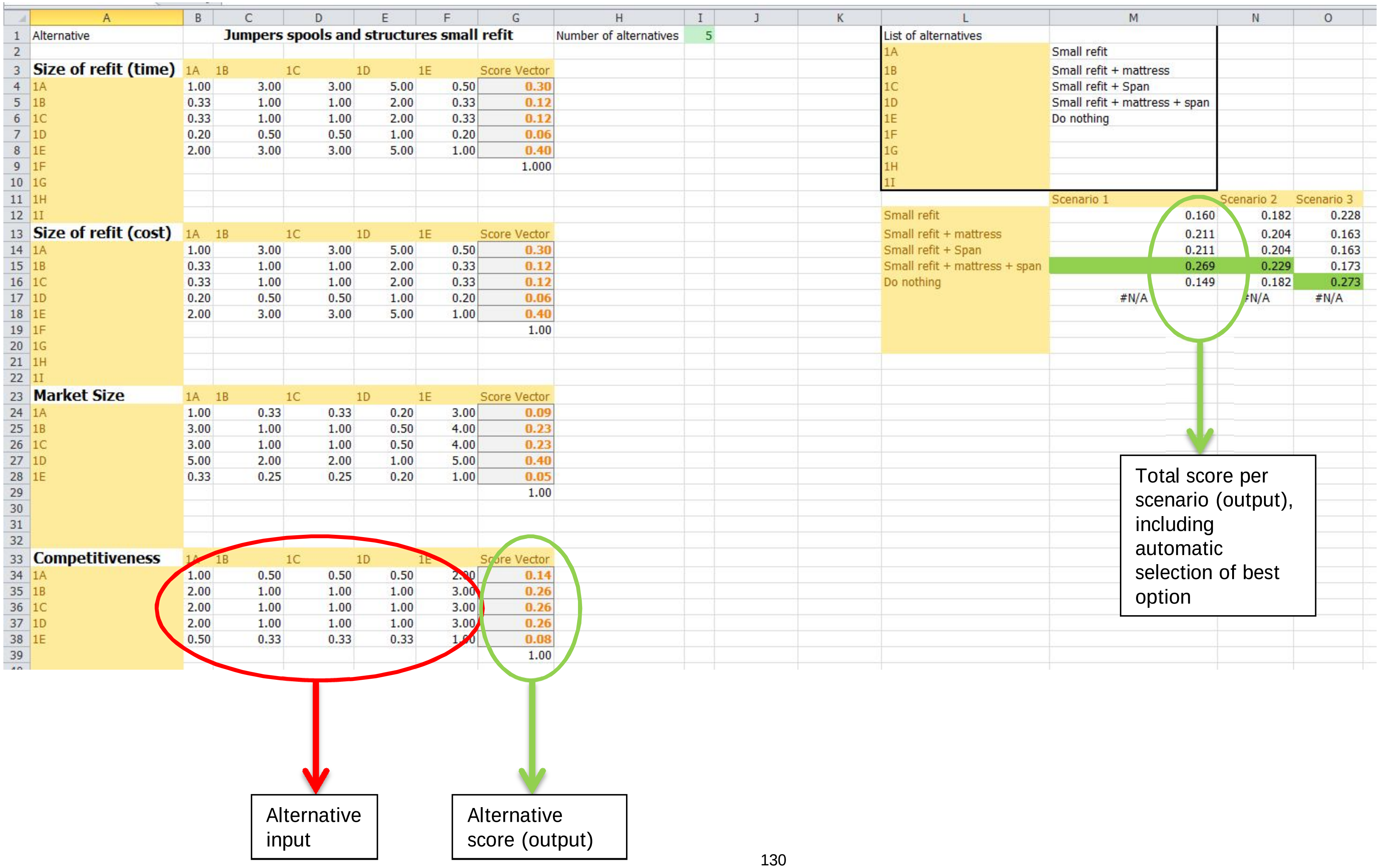
The process of calculating the best alternative starts by the input of the different criteria scores via pairwise comparison. The score for each criterion in each scenario is calculated and used in the following parts of the calculations.



	A	B	C	D	E	F	G	H	I	J	K
1	**Base case**	Size of refit (Time)	Size of refit (Cost)	Market Size	Competitiveness					Number of criteria	4
2	Size of refit (Time)	1.00	0.25	0.14	0.17	0.05				Number of scenarios	3
3	Size of refit (Cost)	4.00	1.00	0.50	0.50	0.20				number of active sheets	7
4	Market Size	7.00	2.00	1.00	1.50	0.42					
5	Competitiveness	6.00	2.00	0.67	1.00	0.33					
6											
7											
8	**Improving market**	Size of refit (Time)	Size of refit (Cost)	Market Size	Competitiveness						
9	Size of refit (Time)	1.00	5.00	1.00	0.75	0.28					
10	Size of refit (Cost)	0.20	1.00	0.20	0.17	0.06					
11	Market Size	1.00	5.00	1.00	0.50	0.25					
12	Competitiveness	1.33	6.00	2.00	1.00	0.41					
13											
14											
15	**Decreasing market**	Size of refit (Time)	Size of refit (Cost)	Market Size	Competitiveness						
16	Size of refit (Time)	1.00	0.13	0.17	0.33	0.05					
17	Size of refit (Cost)	8.00	1.00	3.00	6.00	0.58					
18	Market Size	6.00	0.33	1.00	3.00	0.26					
19	Competitiveness	3.00	0.17	0.33	1.00	0.11					
20											

Input per alternative

The next input that is required is the scores for the alternatives for each criterion. The same method of pairwise comparison is used in this case. Note that there is no difference in the input between the size of the refit (time) and size of the refit (cost). There is however a difference is score between them in the criteria scoring. The score for each alternative per criteria is calculated. These are then summed on the right side to form the total score.



	A	B	C	D	E	F	G	H	I
1	Alternative	Jumpers spools and structures small refit						Number of alternatives	5
2									
3	Size of refit (time)	1A	1B	1C	1D	1E	Score Vector		
4	1A	1.00	3.00	3.00	5.00	0.50	0.30		
5	1B	0.33	1.00	1.00	2.00	0.33	0.12		
6	1C	0.33	1.00	1.00	2.00	0.33	0.12		
7	1D	0.20	0.50	0.50	1.00	0.20	0.06		
8	1E	2.00	3.00	3.00	5.00	1.00	0.40		
9	1F						1.000		
10	1G								
11	1H								
12	1I								
13	Size of refit (cost)	1A	1B	1C	1D	1E	Score Vector		
14	1A	1.00	3.00	3.00	5.00	0.50	0.30		
15	1B	0.33	1.00	1.00	2.00	0.33	0.12		
16	1C	0.33	1.00	1.00	2.00	0.33	0.12		
17	1D	0.20	0.50	0.50	1.00	0.20	0.06		
18	1E	2.00	3.00	3.00	5.00	1.00	0.40		
19	1F						1.00		
20	1G								
21	1H								
22	1I								
23	Market Size	1A	1B	1C	1D	1E	Score Vector		
24	1A	1.00	0.33	0.33	0.20	3.00	0.09		
25	1B	3.00	1.00	1.00	0.50	4.00	0.23		
26	1C	3.00	1.00	1.00	0.50	4.00	0.23		
27	1D	5.00	2.00	2.00	1.00	5.00	0.40		
28	1E	0.33	0.25	0.25	0.20	1.00	0.05		
29							1.00		
30									
31									
32									
33	Competitiveness	1A	1B	1C	1D	1E	Score Vector		
34	1A	1.00	0.50	0.50	0.50	2.00	0.14		
35	1B	2.00	1.00	1.00	1.00	3.00	0.26		
36	1C	2.00	1.00	1.00	1.00	3.00	0.26		
37	1D	2.00	1.00	1.00	1.00	3.00	0.26		
38	1E	0.50	0.33	0.33	0.33	1.00	0.08		
39							1.00		

	L	M	N	O
1	List of alternatives			
2	1A	Small refit		
3	1B	Small refit + mattress		
4	1C	Small refit + Span		
5	1D	Small refit + mattress + span		
6	1E	Do nothing		
7	1F			
8	1G			
9	1H			
10	1I			
11		Scenario 1	Scenario 2	Scenario 3
12	Small refit	0.160	0.182	0.228
13	Small refit + mattress	0.211	0.204	0.163
14	Small refit + Span	0.211	0.204	0.163
15	Small refit + mattress + span	0.269	0.229	0.173
16	Do nothing	0.149	0.182	0.273
17		#N/A	#N/A	#N/A

Sensitivity study

Lastly a sensitivity study is conducted to determine if the choice of best solution is based on a stable system. The percent top and percent any values are calculated for each scenario and both for the criteria weight and the alternatives.

Sensitivity of the criteria weights

Scenario 1

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	
1A 1B	-523.11	-145.30	91.10	0.00	
1A 1C	-523.11	-145.30	91.10	0.00	
1A 1D	-854.04	-237.22	85.35	0.00	
1A 1E	-208.49	-57.91	65.98	59.15	
1B 1C	0.00	0.00	0.00	0.00	
1B 1D	-1941.07	-539.15	80.84	0.00	
1B 1E	-414.13	-115.03	85.42	0.00	
1C 1D	-1941.07	-539.15	80.84	0.00	
1C 1E	-414.13	-115.03	85.42	0.00	12
1D 1E	[illegible]67.54	-185.42	8[illegible].15	0.00	57.91

Percent top and percent any values for criteria weights. In case of a 0 the order is impossible to change

Sensitivity of the alternative scores

Scenario 1

	C1	C2	C3	C4	
1A	0.00	0.00	0.00	0.00	1A
1A	0.00	-157.68	-131.38	-117.65	1B
1A	0.00	-157.68	-131.38	[illegible]117.65	1C
1A	0.00	-919.09	-270.97	-30[illegible].71	1D
1A	**51.39**	**16.07**	**28.46**	**24.5[illegible]**	1E
1B	0.00	0.00	**54.72**	**58.19**	1A
1B	0.00	0.00	0.00	0.00	1B
1B	0.00	0.00	0.00	0.00	1C
1B	0.00	-384.87	-59.12	-82.59	1D
1B	0.00	0.00	67.18	72.07	1E
1C	0.00	0.00	**54.72**	**58.19**	1A
1C	0.00	0.00	0.00	0.00	1B
1C	0.00	0.00	0.00	0.00	1C
1C	0.00	-384.87	-59.12	-82.59	1D
1C	0.00	0.00	67.18	72.07	1E
1D	0.00	0.00	68.67	0.00	1A
1D	0.00	0.00	35.97	57.77	1B
1D	0.00	0.00	35.97	57.77	1C
1D	0.00	0.00	0.00	0.00	1D
1D	0.00	0.00	76.55	0.00	1E
1E	**-71.73**	**-16.53**	**-48.25**	**-39.49**	1A
1E	0.00	-199.08	-273.43	-234.28	1B
1E	0.00	-199.08	-273.43	-234.28	1C
1E	0.00	-3026.84	-512.01	-5[illegible]1.41	1D
1E	0.00	0.00	0.00	0.00	1E

Percent top and percent any values for alternative weights

Summary of sensitivity alternative scores

Scenario 1

	C1	C2	C3	C4
1A	51.39	16.07	28.46	24.56
1B	0	384.87	54.72	58.19
1C	0	384.87	54.72	58.19
1D	0	0	35.97	57.77
1E	71.73	16.53	48.25	39.49

Summary of the calculated values. This table only shows the lowest required value to change the order of two elements.

Appendix H Placement of the fourth tensioner in threshold

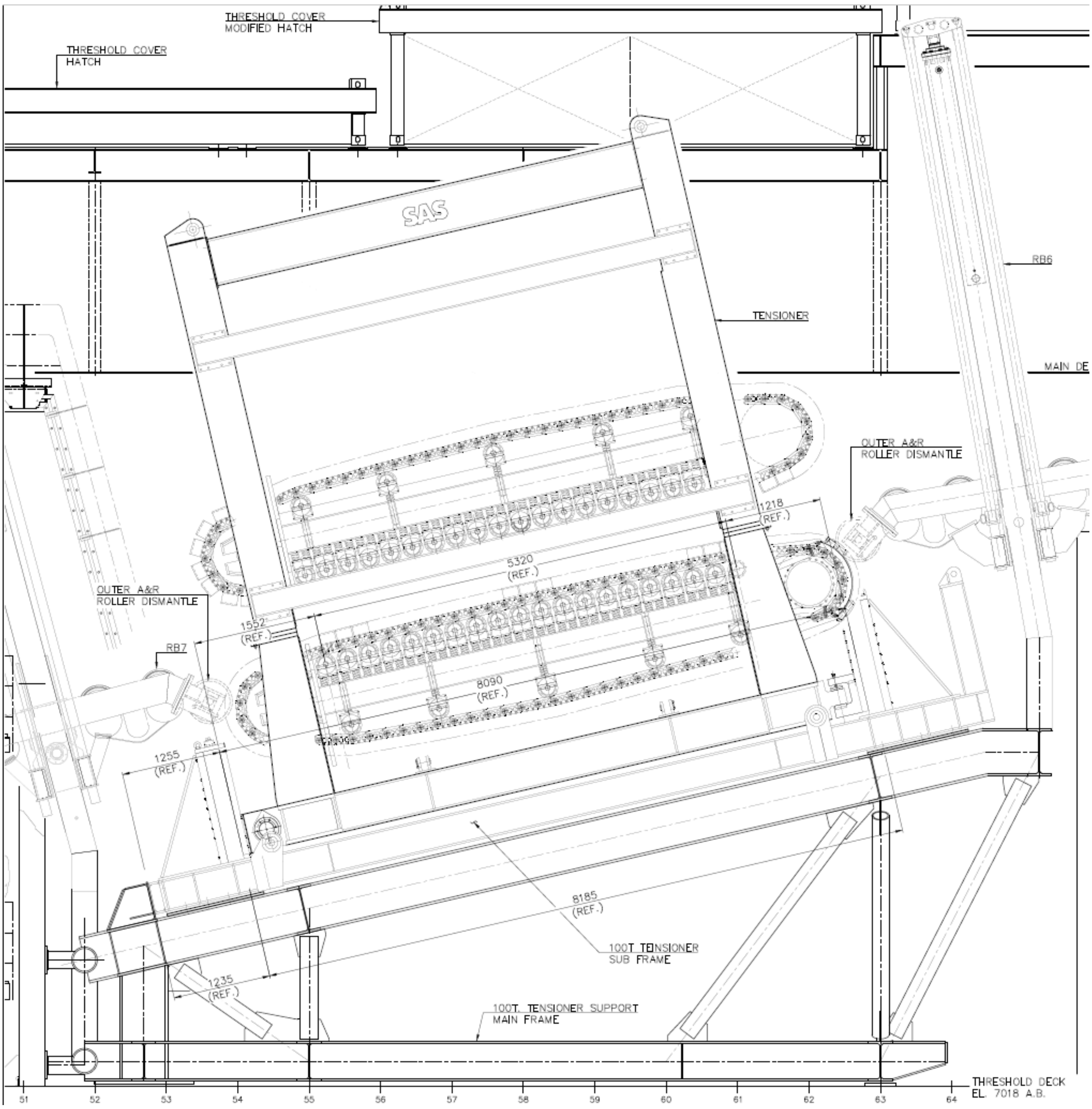


Figure H-1 Placement of the tensioner in the threshold

Appendix I Crane curve for SPC while lifting tensioner 3

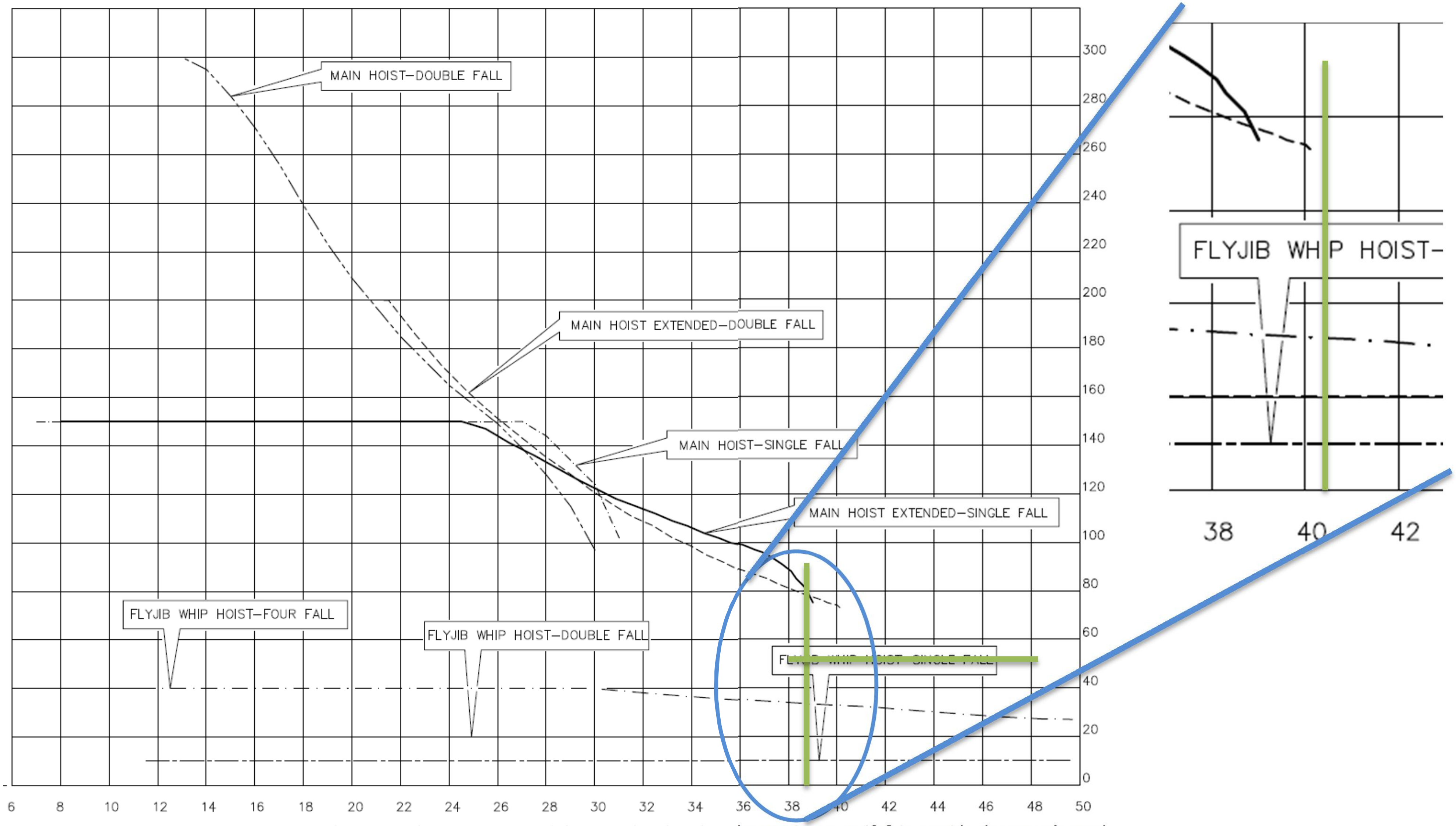


Figure I-1 The crane curve of the SPC showing that the tensioner at 40.3 is outside the crane's reach

Appendix J Stability estimations

In this appendix the stability of the ship is estimated for the ship in pipe laying configuration and for the ship with the units in the hold. This is done by performing a rough calculation using the previously calculated weights.

Stability in pipe laying configuration

To estimate the ship stability a simple calculation is performed. First the centre of gravity in each direction is determined for the new deck and the units. The CoG for the light ship is known. For this calculation the effect of the changes on the light ship stability are calculated since this is constant while the deadweight of the ship changes. The different centres of gravity can be found in Table J-1.

Table J-1 CoG in each direction for ship, deck and units

	Light ship (current situation)	Deck	Units
VCG [m]	13.06	16.02	18.92
LCG [m]	74.39	45.50	55.50
TCG [m]	0.325	3.95	0

The weight of the different elements is also known. The weight of the ship, deck and units is presented in Table J-2. Since the old firing line is incorporated in the light weight of the ship a correction as to be made for this. For this reason the stability in the new situation is estimated by using the difference in weight for the new firing line.

Table J-2 Weight of ship, deck and units

	Weight [t]
Light ship	15168.7
Deck	6
Units [corrected for existing firing line]	7

For this estimation the ship, the deck and the firing line are assumed to be boxes, as visualised in Figure J-1. This also means that the unit and deck are assumed as solids, with a CoG located at their centre, simplifying the calculations of the CoG for each of them.

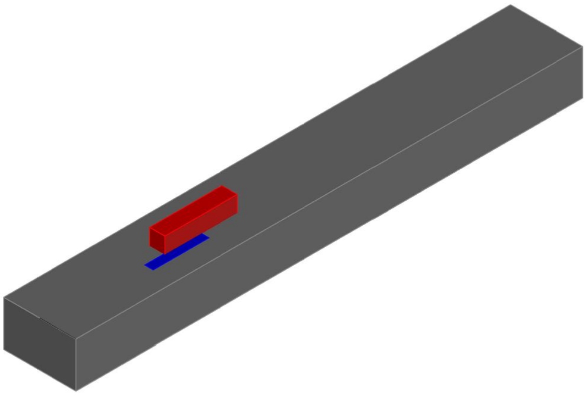


Figure J-1 Visualisation of the simplification of the relevant elements

The effect on the CoG of the ship is calculated using the following formula:

$$\Delta Z = \frac{Z_{ship} \cdot m_{ship} + Z_{deck} \cdot m_{deck} + Z_{units} \cdot m_{units}}{m_{ship} + m_{deck} + m_{units}}$$

In which:

ΔZ : Change in CoG in the relevant direction

Z : CoG location in [m]

m : Mass in [t]

This leads to the following changes in the CoG:

Table J-3 Changes in the CoG in the new situation

	New CoG [m]	Difference to current situation [m]
VCG	13.06	0.004
LCG	74.37	-0.02
TCG	0.326	0.001

As becomes clear from Table J-3 the effect of the new deck and the new firing line are minimal. The changes to the CoG are not significant.

For safety the calculations for the stability are repeated for a situation in which both the firing line and the deck have doubled in weight. The deck is now assumed to weigh 12 tonnes and the firing line weight is taken at 139 tonnes.

Table J-4 Changes to the CoG assuming double weight of deck and firing line

	New CoG [m]	Difference to current situation [m]
VCG	13.11	0.06
LCG	74.20	-0.2
TCG	0.325	0

As seen in Table J-4 the effects of the deck and firing line doubled in weight are still small, a change of 6 centimetres in vertical direction.

Stability with the units in the hold

For the ship with the units in the hold mainly the effect that the units have on the VCG is of interest. This shows how much weight can be added on the deck of the ship by placing the units in the hold. The other two directions are less interesting as they can be adjusted by moving the units to a different location in the hold.

In this case calculations are done with the same lightship as before, meaning that the firing line is assumed to still be placed on deck. This results in rather conservative estimations with regards to the lowering CoG and maximum additional load that can be placed on the deck. The weights and VCG's that are used in the calculations can be found in Table J-5.

Table J-5 Weight and CoG of ship and units

	VCG [m]	Weight [t]
Ship	13.06	15168.7
High units	5.25	54.5
Medium and low units	4.66	77.5

The placement of the units in the hold of the ship leads to a new VCG of 12.98 m, a change of 7 centimetres. This seems like a small change but it does allow for placement of additional weight on the deck without affecting the CoG. The additional weights that can be placed on the deck at different height can be found in Table J-6.

Table J-6 Allowable additional load at different height above main deck

Location of additional load above keel [m]	Allowable additional load [t]
16.02 (main deck level)	362.9
17.02	271.4
18.02	216.7
19.02	180.4
20.02	154.5
21.02	135.1

Appendix K Considered design options

This appendix lists the considered design options per element. It is merely a summation of the considered options, the consideration for which option to use is either discussed in chapter 9.0 or is evident.

Threshold

- Do nothing to the threshold, increase the length of the container hatch to provide access
- Cover the side and part of the centre to decrease the required number of units
- Close of the side of the threshold

Unit shape

- Portal shape
- Prefab, consisting of three loose plates
- Based on the marine system where units are inserted in premade holes in the ship

Unit length

- The units fit exactly over the threshold
- The maximum length of 6.1 meters is used to maximise the available covered space
- Use different length on the units

Unit height

- Make each unit the same maximum height
- Keep the units low, swap out the relevant units for higher ones when required
- Design a system that is similar to the one that is in use now where the roof is raised by a hatch is necessary
- Use different heights to allow for weight saving and potential placement of the tensioner

Removing tensioner 4

- Remove the relevant units completely
- Build the relevant units as prefab, that way the roof can be removed completely to allow for the installation of the tensioner
- Build part of the firing line based on a telescopic concept

Installing inline structures

- Any of the options suggested above for the installation of the fourth tensioner
- Build a small hatch in the roof of the relevant units

Unit to unit interface

- Rubber strips
- H and T shaped profiles
- Placement of watertight covers across the connection

Other ideas for the use of the *Lorelay*

The following ideas have been suggested during the course of the project. Many of these ideas have been discarded very early and others seem relatively random. However, some of the ideas also hold merit and can be combined with the modular vessel concept.

- Drill ship
- Deep sea mining vessel
- Arctic cruises
- Windmill installation vessel
- Leave the ship on a beach somewhere
- Transport specialised cargo such as animals
- Multi-purpose pipe laying vessel specialised in remote field

Appendix L Lifting of a unit in the hold

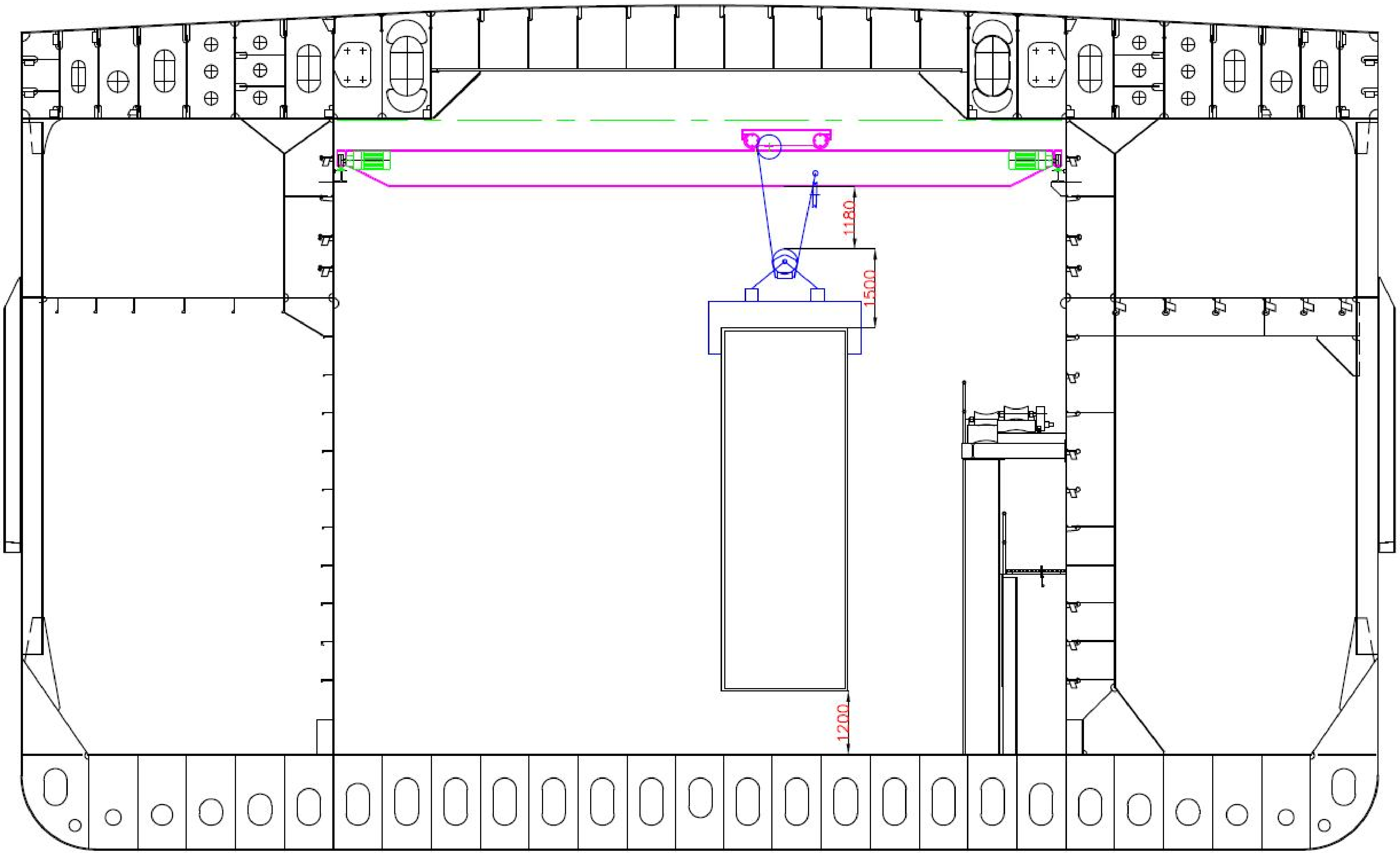


Figure L-1 Cross sectional view of a unit (6.9 m high) being lifted in the hold of the ship