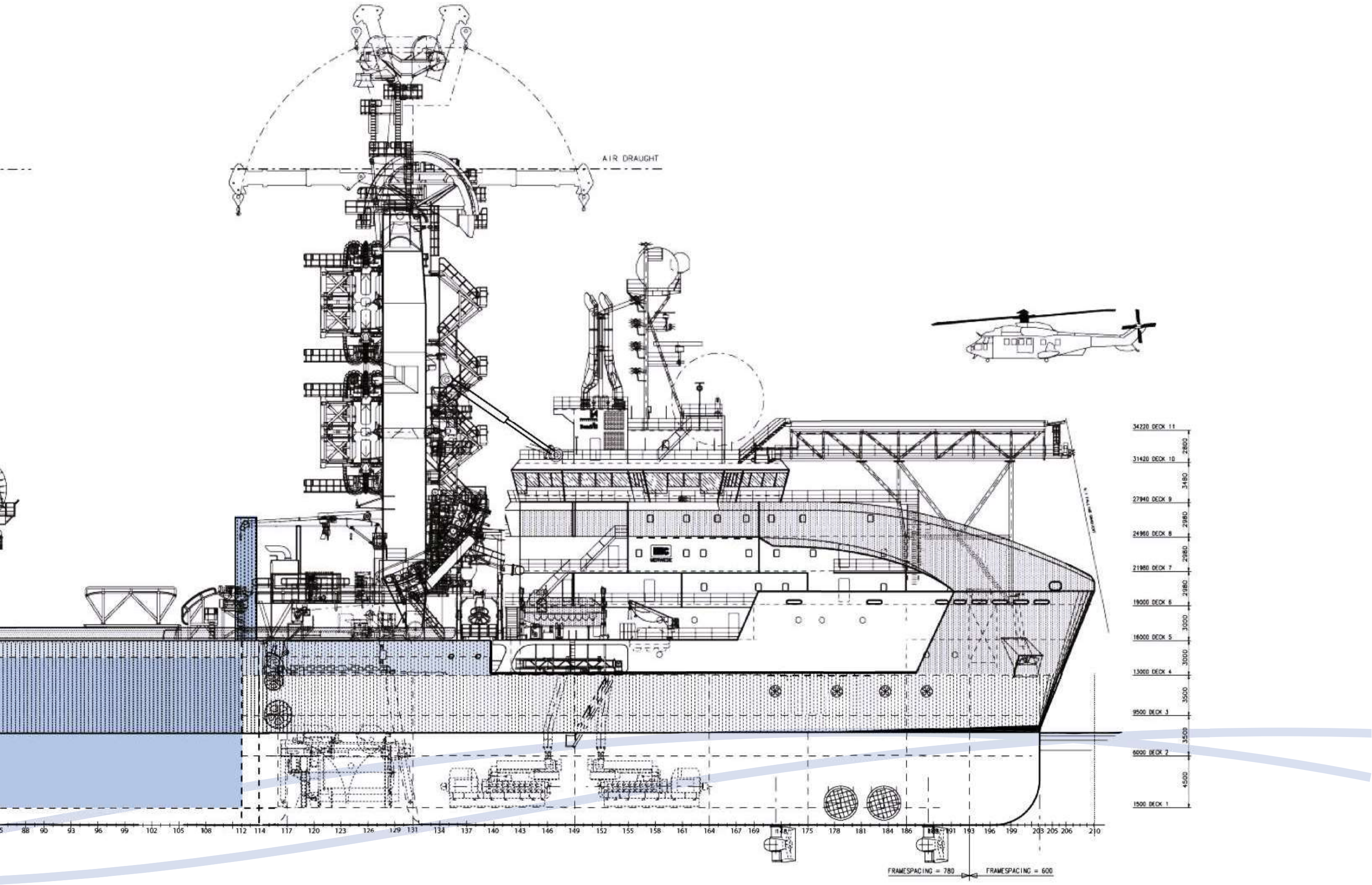
SUPPLYING A FLEXLAY VESSEL AT SEA



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TUDelft Marine Technology
Ship Design, Production and Operation

Performed in cooperation with Royal IHC

Thesis for the degree of MSc in Marine Technology in the specialization of *Ship Design, Production and Operation*

SUPPLYING A FLEXLAY VESSEL AT SEA

By

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Performed at

Royal IHC

This thesis (17.024) is classified as confidential in accordance with the general conditions for projects performed by the TU Delft.

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SUMMARY

This thesis investigated the possibility of alternative ways to loading and offloading flexlay vessels and provides a concept design. This was investigated because currently, the vessels designed by IHC, have to sail back to port to restock on pipes. During this time the expensive pipelayer is not laying pipes and thus not making money for its operator. Some operators have already moved to designs which use cranes to load pipes at sea. However, lifting heavy objects results in limited operability and wide vessels. The problem owner (IHC) wants to avoid this. The goal was to find a way to transship pipes offshore, which improves on the current performance of the reference vessel without resorting to cranes to transfer the pipes.

The research was mainly focused on the modelling of the logistical process of getting pipes from the port to the location. The results of this were used for the conceptual design of a flexlay vessel capable of being supplied at sea. The reference vessel built by the problem owner turned out to be a suitable candidate for adaptation for this purpose. To reach this conclusion, a logistical model was made, which was used as a basis for parametric studies. As input to that studies, a seastate timeseries is generated together with different transshipment methods. Two sets of simulations were used to evaluate the effect of the transshipment method in relation to a range of operational limits, and the effect of the distance on the operation.

The simulation sets vary the distance between 0 and 5000km to gain insight in projects that happen close to a spoolbase, and those that happen on other continents as is common. The assumed seastate limit for different transshipment activities were varied between 0m and 5m. Three methods of transshipment were simulated and defined in terms of transshipment capacity, speed and duration per move between supplier and pipelayer:

1. Transferring individual pipes by spooling.
2. Docking barges to transfer carrousels with pipes
    a. Using two smaller barges with 2000t pipes
    b. Using one large barge with 4000t pipes
3. Craning reels with 500t pipes onto the deck (for reference)

To improve on the performance of the reference vessel two boundary conditions are identified. In a logistical set-up where the pipelayer is supplied at sea there exists a minimum distance at which it outperforms the reference vessel. In addition, transhipping needs to be possible in seastates with a significant wave height of at least 1.75m. Based on the results of the methods, docking is the most likely to succeed and spooling is the least likely. In addition, the docking allows the laying of pipes while being loaded, which greatly improves the overall effectiveness of supply. A financial estimation shows that this vessel may lead up to profits of up to $100,277 per day. This result is dependent on the vessels' used capacity as well as the region of the pipelaying projects.

The resulting pipelayer is fitted with two mailbox type docks in the side, this elongates the vessel and decreases its initial draught. These docks are closed and drained afterwards in order to secure the barge. When the docks open the pipelayers' GM drops from 4.88m to 3.84m. This state requires filling all the ballast tanks which is also needed to acquire the minimum draught for loading in the barges.

The main conclusion is that it is possible to redesign the original pipelayer to accommodate the transshipment of pipes offshore, but some connotations need to be made to this research. The strength of the vessel, after replacing a large part of the portside hull with doors, has not been investigated. This includes the strength of the doors themselves. A detailed financial study can provide more insight in the minimum distance at which the concept solution becomes feasible depending on the region the vessel is operating in. Finally, model testing will be required to accurately determine the docking seastate limits as this is not determinable with software.

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Before diving into the contents, I would like to thank all the people who supported me during the long process of my thesis, so that I am finally able to complete this document, find peace of mind and ultimately start the next phase of my life. Below I would like to highlight a few people, as this thesis is as much build on their support and guidance, as it is on the knowledge gained from the curriculum. They were patient enough to teach me new skills and have helped me through the hardships faced over the last few years.

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TABLE OF CONTENTS

1 INTRODUCTION

Subsea piping is used to transport oil, from the wellhead at the seabed to Floating Production Storage and Offloading units (FPSO's) on the surface for processing. From there it is transported back to shore by tankers or a large pipeline. Pipes can be either rigid steel pipes or composite flexible pipes and are produced on land. The rigid pipes come in sections of 12-48 meters and the composite piping in lengths of 200-1000m. The distance between the wellheads and FPSO is in the order of several kilometres [1] [2] [3]. Both flexible and rigid pipes are laid by dedicated pipelay vessels, designed specifically for this purpose. Rigid pipe is generally supplied at sea, while flexible pipe requires the pipelay vessel to travel back to port to restock.

This thesis investigates the possibility of alternative ways to loading and offloading pipelay vessels for flexible piping. These ships are called flexlay vessels. The problem owner (IHC) wants to investigate various methods of resupplying the flexlay vessel at sea without resorting to cranes. Some existing flexlay vessels use cranes which come with limitations to workability and require very wide, stable vessels. Therefore, other means of transshipment are investigated. This includes looking at the boundary conditions at which transshipment at sea is still possible, while still providing an improvement over the current situation.

To save costs for an operator, it is important to improve their supply operations and decrease the downtime during which the flexlay vessel is not laying pipes. Thus, the goal is to improve the supply logistics of the pipes for the flexlay vessels in order to maximize the time for laying pipes.

1.1 PROBLEM DEFINITION

Two logistical chains are identified for pipelayers:

1. Pipelay vessels sail back to the spoolbase from the offshore location to restock pipes.
2. Pipelay vessels stay on the offshore site and are resupplied at sea by other means, without sailing back themselves.

The most common logistical chain has the flexlay vessel return to port itself. The other is rare due to the technical challenges which transferring heavy loads at open sea brings with it. The two logistic chains are illustrated on the map in Figure 1.1. Usage of supply vessels allows for the continuous presence of a flexlay vessel at the offshore location. This can improve the level of performance of the flexlay vessel depending on the distance to port, the transshipment method, and their workability.

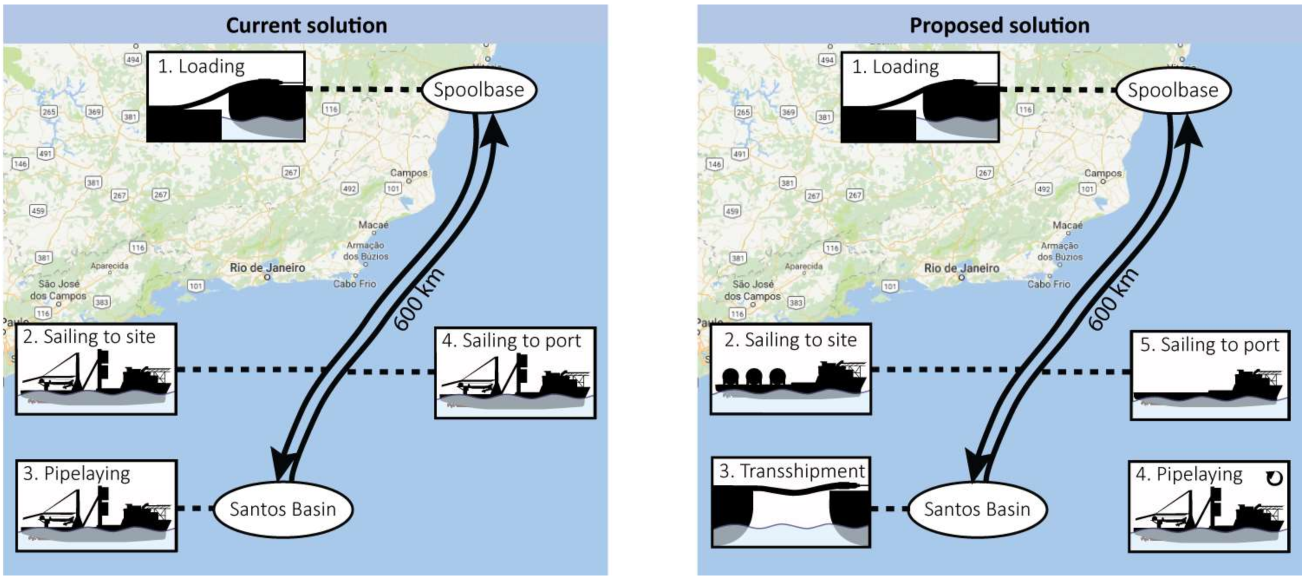


Figure 1.1. Possible logistic chains of flexlay vessels. The example is based on the Santos Basin field development by Petrobras. The left is the current way of operating flexlay vessels, the right is the proposed solution that is being examined in this thesis.

1.2 RESEARCH OBJECTIVE

During this research the effectiveness of the flexlay vessel, defined as the length of pipe laid by the vessel per year, needs to be increased. Laying the pipes is the main function of the vessel and the most important source of income for the owner.

The influencing factors of the effectiveness need to be understood. These are the sailing distance and the workability limits of the transshipment at sea.

1.3 RESEARCH QUESTIONS

The main goal of this research is to find a way to improve the effectiveness of pipelay operations for flexlay vessels. This results in the following main research question: “What is a possible redesign of supply operations and the flexlay vessel which uses supply vessels to improve the effectiveness of the pipelay operation?”.

To answer this question, two sub-questions need to be answered. The first aims at understanding the relation between the number of supply vessels and the sailing distance. The second focusses on the workability of the transshipment activities.

These two sub-questions will be answered by means of simulations in a MATLAB-model of the logistical flexlay process followed by a case study which translates the simulation results into a concept design. The answers feed into a case study which leads to the answer to the main question. This relation is visualized in Figure 1.2.

1.3.1 SUB-QUESTION 1

What are the effects of distance and number of supply vessels on the effectiveness?

The supply operations take up the most time in the pipelaying logistics process. The time required for a single roundtrip increases with increasing distance between port and offshore site. With increasing transit time, more supply vessels are needed to keep the pipelay vessel fully supplied and working continuously. It is desirable to understand this relation between distance and the number of supply vessels on the pipelayers’ effectiveness.

1.3.2 SUB-QUESTION 2

What are the effects of loading method and seastate limits on the effectiveness?

There are several ways the logistical process can be designed in which the pipelayer can be loaded and offloaded at sea. The different methods of transshipment will have their own throughput and will have different workability characteristics. Some of these methods may also allow uninterrupted pipelaying activities during transshipment.

Due to the long nature of the transshipment and pipelaying activities, a statistical approach to workability based on scatter diagrams will overestimate the performance of the vessels [4]. The weather conditions need to be evaluated in a time series simulation and not statistically. A suitable seastate model is required to simulate this.

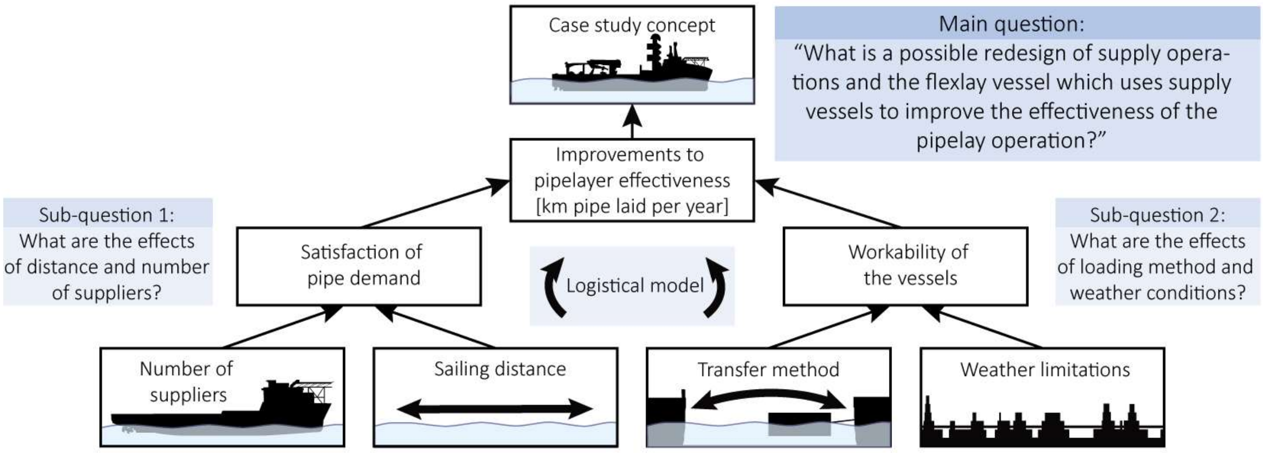


Figure 1.2. Visual representation of the relation between the main research question, the subquestion and the most important parameters. The sailing distance and weatherlimitations are to be counteracted by the suppliers and transfer respectively.

1.4 LOGISTICS TERMINOLOGY

Because the thesis is focussed on pipelaying activities, projects, logistics, and operations a convention needs to be set up for readability. Background information on terminology, pipelay vessels, projects, and flexible piping is included in Appendix A and Appendix B.

Within the pipelaying logistics five distinct supply and pipelaying activities can be defined which were illustrated earlier in Figure 1.1.

1. Loading and offloading in port
2. Transit to the offshore site
3. Transshipment of material
4. Pipelaying activities
5. Transit back to the spoolbase (i.e. the port)

The chosen convention on how to refer to these is shown in Figure 1.3 and will be further explained below.

Pipelay projects

Pipelaying project is stated to be the highest level in the hierarchy. It covers the operations that occur in time and deal with both the supply and installation of pipes needed to complete a certain construction job from beginning to end.

Pipe supply logistics

These are the logistics for supplying the pipe to the offshore location. They cover sailing to port, loading a vessel at port, sailing back to the offshore site and transhipping material between a potential supply vessel and a pipelaying vessel.

Pipelay operation

The operation and activities of laying the pipe at the offshore location. They cover loading the pipe into the pipelay tower, installing appendages, laying the pipes on the seabed, possible abandonment mid-project due to bad weather, and similar activities.

1.5 REPORT STRUCTURE

The research question will be answered in Chapter 7 but a couple of topics need to be tackled before that. First some background information is required to understand pipelaying projects. After this there is a need to understand the range of possible design solutions that are input for the logistical model. And finally, a weather model is needed to simulate the persistence of seastates as this phenomenon affects the effectiveness of long-during activities, before heading into simulations and design.

Chapter 2 will provide background information with relation to pipelaying logistics for the reference flexlay vessels, the location of the projects and spoolbases, the weather at those locations. This information will be used as the basis for the logistical model.

Chapter 3 will discuss the principle solution concepts that are under evaluation. It will eliminate some infeasible concepts, and keep the feasible concepts for logistical analysis.

Chapter 4 will explain the logistical model. It will cover its structure and provides an example simulation to illustrate its workings. This model is used for the simulations.

Chapter 5 will contain input to the logistical model. The variables and constants used in the simulation

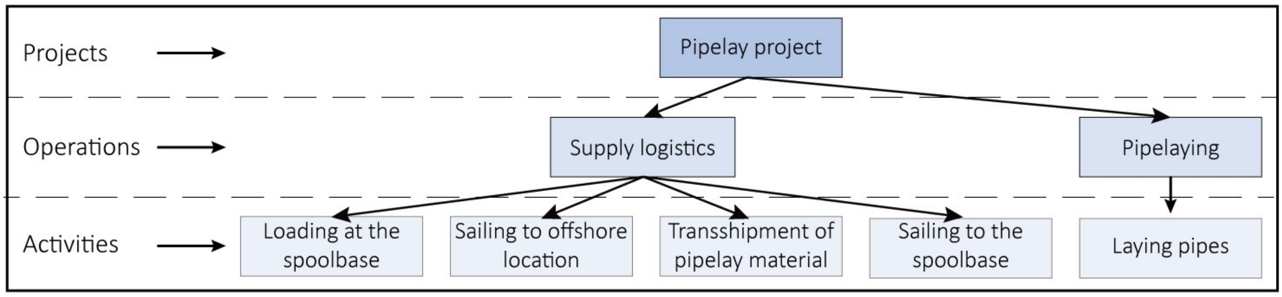


Figure 1.3. Pipelay logistics terminology for consistent use in this report to prevent confusion.

sets will be discussed together with the properties of the transshipment methods. Finally, it discusses the seastate persistence model used to generate a timeseries.

Chapter 6 will contain the results of the logistical simulations. This provides an answer to the first and second sub-question. This chapter aims to provide insight in the effectivity of the possible principle design solutions. Following these two simulation the best performing principle concept solutions will be selected. This concept vessel will be once more simulated to gain its performance under different conditions such as sailing distance and with different number of suppliers. This section will include a short financial study related to the dayrate of the reference and concept vessels.

Chapter 7 will describe the vessel design concept. This includes the design for a new object to transport the pipes with, and the corresponding pipelayer. A weight, stability, and resistance calculation will be made. This essentially answers the main question and concludes the thesis.

Finally, Chapter 8 contains the conclusions and the recommendations for future research.

About Royal IHC

Royal IHC is a shipyard with its own design and research department. The company consists of approximately 3000 employees who are located mainly in the Netherlands. It focusses on the oil and gas industry with pipelayers and offshore supply vessels, and on the dredging industry with a large variety of different custom and standard vessels.

The shipyard is also involved in production and development of mining equipment and equipment for the deployment and maintenance of windfarms. As common with many larger shipyards, it also provides service and repairs for vessels that have been built by IHC and other yards.

This research has been performed at the main office in Kinderdijk in the design and cost estimation department. This department is active in the procurement phase of contracts. The research was performed within the offshore support vessel group

2 REFERENCE PROJECTS AND VESSEL LOGISTICS

This chapter introduces background information on pipelay projects in and the conditions in which these take place. The first section looks at the reference vessel. This provides information on the use of the vessel that is subject to improvement. The second section describes the logistics and ballpark figures for the reference vessel in projects for Petrobras. They are the client for the 16-year long contract these vessels were commissioned for. The third section looks at the spoolbase and offshore locations. This will give insight in possible distances that have to be traversed and the weather at those locations. The information in this section is used to set up the logistical model.

2.1 REFERENCE VESSEL DESIGN

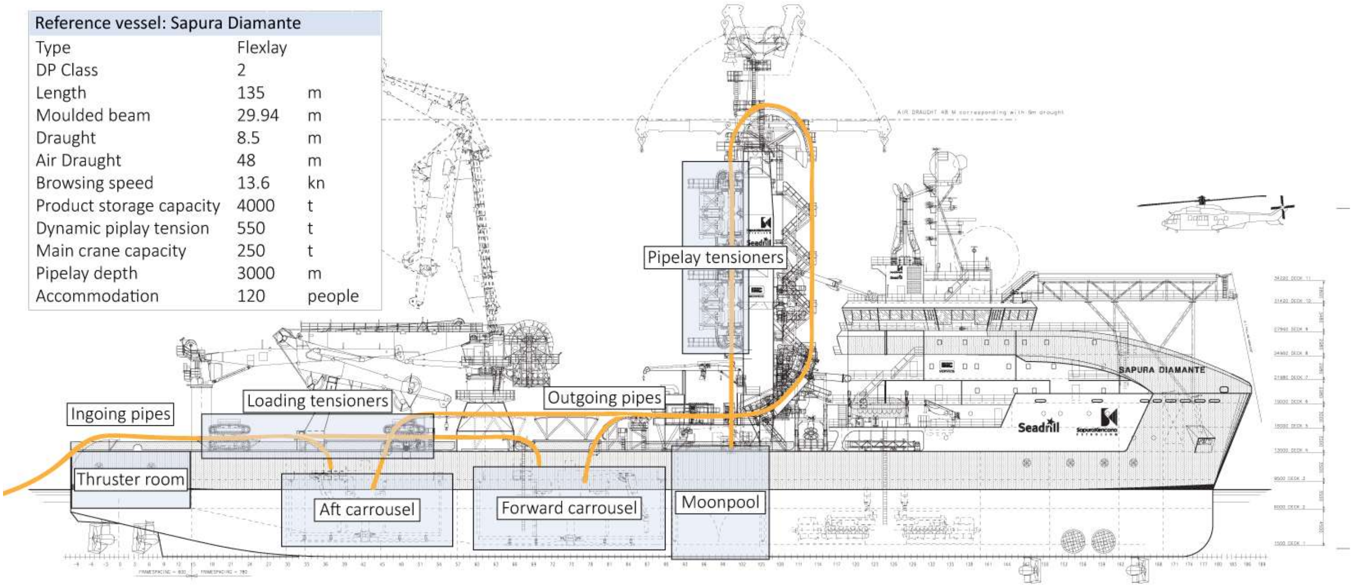
IHC has built a number of similar flexlay vessels for Sapura and Subsea7 shown in Figure 2.1. The vessels have two main carrousels belowdecks in the aft of the vessel. These carrousels are where the pipes are generally stored. The capacity of these carrousels is 2500t and 1500t respectively. The smaller is located in the aft of the vessel where its beam is getting smaller and is positioned a bit higher. The vessel is loaded by having the flexibles pipes dragged into the carrousels from the aft of the vessel. This is done with so called loading tensioners located on the deck.

The moonpool and tower are located above the centre of gravity in the middle of the vessel. This is preferred due to ship motions. This is not critical however and towers are often placed at the side of the vessel or the rear as well.

To get the pipe from the carrousels into the tower a hatch is opened in de main deck and the pipe is lifted out from the carrousel with the large knuckle boom crane. From there it is led up the pipelay tower along the side of the deck house, loops over it towards the stern of the vessel. It is then pulled down into two pipelay tensioners located in the tower. From there the pipe travels down vertically through the moonpool during pipelay operations. Note that because of the length of the pipe, most of it will still be resting in the carrousel. The carrousel is rotated by traction engines to rotate it along when the pipe is lowered through the tower.

Three thrusters located in the aft vessel deliver the vessels' dynamic position capability (DP2) together with two retractable thrusters and two bow thrusters in the bow.

During pipelaying activities, the deck is used for the storage of subsea equipment and mission containers. Depending on the project, the deck can be loaded with reels with piping instead of loading the pipe into the carrousel.



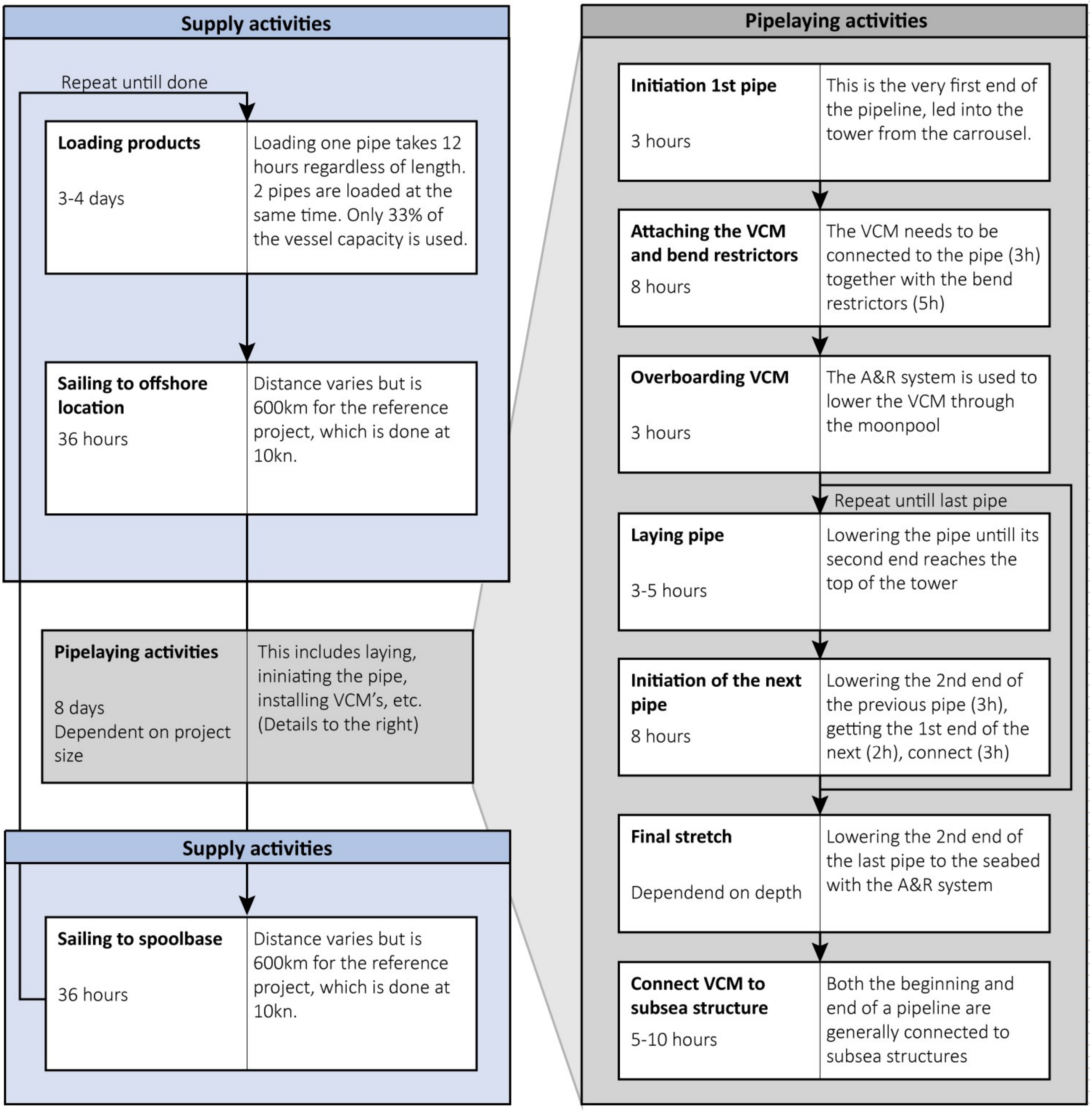
Reference vessel: Sapura Diamante		
Type	Flexlay	
DP Class	2	
Length	135	m
Moulded beam	29.94	m
Draught	8.5	m
Air Draught	48	m
Browsing speed	13.6	kn
Product storage capacity	4000	t
Dynamic piplay tension	550	t
Main crane capacity	250	t
Pipelay depth	3000	m
Accommodation	120	people

Figure 2.1. Reference vessel (IHC PLSV Type 550-30) [34]. This vessel is the baseline with which the alternate solutions will be compared.

2.2 REFERENCE VESSEL LOGISTICS

Pipelaying logistics can be split up into supply and pipelaying operations. The pipelaying operations are the main mission of the pipelay vessel and the speed with which this done is mostly dependent on the performance of the mechanical installation on board the vessel. The pipe supply operations make sure that the material arrives on the offshore site. The time required for this is related to the distance from the port to the locations where pipelay operations take place.

Statistics on any of the operations are not openly available. Instead, rough estimations based on the Brazilian field developments were provided by Sapura Navegacao [1]. The estimations are shown in Figure 2.2 as part of a 'standard' pipelay project. To match the activities from section 1.4 the left side of the figure is split into the four regular activities. The blue fields represent the supply operations, the grey fields the pipelaying operation and activities. This interpretation of pipelaying projects will be used in chapter 4 to set up the logistical model. The numbers in the figure are verified with various



Loading one pipe takes 12 hours regardless of length. 2 pipes are loaded at the same time. Only 33% of the vessel capacity is used.

Distance varies but is 600km for the reference project, which is done at 10kn.

This includes laying, ininiating the pipe, installing VCM's, etc. (Details to the right)

Distance varies but is 600km for the reference project, which is done at 10kn.

This is the very first end of the pipeline, led into the tower from the carrousel.

The VCM needs to be connected to the pipe (3h) together with the bend restrictors (5h)

The A&R system is used to lower the VCM through the moonpool

Lowering the pipe untill its second end reaches the top of the tower

Lowering the 2nd end of the previous pipe (3h), getting the 1st end of the next (2h), connect (3h)

Lowering the 2nd end of the last pipe to the seabed with the A&R system

Both the beginning and end of a pipeline are generally connected to subsea structures

Figure 2.2. Estimated time spend on different operations for which the current flexlay vessels are used. The laying procedures aren't subject to change during this thesis, so the figures on the right can be used to model the need of pipe for the flexlay vessel.

simple calculations that can be found in Appendix C. An explanation on the numbers is given below for the loading and laying activities and the seastate requirements.

Loading pipe

One pipe takes about 12 hours to load by spooling it from the shore onto the vessel. This time is not dependent on the length or diameter of the pipe but consists mostly of time spent on preparations and handling the pipe. Because the length and diameter of pipes do influence the amount that fit into the carrousel, the total loading would in real life be influenced indirectly. The time required for loading per pipe is halved in port as two pipes can be loaded in parallel. One to each of the carrousels.

Laying pipe

A 1000m pipeline will move through the tower in 3-5h at 200-300m/h. Supporting activities include: lifting pipe from the carrousel and through the tower, adding bend restrictors when necessary, and adding vertical connection modules (VCM's). These may happen all together and can add up more than 10h. This means the supporting operations have to be taken into account when simulating the pipelayer later.

Project size and water depth

In Petrobras field developments, a project is defined by all activities a pipelay vessel does between port visits [1]. This is not limited to pipelaying projects. However, since the pipelayer is no longer leaving the offshore location, and only used for pipelaying projects, a project is redefined to be a certain length of pipes to be laid, based on the average project size in their field development projects [5]. The average Brazilian project (as found in Appendix C) consists of 4.8km pipe which is laid at depths between 1500 and 3000m.

Operating requirements

Petrobras defines the operating conditions in which the pipelaying vessels have to be able to operate in Brazilian projects. These requirements specify that the pipelay vessels have to be able lay pipe up to 4.5m significant wave height, and that abandonment of the entire operation should only happen when the significant wave height is higher than 7m. For now, it will be assumed that in between these two limits the pipe is still connected to the vessel, but the actual laying is postponed. When the storm has passed pipelaying can continue directly without recovery procedures.

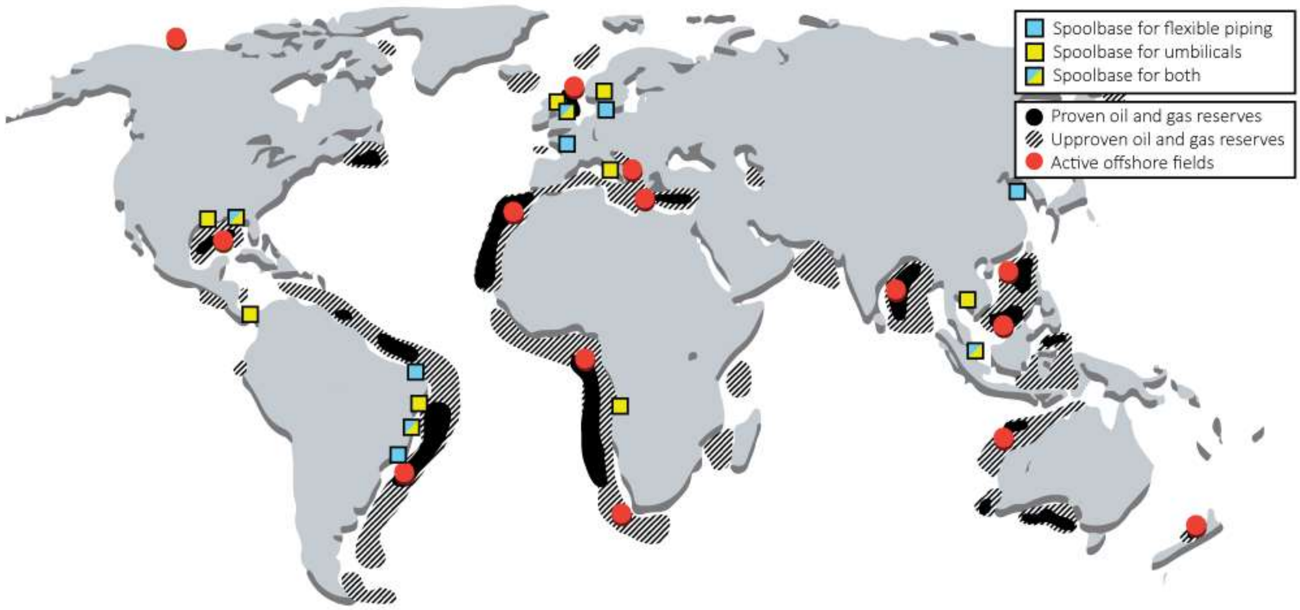


Figure 2.3. Major offshore, pipe, and umbilical production sites and oil reserve locations. This shows that some offshore fields are located remote from spoolbases for flexible piping and umbilicals. (Sources: [18], [32], [33])

2.3 REFERENCE PROJECT LOCATIONS

Flexible piping is used in various field development projects with their own weather characteristics. These fields are developed at increasing distances from shore. As new fields are developed it may happen that the nearest spoolbases are at great distances away. This may result in transit times for example when the production of flexible piping is done in Scotland and transported from there to the western coast of Africa (Figure 2.3).

Weather conditions

The weather may have large influences on the workability. Brazil and the Gulf of Mexico are known for having gentle waters, whilst the North Sea and African regions are more unpredictable in nature and experience higher seastates. The differences between regions can be observed in Figure 2.4.

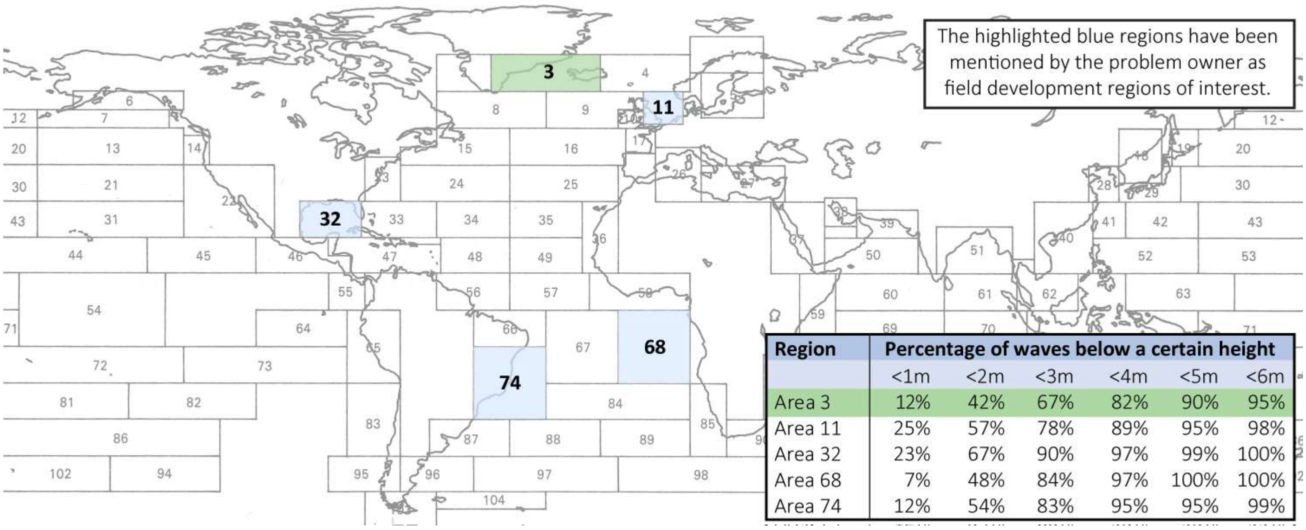
Due to the expected, significant, duration of pipelay and transshipment activities it is necessary to consider the persistency of seastates as done for other offshore operations [4]. Persistency in this case, is defined as the continuous duration during which a certain seastate persists. This information is lost in scatter diagram statistics where only the percentage of time a seastate occurs is recorded. Persistence data allows to find the number of occurrences during which there is a large enough weather window with favourable conditions.

Availability of data on weather

The regions of interest to an operator, and the problem owner are regions like Mexico, Brazil, Angola and the North Sea. For Petrobras project simulations from Brazil is desired. This data isn't available for free at the time of research. The only available time-series data of a large enough length is limited to the Icelanding region. The Icelandic region is harsh with waveheights up to 14m measured. This means that pipelaying performance will be underestimated. To make up for this later during the simulations, runs will be done without the weather considerations to get a range between 'realistic' and 'ideal' conditions. In reality, Brazilian weather is very forgiving and projects are rarely influenced by bad weather, whereas projects in the North Sea are often affected by weather [1] [6]. This is supported by the statistics in Figure 2.4 [7].

Availability of data on projects

The Brazilian subsea development projects consist mainly of flexible pipes and construction has been continous for years, providing good and stable data to validate simulations. The simulations will therefore be based on these projects. The advantage is that it is easier to compare a long duration of continuous pipelay operations with long simulations, where single trip projects are more difficult to simulate as they take place in a wide variety of circumstances.



The highlighted blue regions have been mentioned by the problem owner as field development regions of interest.

Region	Percentage of waves below a certain height					
	<1m	<2m	<3m	<4m	<5m	<6m
Area 3	12%	42%	67%	82%	90%	95%
Area 11	25%	57%	78%	89%	95%	98%
Area 32	23%	67%	90%	97%	99%	100%
Area 68	7%	48%	84%	97%	100%	100%
Area 74	12%	54%	83%	95%	95%	99%

Figure 2.4. Wave height statistics for five offshore locations. The blue regions are selected based on field development activity and for outspoken examples of weather conditions. The green area is the source of weather data available in this research [7]

3 PRINCIPLE SOLUTION CONCEPTS

The logistical model requires some input before simulation parameters can be determined. This chapter covers some proposed solution concepts leading up to the case study. In this chapter, solutions that are not feasible off the bat will be eliminated, and the solutions that are feasible for transshipment of material to the pipelay vessel are selected. Those solutions form the core of the logistical design problem that will be evaluated in the logistical model later.

3.1 MATRIX OF SOLUTION CONCEPTS

A principle solution chart is a method which splits a problem into smaller chunks that can then be analysed and solved individually. The resulting solution concepts can be mixed and matched to develop different final solutions. This method is applied to the design of the pipelayer and the logistics process. The solutions for the logistical design problem are shown in Figure 3.1. The top three rows (green) in the figure contain the supply operations. The last row (blue) contains different storage methods. These storage methods affect the amount of material that can be transferred per move and the design of the vessel.

Loading and transshipment methods will be identical to each other in the runs to reduce the complexity of the simulation. This means that a vessel is loaded in the same way on sea and in port.

3.2 ELIMINATION OF CONCEPTS

Not all of the principle solutions will be examined in the logistical simulations since a few solutions can be dismissed early on. This will reduce clutter in the amount of data coming from the simulation and simplify the programming of the logistical model. The affected principle solutions and the reasoning of their dismissal will be discussed below. The resulting morphological table with the remaining options is shown in Figure 3.2. The dismissed transshipment solutions will also be removed from the possible loading solutions.

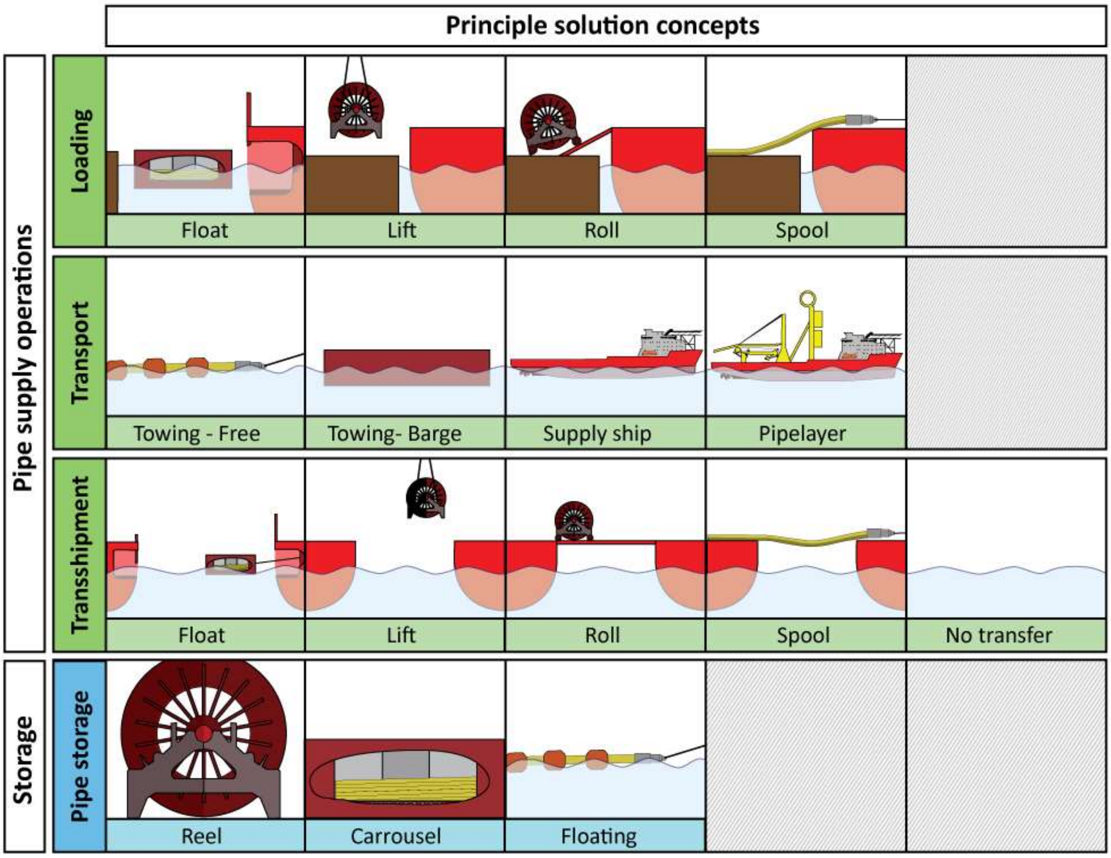


Figure 3.1. An overview of possible principle solution concepts for the redesign of the flexlay vessel.

Free floating

Free floating pipe is kept afloat with buoyancy modules above or below the water and towed to location by one or two tugs. Excessive motions in the flexible piping during transport may damage the pipes during harsh weather. In addition, loading the free-floating pipe onto the pipelay vessel will be a slow process where the buoyancy modules have to be disconnected regularly.

Barge

Transportation by towed barges may have financial advantages over transportation by ship, the main disadvantage being more sensitive to higher seastates and slower transit speeds than a ship. In the thesis costs are not included and the advantage of using a barge can't be quantified. Because this solution doesn't influence the eventual vessel design this option is not considered.

Roll

Self-driving reels need a ramp to drive from one vessel to the other. Independent vessel motions will disconnect the ramp and create gaps that are difficult to traverse. This operation will also require a lot of space on the pipelay vessel as self-driving reels have to pass by each other in the hold.

Lift

Lifting reels filled with pipe from on vessel to another by crane is done by some operators. This method however will not be used in the final design because of the large width required for stability. In addition, the operation can only be done up to a seastate of 1.5m which puts large limitations on the workability of the vessel. The method is, however, tried and tested and will therefore be included in the simulations to see how it compares to the other solutions.

3.3 SIMULATED LOADING CONCEPTS

The three methods: 'no transfer', 'spooling, and 'floating' will be compared against the existing solution for 'lifting' because it is undesirable to not understand the potential gains of this method that is not part of the targeted solutions, while at the same time it has been proven to be a feasible

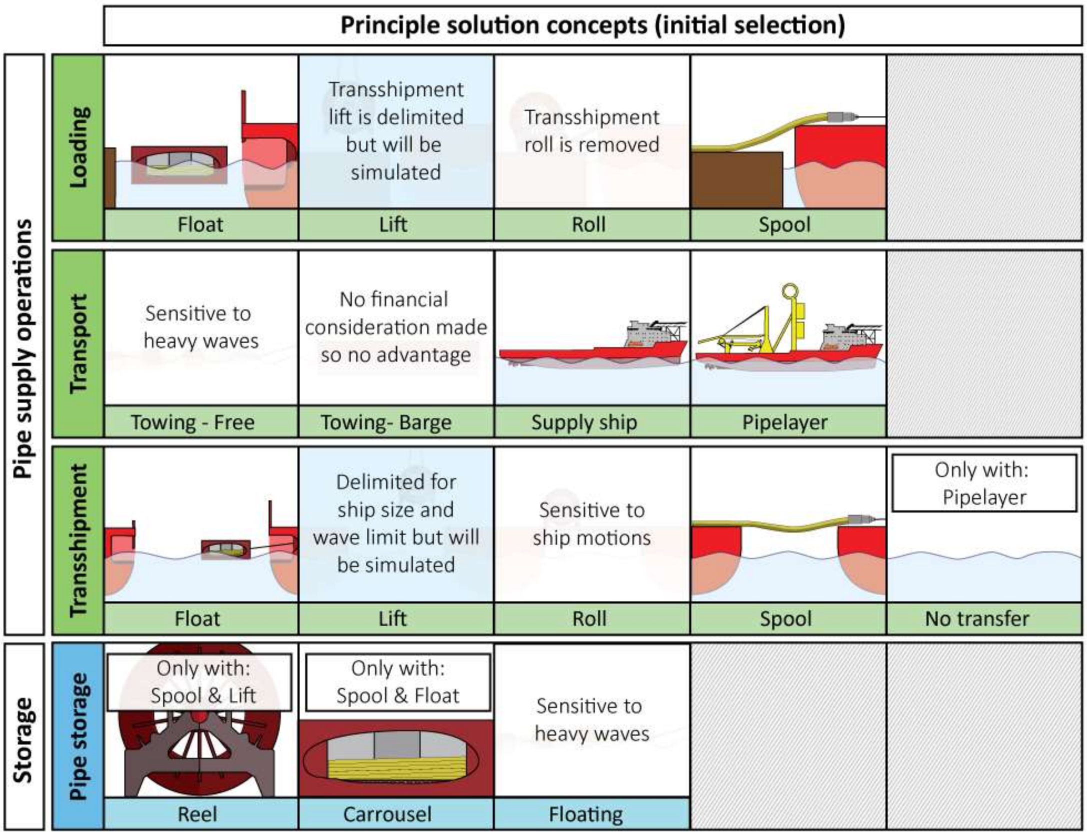


Figure 3.2. Initial elimination of principle solution concepts based on understanding gained during literature research. This reduces the number of solutions to be evaluated later.

concept. The first three will be discussed below, lifting has been discussed in the previous section.

No transfer

The expectation exists that the reference vessels' design (which requires it to sail back to port itself) may outperform the new concepts on closer distances to port. This could be either in a financial way since there is no need for a separate supply chain, as in the performance, since loading and unloading at sea might be slower than loading and offloading in port. This method is therefore examined as a reference line for the new concepts.

Spooling

This method is currently used in port to load the pipelay vessel. The same method could be used at sea as pipes are already handed over between pipelay vessels and FPSO's. This method could lead to various designs, but most importantly, might not require the reference vessel to change when it would be loaded from the stern.

Floating

Floating transhipment of material is regularly seen in semisubmersible heavy lift vessels, and is therefore considered a feasible option to simulate. The ships that use this way of transshipment of material often have a dock or deck that can be submerged onto which heavy material is loaded either at sea or in port. This way, large amounts of pipes can be stored in floating reels or carrousels and transferred in one single move.

3.4 STORAGE SOLUTIONS

The storage solutions will not be eliminated, but not all are feasible to combine with all of the loading and transfer solutions. Feasible combinations will be defined below.

Floating

There are concepts where the pipe is spooled into large circles and unwound during the pipelaying process [8]. This however requires tugs to stay with the material to provide the needed control of tension during all of the pipelaying activities.

The design requirements from Petrobras for the pipelaying operation state that abandonment is only required at a wave height of 7m. Pipes will be subject to large relative motions between any storage unit and the pipelaying vessel. Fixing a floating object to a vessel in these wave conditions to prevent damage to the pipe is not possible per educated guess.

Reel and carrousel

Heavy lifting is only possible with smaller reels containing a limited number of pipes. Floating transport can be done with either barges or reels. However, the depth a floating reel would be very large and the reel is expected to come with challenges to fixating it on the vessel. It will need to be fixated in a way that its rotation speed can be controlled. A horizontal carrousel can be much less deep. The barge it will be transported in provides extra buoyancy in addition to space for engines that can control the rotational speed. Summarizing, lift solutions can only work with reels and floating solutions are better with carrousel.

4 LOGISTICAL MODEL

This chapter will discuss the main structure of the logistics model, based on the Brazilian projects as visualized in Figure 4.1. A standard project has a size of 4.8 kilometre, consisting of six 800-meter pipes and is located at a distance of 600km from the spoolbase. The standard activities in these projects were defined in chapter 2. The pipelaying and transshipment operations are affected by the weather, how this is implemented will be discussed in chapter 5. The focus now will be to briefly discuss the way in which the logistical process is implemented in the model. A more detailed explanation with the flowcharts of the different sections can be found in Appendix E.

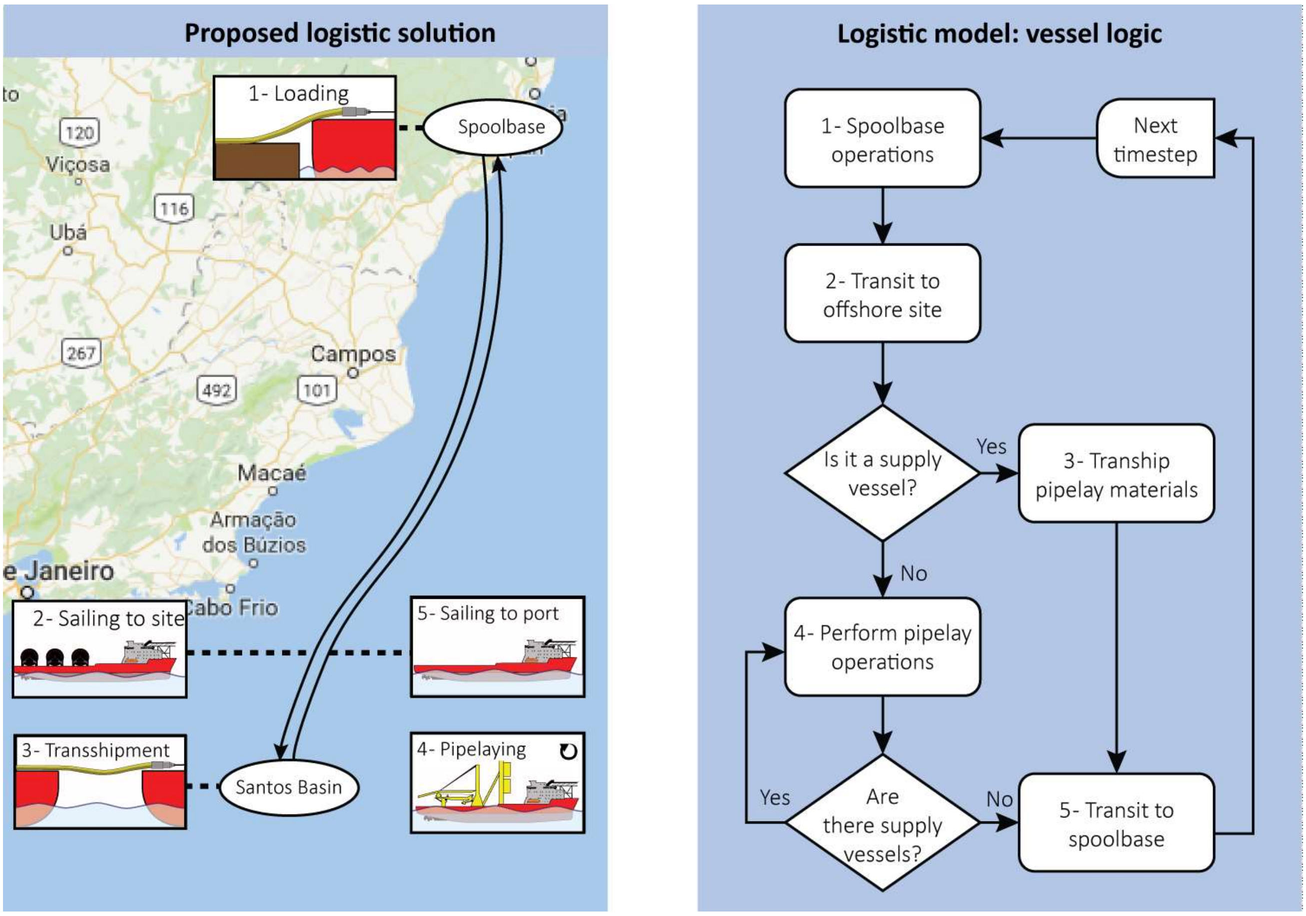


Figure 4.1. On the left pipelaying logistics are shown on the world map with some of the possible solutions for visualization. To the right a schematic version of the logistical model is shown.

4.1 GENERAL ARCHITECTURE

The model starts with loading the standard settings for the projects and vessels and overwriting any internal data left over from the previous simulation, then a function is run which overwrites the standard parameters for every simulation in the parametric study. After this a seastate timeline is created and a simulation is started. The model that runs these simulations is divided into separate blocks of code that represent the different phases of the pipelaying logistics. The vessels are 'physically' passed around as data structures between these blocks and are stored within the variables of a certain block, and not globally. The code in a function block checks if there is a vessel present, what it is doing (e.g. waiting on weather), what it should be doing (e.g. laying pipes), and if there is time to do so. This is done while taking into account the duration of the following operation and the available weather window based on the limits for an activity.

As the simulation progresses, the model keeps track of how long a vessel has been performing certain activities, such as sailing or waiting on weather, aborting operations, and how much pipe it has laid.

4.2 MODELLING INDIVIDUAL ACTIVITIES

A short description will be given here for the separate numbered activities indicated in Figure 4.1. An example flow chart, for the transshipment of material, is shown in Figure 4.2. A more detailed description and flowcharts for every block are found in Appendix E.

1 – Loading/Spoolbase activities

Vessels arriving at the spoolbase will be assigned to one of two quays when they are available. At these quays the loading of material will be continuous, and the available material infinite. This excludes the spoolbase production capacity as bottleneck. When vessels arrive, they will load the material up to their capacity at the speed set for the transfer method.

The exclusion of spoolbase production capacity, and queuing, is done because there is limited knowledge about the capacity of the spoolbase and other production facilities in the region in addition to limited knowledge about the amount of pipelay vessels that have to use the same port to resupply. This results in overestimation of effectiveness.

2 & 5 -Transit back and forth

Transit will take place over a constant distance between the offshore site and the spoolbase throughout a simulation. Not taking the variance into account will have a negligible effect on the accuracy of the already simplified projects run in the simulation.

The speed at which fully loaded and unloaded vessels sail is identical based on the interview with the operator [1]. This makes the transits identical.

3 – Transshipment (dependent on seastate)

During the transshipment operation, pipelay material is moved in units of multiple pipes. The speed at which this is done and the number of pipes depend on the transshipment method. As with pipelaying activities, the code will check whether there is enough time to perform this operation based on the timeseries generated by the model in chapter 5.

In all cases, except for the spooling of pipe, the pipelay vessel needs to be unloaded as well, taking out the empty reels and barges. The code makes it possible to perform this operation while the vessel is laying pipes if there is more than one hold available. The effect of this feature will be evaluated in chapter 6 when running simulations.

In the reference projects by Petrobras, fuel, personnel and stores are loaded on the offshore site by tankers, helicopters and offshore supply vessels. This part is excluded from the simulation.

4 – Pipelaying (dependent on seastate)

The time required for this operation is dependent on the progress into a project. If it is the start of a

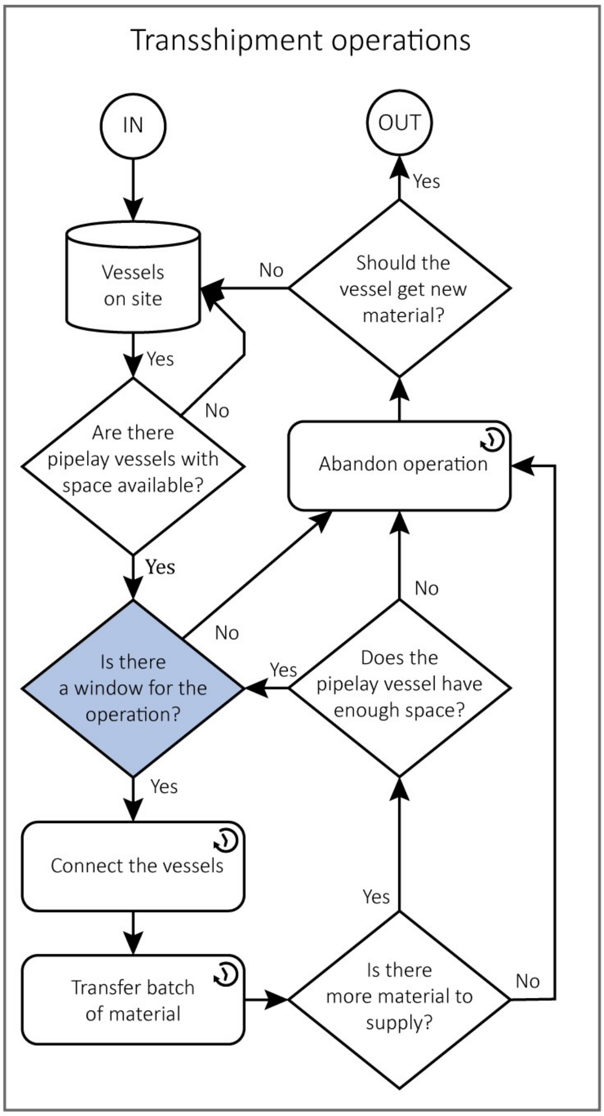


Figure 4.2. Example: flowchart of the transshipment code. This code uses the persistence timeseries to determine if an operation can be performed or needs to be abandoned.

project, it can only start when the first pipe can at least reach the seabed, before having to be abandoned. Otherwise it has to be completely retrieved and no progress could be made. At 3km depth this means that a large enough weather window is needed for the first 3-4 pipes. From that point on the weather windows for every pipe are checked separately. As with transshipment activities, the model will check whether there is enough time based on the timeseries

The mentioned abandonment of the pipe is also dependent on the water depth and the duration required to perform can take up to 12h, and another 12h to recover the pipe.

4.3 SIMULATION EXAMPLE RUN

Figure 4.3 shows the results of a single simulation without supply vessels. The lines represent the fraction of time a vessel has spent on a certain operation and will therefore stabilize as time progresses. The effect of seasons is also visible, where most delays due to bad weather are experienced in the autumn and winter seasons, and less in spring and summer, creating a jagged behaviour of the waiting on weather line.

The fraction of time spent on pipelaying shown in the graph stabilizes after 12,000h. The yellow working line includes all effective on-site activities, excludes waiting on weather, sailing and loading, and stabilizes after about 20,000h. However, the waiting on weather only stabilizes after 45,000h. The time set for individual simulation runs will therefore be set at 6 years to allow all statistics to stabilize and is scaled back later to an average yearly performance. This is common in the industry where workability simulations are run over at least 5 years and then scaled back [9].

Data arrays

The code may store the intermediate results per timestep in arrays. This allows an example of the interaction between a pipelay vessel and two suppliers to be provided in Figure 4.4. This data is based on an extract from the raw simulation data over the same timesteps for the three vessels. The seastate is added next to the time index to show the interaction with the seastate persistence model.

The pipelay vessel in the array starts at the offshore site and is waiting for the first supply of materials. During this time the two supply vessels are loading in port. When the supply vessels sail to and arrive at the offshore site a storm window is coming in 12h and thus the vessels have to wait with transshipment until it has passed. After it has passed transshipment commences but it has to be aborted halfway due to another incoming storm (the limit for transshipment is here arbitrarily 4m). However, it isn't bad enough for laying pipe (the limit for pipelaying is set at 4.5m) so the pipelay vessel will start laying the already transhipped pipes until it has to stop or runs out of material.

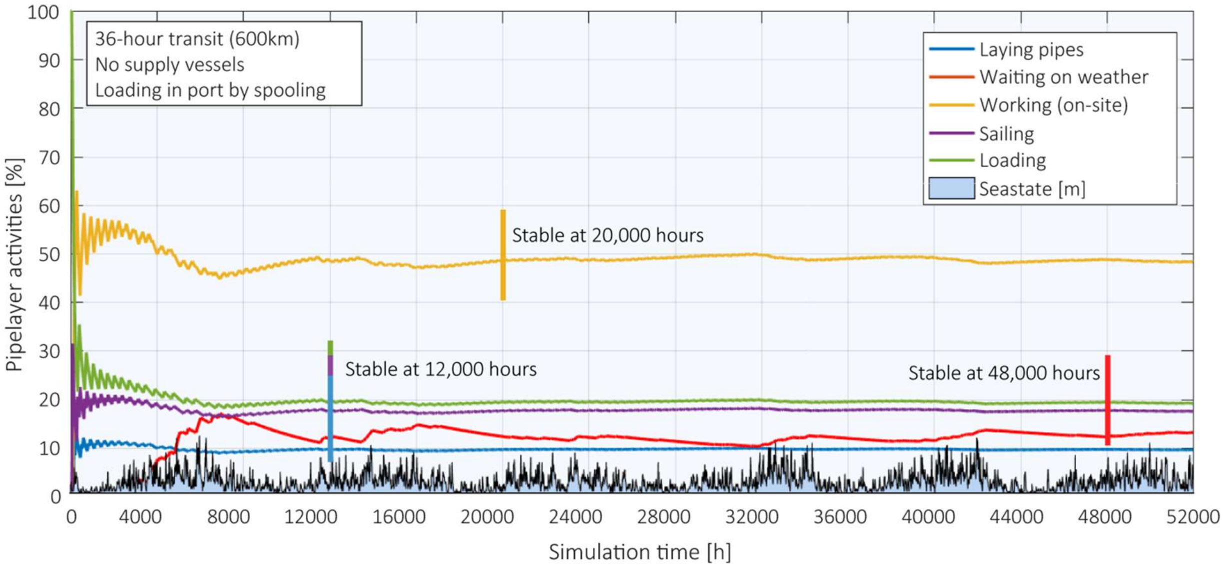


Figure 4.3. Operability results from the initial simulation. The data are averages over time and will stabilize at different moments in time. This result shows that 6 years of simulation start producing a stable average value.

In the example the pipelayer starts without material on-site and both supply vessels start loading at the same time in port. The suppliers arrive at the same time at the offshore site which results in one of them not able to deliver pipes. Saturation effects like these will always occur when the supply capacity is larger than the speed of laying pipes.

4.4 CHAPTER CONCLUSION

A model is created based on the pipelay logistics that were defined in the introduction, and the pipelay activities of the operator defined in the second chapter. It uses a wave height timeline created by the seastate persistence simulation in the fifth chapter to determine if a weather window is suitable to perform required transshipment and pipelaying activities.

The logistical model will be used in chapter 6 for the simulation to get a better understanding of the effect of supply vessels on the effectiveness of the pipelay vessel. The results are used to decide which principle solution concepts will be used for the concept design in chapter 7.

Time	Hs	Supply vessel 1	Supply vessel 2	Pipelayer	Pipe laid
1	5.00 m	'Loading'	'Loading'	'Waiting for material'	0 m
...	...	...	...		
72	4.75 m	'Done loading'	'Done loading'		
73	4.50 m	'Sailing to site'	'Sailing to site'		
...	...	...	...	...	...
105	2.50 m	'Sailing to site'	'Sailing to site'	'Waiting for material'	0 m
106	2.50 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Waiting for material'	0 m
107	2.50 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Waiting for material'	0 m
...	..	...	...	...	...
117	4.00 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Waiting for material'	0 m
118	4.50 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Waiting for material'	0 m
...	..	...	...	...	...
129	4.25 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Waiting for material'	0 m
130	3.75 m	'Connecting to Pipelayer'	'Queued at site (Waiting)'	'Loading'	0 m
131	3.75 m	'Connecting to Pipelayer'	'Queued at site (Waiting)'	'Loading'	0 m
132	3.75 m	'Connecting to Pipelayer'	'Queued at site (Waiting)'	'Loading'	0 m
133	3.50 m	'Connecting to Pipelayer'	'Queued at site (Waiting)'	'Loading'	0 m
134	3.50 m	'Transferring'	'Queued at site (Waiting)'	'Loading'	0 m
...	...	...	...	...	...
204	2.50 m	'Transferring'	'Queued at site (Waiting)'	'Loading'	0 m
205	3.00 m	'Transferring'	'Queued at site (Waiting)'	'Loading'	0 m
206	3.00 m	'Abandoning transhipment (weather)'	'Queued at site (Waiting)'	'Loading'	0 m
207	3.00 m	'Abandoning transhipment (weather)'	'Queued at site (Waiting)'	'Start initiation of pipe'	0 m
208	3.50 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Initiating pipe'	0 m
209	3.50 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Initiating pipe'	0 m
...	..	...	...	...	...
213	4.00 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Initiating pipe'	0 m
214	4.25 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Initiating pipe'	0 m
215	4.25 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Initiating pipe'	0 m
216	4.25 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Initiating pipe'	0 m
217	4.50 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Initiating pipe'	0 m
...	..	...	...	...	...
222	4.50 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Initiating pipe'	0 m
223	4.25 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Laying pipe'	300 m
224	4.25 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Laying pipe'	600 m
225	4.25 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Laying pipe'	900 m
226	4.00 m	'Waiting on Weather'	'Queued at site (Waiting)'	'Start initiation of pipe'	900 m
...	...	...	...	...	...
52560	4.00 m	Waiting on Weather'	Loading'	'Waiting for material'	2216000 m

▨	Transfer limit (4.0m) exceeded
■	Pipelaying limit (4.5m) exceeded

Figure 4.4. Simulation flow for a pipelay vessel and two suppliers. The simulation runs in 1-hour steps for 6 years. (Operations can't start when the remaining weather window is too small). The weather from the persistence model results in delayed supply operations.

5 LOGISTICAL SIMULATION INPUT

Two things are needed as an input to the logistical model, parameters that vary between runs that are related to the vessel logistics, and some form of weather data. The input parameters can be divided into variables, constants and transshipment methods. Some of these parameters relate directly to the research questions, others are indirectly related but impact the design later, such as the number of holds in the vessel, or how beneficial it is to be able to simultaneously lay pipes and transferring new material.

The weather data will be acquired with a seastate persistence model. This model makes it possible to take the persistence of seastates into account when making the analysis for the pipelaying and supply operations. Persistence accounts for the gradual change in seastate over time as storms and calms tend to last several hours. This allows taking into account the size and number of weather windows in which the pipelayer will be performing long operations at sea bound by strict seastate limitations as will be explained later.

5.1 VARIABLES

The variable parameters are divided over two sets of simulations, one for each sub question.

First simulation set (distance and suppliers)

The first sub- question: “What are the effects of distance and possible supply vessels on the effectiveness?” aims at understanding the relation between the distance and the offshore base, and the usage of supply vessels. The distance will be evaluated up to 5000km as some projects require the pipelayer to sail between the UK and Africa [6].

The number of supply vessels is varied between 0 and 3. Here 0 represents the pipelayer sailing back to port. These ranges showed the most valuable results during coding and exploratory runs. Further increasing the distance will only show that more supply vessels are necessary to keep the pipelayer functioning at full capacity.

Second simulation set (methods and limit)

The second sub- question: “What are the effects of loading method and seastate limits on the effectiveness?” aims at understanding the effects of the seastate at the location where pipes are laid, and the method of transshipment. The seastate limits on transshipment activities will be varied in order to examine the influence of the seastate. This allows to find the limits for transshipment such that the pipelay vessel is at least as effective as the reference vessel. To examine this, the limit is varied between 0m and 5m. This upper limit showed limited increase in gains during exploratory runs.

Seastates

As discussed earlier two weather scenarios will be used during the simulations runs, an ‘ideal’ and a ‘realistic’ scenario. The first simulation set will be run for both scenarios. The second simulation set looks at the seastate limits for transshipment and will be run for the realistic scenario.

Transshipment during pipelaying

If transshipment is possible during pipelaying downtime is reduced. However, this complicates both the pipelaying and transshipment. The simulation sets will be run both with and without simultaneous transshipment. This is done because when distance increases in the first simulation set, transshipment time becomes less significant. It also fits in the second set because this allows to use the weather windows that appear during pipelaying.

Capacity of the vessels

In Brazilian projects pipelayers are usually only sailing with 1/3rd of their holds filled for various logistical reasons. This suggests that the vessels may be overdesigned. However, the vessel capacity is strongly linked to the transshipment method and directly relates to the amount of moves during loading and transshipment so this parameter is evaluated as part of the method consideration. The capacity of both the pipelayer and supplier are kept identical to reduce the complexity of the results.

5.2 CONSTANTS

Constants are set to represent Brazilian projects. Short explanations for why these parameters are fixed will be given below.

Speed

The effect on the time spend in transit by doubling the distance has the same effect as halving the speed. Varying the speed does not provide enough new insights for now. A speed of 10kn will be used for all vessels. This value is based on the Brazilian design requirements.

Seastate limits

The pipelaying activities can only be performed in seastates with significant wave heights of up to 4.5m and have to be abandoned at 7m. These limits are fixed as no changes are made to the equipment. The limits for transshipment will be set to 4m for the first simulation set. This value is in the range where increasing it does not change the result.

Number of holds and capacity

The pipelay vessels and supply vessels need to be defined only by parameters that influence logistics which are their speed, performance and capacity related parameters. Length, beam, depth, displacement, and other geometric parameters that are used for the design are not included here. In this model specifically the performance of the various transshipment methods is evaluated.

The number of holds and the capacity of the pipelayers and suppliers kept constant in the first set. They are set to match the reference vessel and project: 2 holds, both filled for 33%.

All the tuneable parameters are loaded before the simulation starts and are constant during a single run. Some of these parameters may be constant throughout this thesis, but all of the possible tuneable parameters are listed in Table 5.1.

Project parameters

The field development is assumed to be infinite, but before and after a project, modules have to be connected to the pipe which allow it to connect to subsea structures, and the pipe has to be dropped to the seabed. At a depth of up to 3km this can take a significant amount of time, more than laying at 200m depth in shallow regions. This is an influential parameter to take into account when one would investigate pipelay projects in other regions.

5.2.1 METHODS OF TRANSSHIPMENT

The method of transshipment changes the capacity and speed at which a unit of pipes is transhipped. In some cases, all the material can be transferred in one go, and in others little bits of material are transferred after each other. Educated guesses are used to set the characteristics of a transfer method. The four principle solutions for transshipment selected in chapter 3 were:

1. Floating (carrousels)
2. Lifting (reels)
3. Spooling between vessel (pipes)
4. No transfer

The way in which these four are implemented in the model will be discussed per method below.

1. Floating (barge)

In this thesis it is assumed that a barge cannot be fixed to the vessel in rigid enough way where it can be used in all the required operating conditions. These require uninterrupted activities up to seastates of 4.5m. This assumption means that the barge needs to be loaded in a dock instead.

Table 5.1. Model parameters used to define the vessels, the project and the transshipment methods.

Project	**Vessel**	**Transshipment method**
Distance to port Project size Water depth Individual pipe length Number of supply vessels Number of pipelay vessels	Speed Number of holds Number of pipes per hold Seastate limit for pipelaying Seastate limit for abandonment	Number of pipes per transfer Time required per unit for transfer Time required per unit for loading Seastate limit for transfer

Based on interviews, submerging the vessel and pulling in the barge takes about 10h including preparation. This is regardless of the barge since most of the time is spent on preparations such as ballasting [10]. A barge will be unloaded in the same 10 hours for now.

This operation may transfer two carrousels in a single double-sized barge or use two smaller barges. The first would have all the material loaded in 20h, but the second option allows for loading a new barge while the vessel is still laying pipes from the barge in the other dock.

Slender frigates have been loaded into dockships with 1m clearance in 1.5m high waves. This leads to the educated guess that a flat barge could be loaded in seastates up to 2.5m wave height [10].

2. Lifting (reels)

The capacity of reels ranges from standard reels of 500t [11] to large reels of 1200 ton [12]. To scale this method equally with the others in the model, a multiple of 3 pipes per reel is required and standard reels are used to avoid very large heavy lifting installations. Three pipes are already 150% of the standard reel. The size impacts the number of moves required per supply operation, their duration and consequently pipelay performance. The time for this kind of transfers is estimated to take around 3-4h [1] [10] [6]. In this study, the upper 4h is assigned to loaded reels and 3h for empty reels. This operation may be executed in seastates of up to seastates of 1.5m. [12] [13].

3. Spooling (pipes)

In spooling pipes are unwound from the suppliers' carrousel or reel and guided into the carrousel of the pipelayer. This method is now only used to load pipelayers in ports and not out at sea. Therefore, the time required for this operation in port will be maintained. This is 12h for transferring a single pipe. Due to the expected difficulties with spooling pipes between two vessels and having to support them with a crane, only 1 pipe may be transferred at a time. Although this assumption makes this a slow process, the method doesn't require unloading. Based on pipe handover missions between FPSO's and supply vessels, an expected operational limit is set at 3.5m [14].

4. No transfer

This method represents the reference case where the pipelayer has to sail back to port itself. The way of loading the vessel still influences the pipelayer. To reflect the reference vessel, spooling is used.

5.3 OVERVIEW OF INPUT PARAMETERS

Table 5.2 contains the overview of the input parameters. The bold parameters are the ones directly related to, and mentioned in, the research questions. The other parameters are indirectly related to the logistics but have an effect on the design of the flexlay vessel.

Table 5.2. Simulation variables and constants. The four bold parameters are directly related to the research questions.

First simulation set: Distance and supply vessels			*(Section 5.2)*
Project distance varied	**Variable**	**0 - 5000**	**km**
Number of supply vessels	**Variable**	**0 - 3**	**vessels**
Hs limit for transfer	**Fixed**	**4**	**meter**
Transshipment method	**Fixed**	**Spooling**	
Number of holds	Fixed	2	holds
Capacity of holds	Fixed	12	pipes
Simultaneous transfer	Variable	No / Yes	
Second simulation set: Transfer limit and methods			*(Section 5.3)*
Project distance varied	**Fixed**	**600**	**km**
Number of supply vessels	**Fixed**	**2**	**vessels**
Hs limit for transfer	**Variable**	**0 - 5**	**meter**
Transshipment method	**Variable**	**Various**	
Number of holds	Variable	1 - 2	holds
Capacity of holds	Variable	6 - 24	pipes
Simultaneous transfer	Fixed	Yes	
Constants for both simulation sets			
Speed	Fixed	10 kn	knots
Hs Limit for pipelaying	Fixed	4.5	meter
Hs Limit for abandonment	Fixed	7	meter
Project size	Fixed	4800	meter
Project depth	Fixed	3000	meter
Pipe length	Fixed	800	meter
Number of pipelayers	Fixed	1	vessel

5.4 PERSISTENCY MODEL

A persistency-based model approach should be used when short storms and calms have a significant, negative, effect on the vessel's workability [4]. For example: a 3-hour storm in the weather forecast may cause a 10-hour operation to be postponed 9 hours in advance. This is visualized in Figure 5.1. The workability drops from 77% based on scatter data analysis to 58% for a persistence-based analysis over the observed 190-hour interval.

With approaching storms, two different scenarios exist depending on their severity. In the case of mild storms, new pipe cannot be connected to the previous one. In the case of severe storms, the pipe needs to be lowered and abandoned. It then needs to be recovered from the seabed once the storm has passed. Both abandonment and recovery take about half a day in addition to the storm duration.

Time domain simulation

One of the goals of the logistical scenario simulation is to find the effect on the productivity of the pipelay vessel in combination with one or more supply vessels. These suppliers can arrive while the pipelay vessel is still laying pipe, or the pipelay vessel may be waiting for the supply vessel to arrive. Both affect the efficiency of the entire operation heavily. Because of this interaction and consequential decision-making processes in the logistical model, both seastate and logistics need to be modelled in the time domain.

Persistency data format

Persistency data comes in the form of tables which contain on one axis the different durations, and on the other the different wave heights. The occurrences are measured in which a wave height is higher than a certain threshold. In the persistence

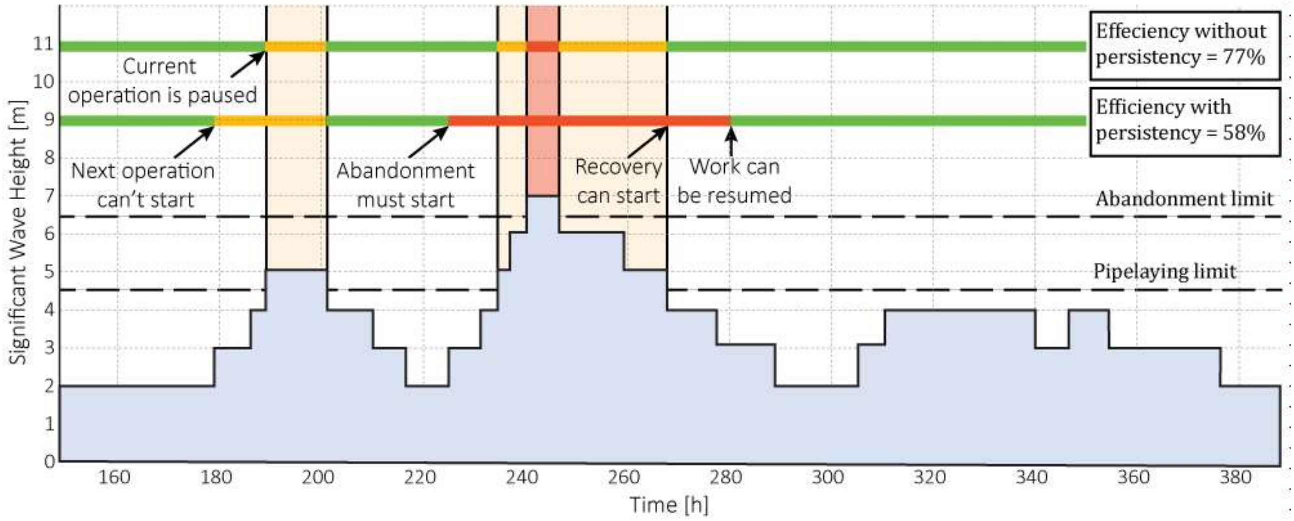


Figure 5.1. Influence of persistence in workability studies. Long operations need to be cancelled ahead of storms, which causes efficiency estimations based on scatter diagrams to overestimate vessel performance

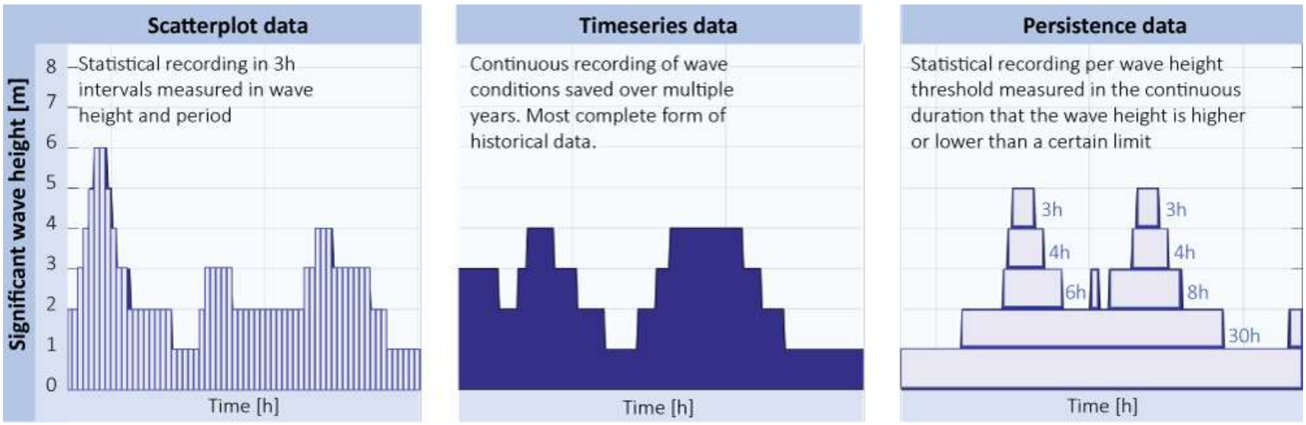


Figure 5.2. Visualization of three different ways to record historical wave data. The first is the most commonly used, the second is the most complete but harder to handle, the third is least common but required to include the time component in statistics.

part of the example in Figure 5.2, there are 2 occurrences in which the wave height is 4 meters or higher lasts 4 hours. In the same example there is only 1 occurrence where the wave height is 1 meter or higher over the entire interval but it lasts the entire 120 hours. Note that two 3-hour occurrences do not make one 6-hour occurrence.

5.5 PERSISTENCE ALGORITHM

The persistence data can be used in reverse to create a time-series of data with persistence characteristics [15]. A combination of wave height and duration will be interpreted as a block visualised on the right of Figure 5.2. These blocks will be stacked in layers to simulate the wave height over time. Each layer of wave heights will be modelled individually and placed on top of blocks from the previous layer so that there are no overhanging blocks present.

An algorithm, visualized in Figure 5.3 places the blocks one by one on available positions in time represented in green. Every time a block is placed the number of available positions decreases. The red areas represent invalid starting points for the occurrences. Occurrences don’t touch each other and they can’t end later than a lower wave height ends: an occurrence can never be higher than 4m if it’s not higher than 3m.

The occurrences are randomly placed starting with the largest block and filling the rest of the space with increasingly smaller ones. If random blocks were to be taken every time, smaller blocks might start blocking space for larger ones.

Algorithm performance

This validation consists of a visual comparison of the data and statistical scatter analysis of the occurrences of wave heights on both season and yearly basis. Because of the random results of the model, a study is made to see how many simulations need to be run for the average of the results to become stable, which happens after the 10th of the 50 simulations. The spread of the results is relatively small, but more importantly it is the same for both the simulated time series and the original timeseries. This can be seen in Figure 5.4, where two results are measured. The time spent waiting on weather, as is created by this algorithm and the final effectivity of the pipelaying activities. Further validation of the introduced algorithm is included in Appendix D.

Figure 5.3. Visualization of weather simulation algorithm as it builds up the seastate timeseries step by step.

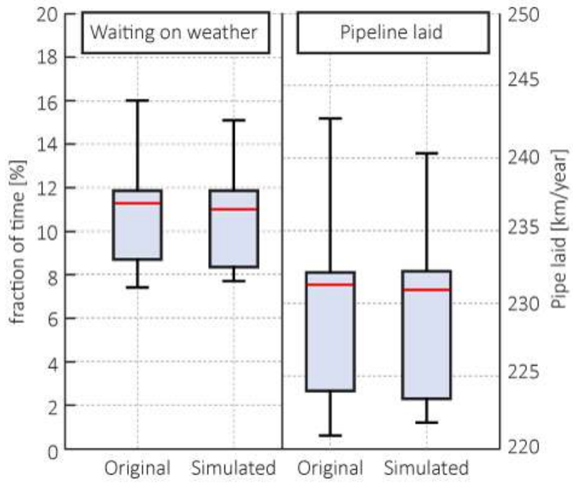


Figure 5.4. Verification the weather model over 50 simulations comparing results with the original and simulated timeseries.

6 SIMULATION RESULTS

This chapter will discuss the results of the logistics simulation runs. The simulations are used to determine the potential gains of using supply vessels in the pipelay logistics chain. Both of the sub-questions will be answered in a separate set of simulations. The answers are used to select the solution concepts that will be used for the design. This resulting concept will then finally be evaluated and compared to the reference vessel in more detail.

6.1 SIMULATION: TRANSIT DISTANCE AND NUMBER OF SUPPLY VESSELS

This set shows the relation between the number of supply vessels and the effectiveness of the pipelay vessel in relation to distance. It will also display the difference between ideal and Icelandic weather. And it will show the difference between a situation where the pipelayer can be loaded during pipelay activities, and where it can't.

6.1.1 RESULT DISCUSSION

The results and observations made with this simulation set are discussed below per parameter, ordered in their respective importance to the answer of research question.

Number of supply vessels

In Figure 6.1 and Figure 6.2 most of the graphs start out horizontally. This means the pipelay vessel is operating at maximum capacity, with a supply of material that is greater or equal to the demand. In these cases, a supplier is always present when the next batch of material can be loaded. A single supply vessel seems to provide no advantage over the status quo. This is the result of the loading and transshipment method (spooling). That method is slow enough so that the time saved is less than the extra time required for loading at sea. This indicates that supply vessels may not always be good for the pipelaying performance.

More than one supply vessel ensures optimum performance, and an increase over the status quo, but only for certain conditions. The first is that the transshipment should occur faster than it takes for the pipelayer to sail to port and back. or at the very least create less downtime. This can be achieved by starting the transshipment process when the pipe is being laid. In this case, the pipelayer will always be more effective than the reference vessel, even when it has to wait for suppliers to get back.

Distance

The effectiveness lost on waiting shows after the distance for which supply can no longer keep up with the demand from the pipelayer. On the other side of the spectrum; when the distance gets under a limit it is more effective to sail back and forth with the pipelayer itself. With a mental experiment at 0km: transferring material to a supply vessel before moving it to the pipelayer in port is slower than transferring it to the pipelayer directly. If simultaneous transshipment is allowed, supply vessels can increase the effectiveness greatly for the reference project. This increase can reach 73% at 600km and 116% at 1250km.

Simultaneous transshipment

The effect of being able to perform transshipment activities during pipelaying can be observed between Figure 6.2 and Figure 6.1. The gain from this feature is 67% in both good and bad weather conditions. This gain comes with the side note that more than one hold needs are required so that pipelaying activities are not disturbed by the transshipment.

Verification of the simulations

The simulation can be verified with performance data on the projects in Brazil. The blue dashed line in the figures represents perfect weather, which is right now the best approximation to the Brazilian environment [1]. The average performance of four flexlay vessels (Appendix C) is shown at a distance of 600km [5]. The results of the ideal case are matching this performance at that distance. In Figure 6.1 the performance of the pipelayer at increasing distances increases before decreasing. This effect is caused by the code architecture, which prioritizes transshipment. In Figure 6.2 this disappears as the pipelayer is not interrupted by supply vessels whenever it is receiving new pipes.

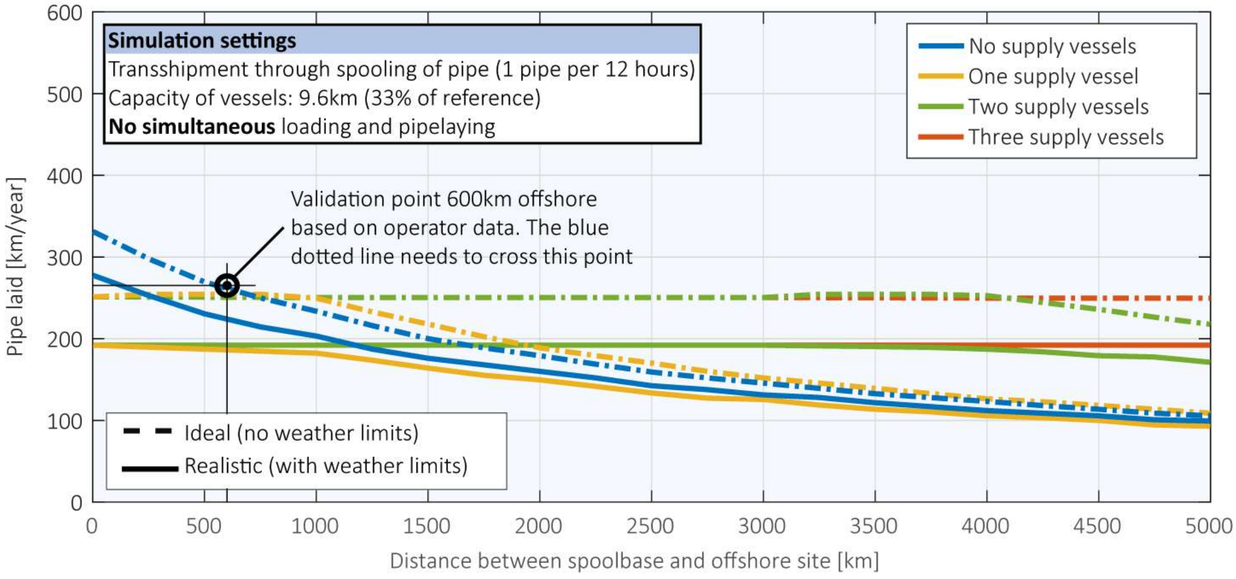


Figure 6.1. Pipe laid in relation to distance and feeders (no transferring while laying). The advised way to read these graphs is to pick a colour (number of supply vessels), compare the dotted and continuous lines (the effect of the weather) and how they change over the increasing distance (to the right). Then finally compare these with a different colour (number of suppliers).

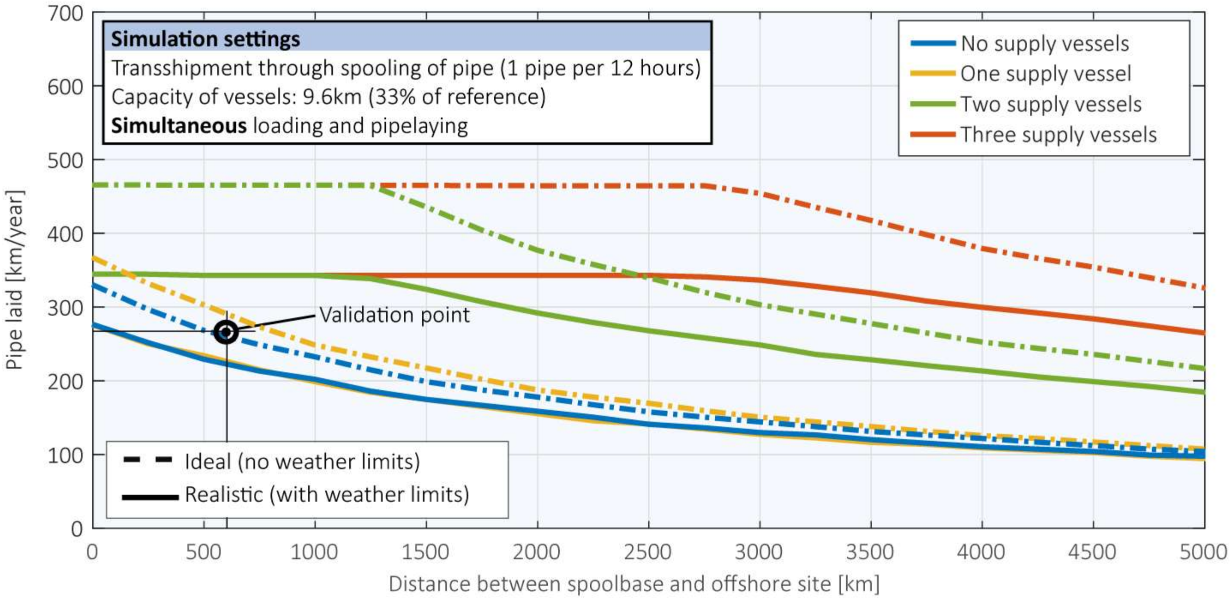


Figure 6.2. Pipe laid in relation to distance and feeders (transferring while laying). This figure is built the same as the previous with the change in transshipment possibilities. Any line here can be compared with the corresponding line in the previous figure.

6.2 SIMULATION: TRANSSHIPMENT AND SEASTATE LIMITS

This simulation set shows the relation between the transshipment methods and seastate limits. It also shows the effect of increased capacity of the ships to find if the vessels are overdesigned in capacity for the Brazilian projects. Both relations will be shown with and without simultaneous transfer.

The following results show how different loading methods perform at different operating limits. The expected operational limits included in the figures are based on various sources from both industry and documents [1] [6] [10] [12] [14] [13].

6.2.1 SIMULATION RESULT DISCUSSION

The results and observations made with this simulation set are discussed below. First the results with respect to the main parameters will be discussed followed by the results with respect to the secondary parameters.

Method of transshipment and loading

Figure 6.3 and Figure 6.4 show that the barges outperform the other methods. Using a supplier with 2 barges improves the effectiveness by 33% from 267km for the reference vessel to 354km for the concept vessel if simultaneous transfer is possible. This result is in line with the expectations: using barges requires two weather windows of 20h to fill the pipelayer, but the other methods require multiple shorter windows.

Seastate limit

The effects of the weather region can be observed by looking at the shape of the lines in Figure 6.3. At the lower end of the limits, no transfer activities can take place, but more weather windows become available when the operational limit increases.

When assuming the simultaneous transfer of pipes is possible, the pipelay vessel starts to lay more pipes than the reference case around 1.75m. Neither the crane or pipe spooling provide an improvement over the reference scenario. Another important influence is the Brazilian project at 600km. There will be a transition point at which the reference vessel becomes less effective than any transfer method at larger distances. This is determined by the time lost in transit compared to the time required for loading and unloading at sea.

Capacity

The effects of using different sized barges can be seen in Figure 6.5 and Figure 6.6. For each barge, a reference value is calculated with the reference vessel. The chosen barge capacities are respectively 6 (25%), 12 (50%), 18 (75%) and 24 (100%) pipes. Saturation effects can be observed in the graphs when looking at the highest capacities, but the 100% concept still has a better performance than the 75% case. This extra capacity also increases the effectiveness of the pipelayer at greater distances.

Convergence of lines

The lines in Figure 6.3 and Figure 6.5 do not converge to a single point like in Figure 6.4 and Figure 6.6. This is because time is lost during transshipment activities on separate moves of reels, barges etc. Each concept has different losses and therefore the final ‘maximum’ performance of the pipelayer will be different with each method. When simultaneous transshipment is allowed the lines convert as the limiting factor becomes the pipelayer itself.

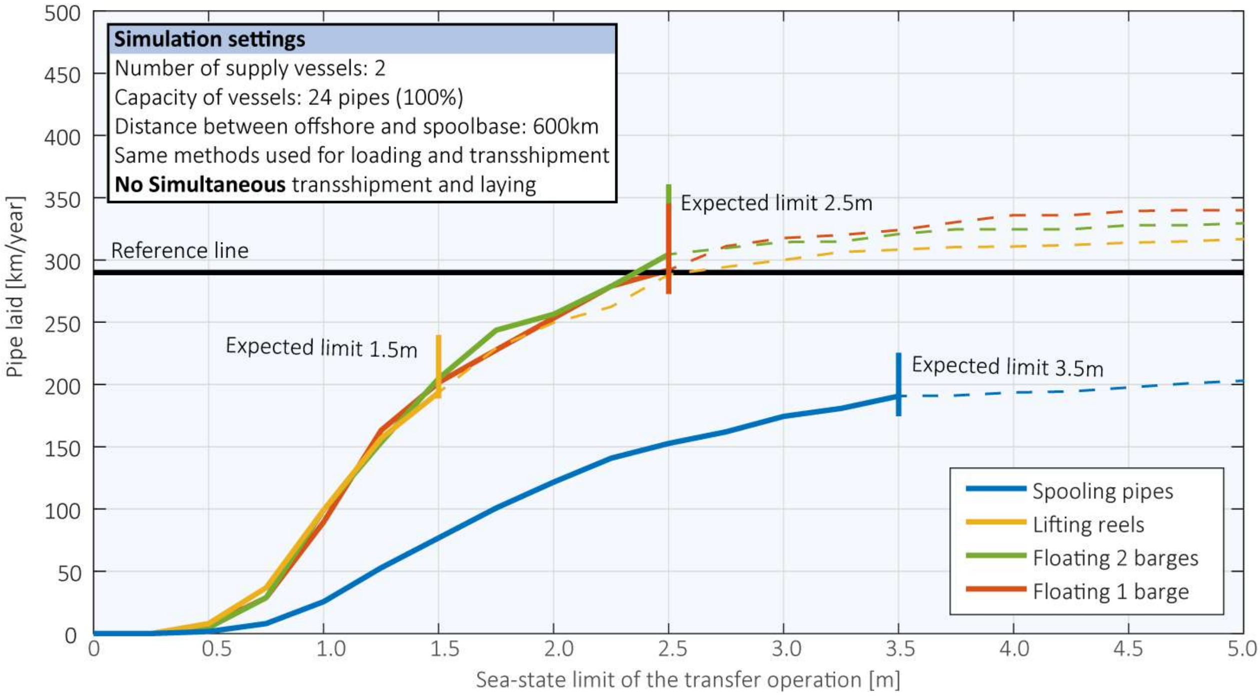


Figure 6.3. Effectiveness of a pipelayer in relation to transshipment method (colours) and transfer limit (x-axis). This simulation set is done without simultaneous pipelaying. The expected limits for transshipment methods are included,

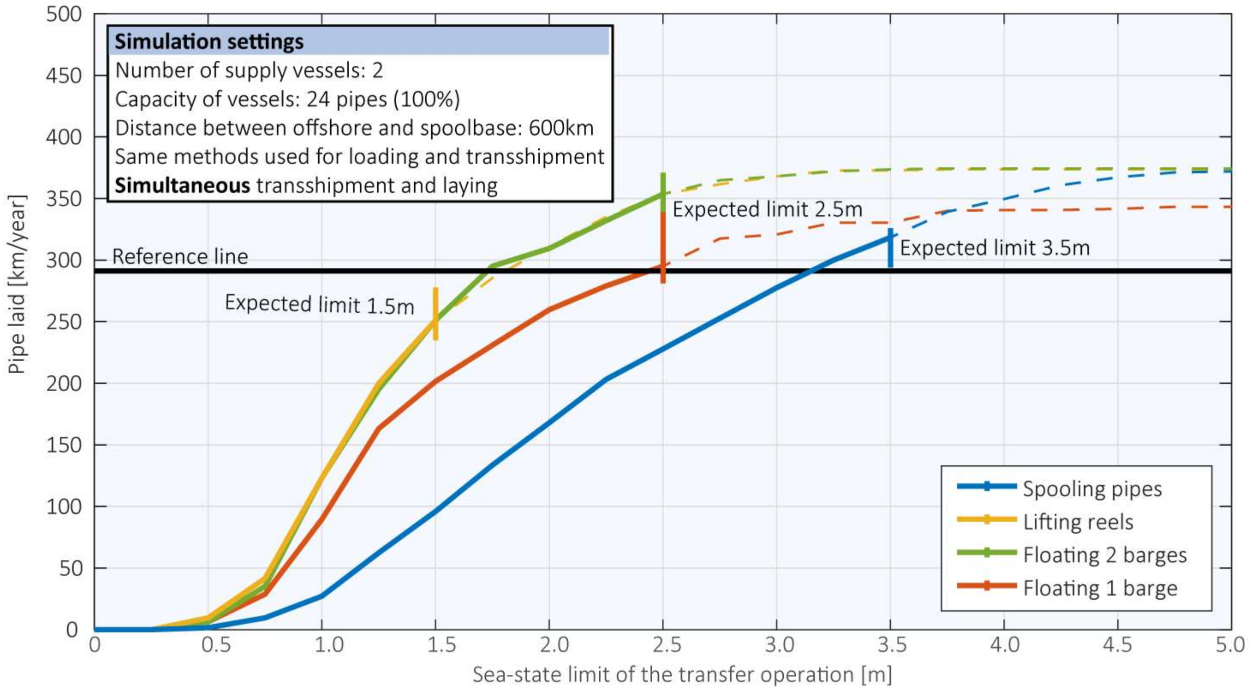


Figure 6.4. Effectiveness of a pipelayer in relation to transshipment method (colours) and transfer limit (x-axis). This simulation set is done with simultaneous pipelaying and transshipment if possible. This makes the red line identical to the previous figure. The expected limits for transshipment methods are included as in the figure above.

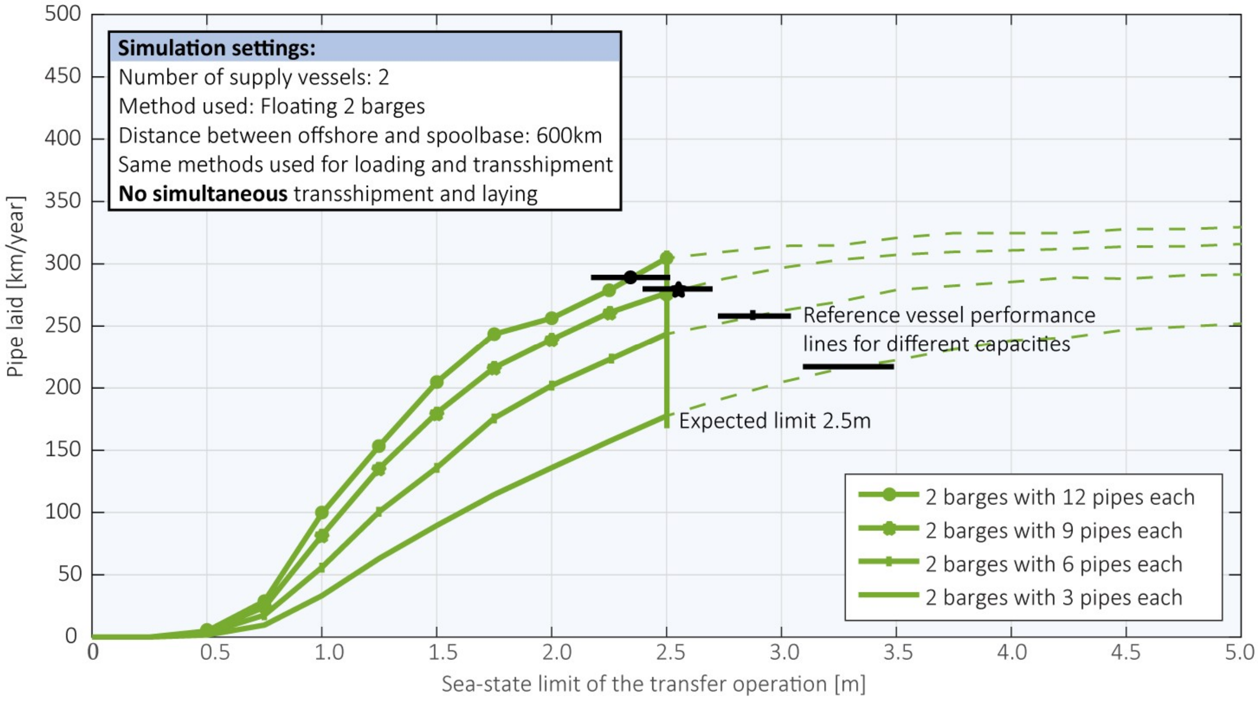


Figure 6.5. Pipe laid in relation to vessel capacity and weather limit (without simultaneous pipelaying). The reference vessel tends to perform better in all cases, except at 100% capacity, when simultaneous transshipment is not allowed.

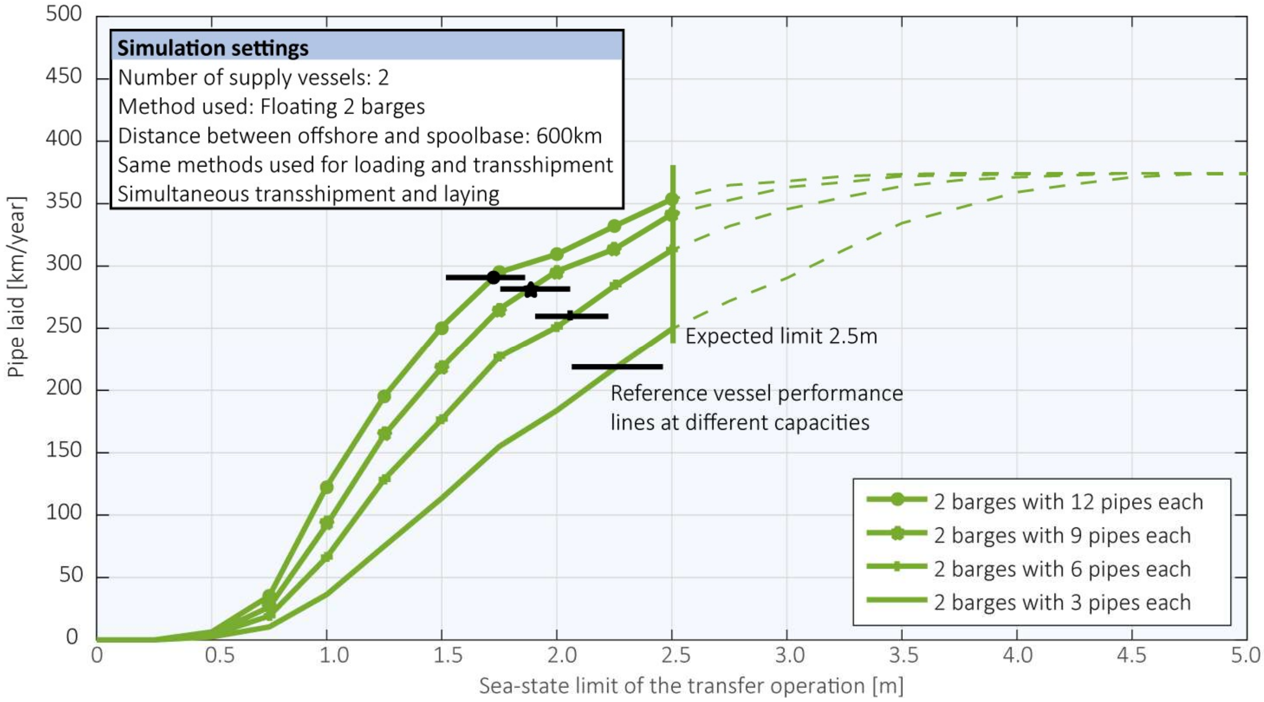


Figure 6.6. Pipe laid in relation to vessel capacity and weather limit (with simultaneous pipelaying). The barge concept solution performs better in all separate cases when simultaneous transshipment is possible.

6.3 DESIGN SOLUTION PATH AND FINAL SOLUTION PERFORMANCE

In this section the principle concept path resulting from the simulations is explained and simulations are run based on various ways of transporting barges to the pipelayer. The solution path is shown below in Figure 6.7. It follows from the previous simulations that the most effective means in terms of pipe laid per year is to transport material in barges. Because free floating barges aren't an option due to heavy seastate operating conditions as discussed in chapter 3, they have to be loaded into a dockship. The dock needs to be closed afterwards so the water can be drained and the barge positioned solidly for pipelaying.

Simultaneous transhipment has to be possible. For this at least two docks will be necessary so that one dock can be opened for loading as pipelaying activities continue from the other. The most intuitive way to approach this is placing the doors at the side of the vessel.

Performance

The question that follows is how this set of parameters performs compared to the reference vessel. It was observed that the number of supply vessels, the capacity of the barges, and the distance to port can have a great impact on the vessels' performance. As alternative to the supply vessel a tug can be used. These are likely to only sail at a speed of 5kn and only transports a single barge.

For the comparison, the reference project is used and a distance which is twice that much. In addition, the capacity is varied from 100% to 50%. The latter closer to the 30% maximum in Brazilian projects. The halved capacity is chosen as it lends itself to easy comparison with doubling the distance. The results of this simulation are shown in Figure 6.8. Boxplots are used to capture the effect of good and bad weather over 50 simulations to find the range of the pipelayer performance in better and worse conditions.

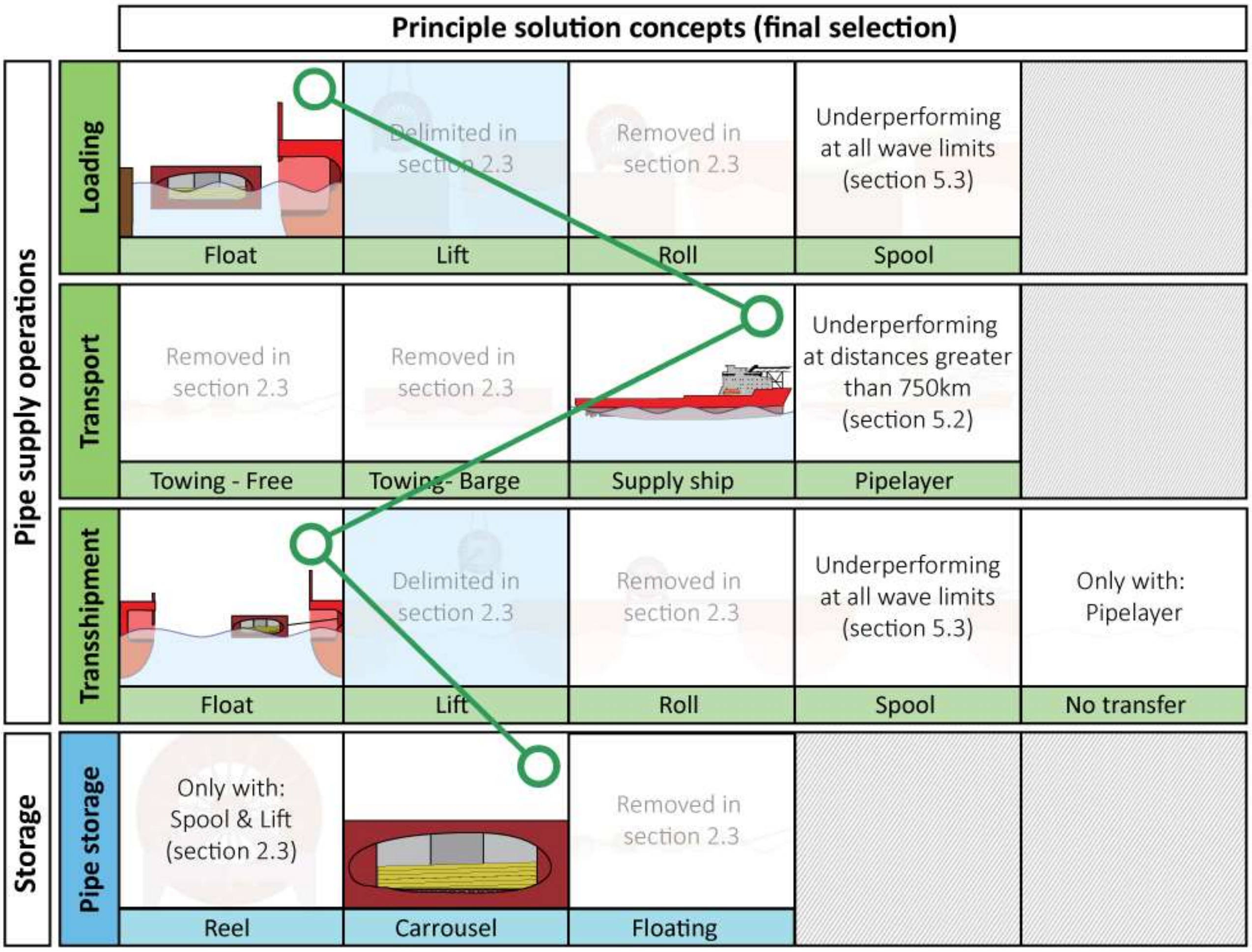


Figure 6.7. Morphological design path for the final concept design.

The results also show that the barge capacity has a very large influence on the performance of the different supplier scenarios and as such should be considered when evaluating projects that are not using the full capacity of the vessels.

100 Percent capacity – the effect of suppliers

When looking at the light-blue boxplots, the performance does not change significantly between the different forms of supply. This is the result of saturation of the pipelayer and the time with which the laying overlaps with the supplier sailing back to the port. The high performance of the tugs is the result from their flexibility. When one tug finishes its transshipment operation, it can already start sailing back to port while the second waits its. This counteracts the slow speed of the barges. For a supply vessel this can't be done because it will unload both carrousels before returning to port. Note that two suppliers at 50% perform worse than one supplier at 100%. This is because the vessels have to wait for good weather twice as often for the extra transfers.

1200km – the effect of distance

This advantage is quickly lost however when the capacity of the barges is halved. In that case the pipelay vessel needs twice the barges. Especially at longer distances, the reduced capacity impacts the effectiveness of the pipelayer. At 1200km, the pipelayer itself (capable of sailing 10kn) becomes better suited to sail back and forth than the slow sailing tugs. Projects in the Brazilian region however may want to consider the usage of tugs to replace the likely more expensive supply vessels.

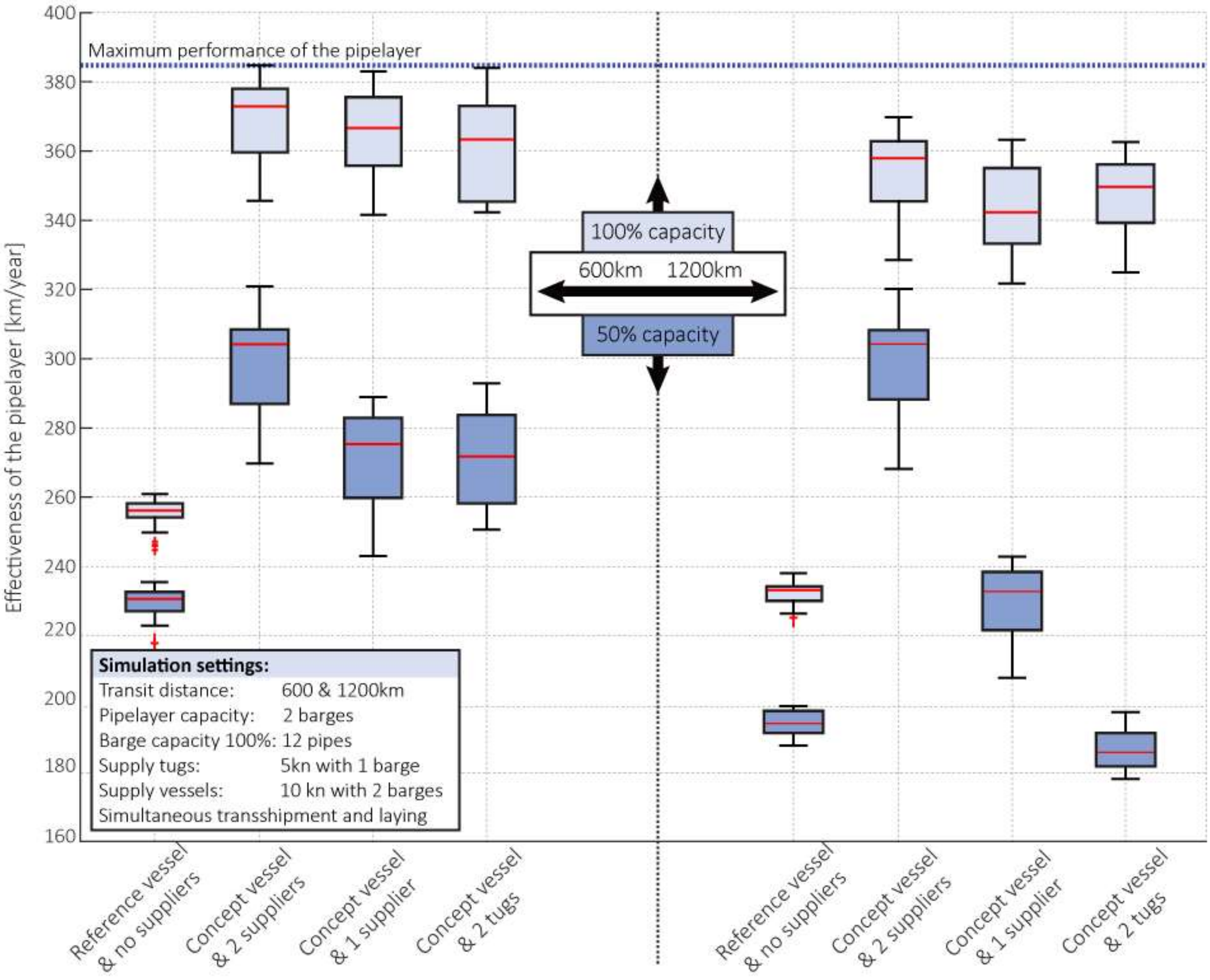


Figure 6.8. Comparison of the performance for concept and reference vessel. For each instance, 50 simulations are run. The boxplots represent the spread of performance due to randomness in the weather.

Table 6.1. Average results (red lines) from Figure 6.8

Method	Capacity	Effectivity	Relative
2 Supply ships	50%	310 km/y	122 %
1 Supply ship	50%	275 km/y	107 %
2 Tugs	50%	270 km/y	106 %
No supply (ref)	50%	230 km/y	90 %
2 Supply ships	100%	375 km/y	147 %
1 Supply ship	100%	367 km/y	144 %
2 Tugs	100%	362 km/y	142 %
No supply (ref)	100%	255 km/y	100 %

6.4 FINANCIAL ESTIMATION

It is possible to make a rough estimation of the costs per km pipe from the results shown in Table 6.1. A dayrate of $270,000 is assumed for the pipelayer based on similar vessels built for Subsea7 [16]. A dayrate of $60,000 is assumed for a submersible supplier based on the smaller vessels owned by Dockwise [17]. Only a single supply vessel will be used, extra suppliers do not add to the effectiveness in the results of Table 6.1. Thus, the reference vessel alone costs $270,000 per day, and the concept vessel plus a single supply vessel costs $330,000 per day.

First, the optimal used capacity (100%) for the flexlay vessel is assumed. Subsequently dividing the costs per year by the amount of pipe laid results in $386,470/km pipe for the reference vessel and $328,201/km pipe for the concept solution. The numbers change in favour of the reference vessel when only 50% is used. In that case the result is $428,478/km for the reference vessel compared to $438,000/km for the concept solution.

The pipelayers are paid over time by Petrobras, and not per km of pipe laid [1] [13]. But any gains in performance could be translated to a higher dayrate, and a higher profit. Knowing the dayrate of the reference vessel ($270,000) and the average amount of pipe they lay (Appendix C) it is possible to determine the costs per km of flexible piping which is acceptable to Petrobras. Which lies between $273,750/km and $450,000/km with an average of $362,316/km.

Table 6.2. Estimation of the profit that can be made based on rough estimations of the dayrate. Based on the concept solution with a single supply vessel.

Composition	Pipe laid	Rate/km	Profit/km
Reference vessel (50%)	230 km	$ 428,478	$ 0
Concept vessel (50%)	270 km	$ 438,000	$ -9,522
Reference vessel (100%)	250 km	$ 386,470	$ 42,008
Concept vessel (100%)	367 km	$ 328,201	$ 100,277

The results are summarized in Table 6.2. The profit in that table is relative to the reference vessel at 50%. These figures are affected by the weather of the region. Because of the doubled number of required transfer moves in the 50% capacity case double the amount of weather windows are required. This lowers the performance of the concept solution by 25%. Using weather data related to the region of operations is advised in order to better evaluate the concept solution.

6.5 CHAPTER CONCLUSION

To answer the first research question: supply vessels will increase the effectiveness of pipelaying operations after a tipping point dependent on the distance. This percentual gain grows with the distance up to an optimum performance point. However, there is also a minimum distance where the gains will not wage up against the extra investments that are required. The effectiveness of the pipelayer can go up to 215% when doubling the project distance to 1200km. This effective distance grows larger with increasing number of supply vessels and faster transshipment methods.

To answer to the second research question: the concept solution which supplies two (single carrousel) barges to the pipelay vessel performs better than the other solution concepts. However, at the reference distance, the minimum seastate limit for transshipment need to be above 1.75m in order to outperform the reference vessel, which again illustrates that there is a minimum distance at which new solutions will be more effective as well as financially interesting

The ability for simultaneous transshipment shows large improvements for slower transfer methods. This effect is less significant for faster methods. It provides however more flexibility to the vessel and it means that weather windows at lower seastates are used more effectively as the pipelayer can keep laying pipes in heavier conditions. That also means that the operator can wait for more favourable weather conditions for transshipment without impacting pipelayer effectiveness.

The capacity of the carrousel in the barges will be kept similar to the design criteria for the reference vessel. This is done even though for the reference project it could be reduced by 25% with only a 4% loss in performance of the pipelayer in Brazilian projects. This capacity may be changed later without too much change to the vessel design.

The final simulations comparing the concept vessel and the refence vessel show that it is possible to use tugs instead of supply vessels in projects close to port without much loss in the effectivity. In the first simulation set (section 6.1) one supplier was not enough to satisfy demand. This chapter however shows that one supplier can suffice if the transshipment method is fast enough to keep up with the pipelaying activities.

Supply at sea solves the problem of having to go to port from time to time, being able to operate close to peak effectiveness even further from the shore. The final simulation of the resulting principle solution path shows that effectiveness of the pipelayer can be increased from around 260 to 380 km/year by using supply vessels with fully loaded vessels. But the result also increases from 230 to 305km/year when the barges are only 50% loaded.

A financial estimation shows that in the most optimal situation where the pipelayer is used to its maximum efficiency, it is possible to achieve a $100.000 profit per day. This profit dissipates however when it is only used with a 50% capacity as is common practice in Brazil. Note that these figures are using simulation data taking place in Iceland and are underestimating the gains to be had, they however do give insight and value to the potential this solution has.

7 DESIGN CONCEPT

This chapter contains the new concept design of the pipelay vessel. A few things are critical: a design is needed for the barges, the docks that they are loaded in need to be defined, and the pipelayer itself needs to be designed. The next step is to determine stability, structural strength, hydrodynamic motions, and resistance of the pipelayer. However, due to time limitations and the complexity of the problem, strength has not been evaluated as the other points are deemed more critical. Calculating hydrodynamic motions was attempted but has not been solved due to software limitations as further explained in Appendix H.

The first section will discuss the design of the barge which is to be used for the supply of material to the pipelay vessel. The second section will then discuss the resulting pipelay vessel concept which allows continuous operations at sea without the requirement of sailing back to port to get new material. The third section will evaluate the resistance calculation. The last section will summarize the differences between the concept design and reference vessel.

7.1 BARGE DESIGN

The barges will be designed around the carrousels from the reference vessel. This section will discuss their dimensions, weight, draught and stability.

7.1.1 DIMENSIONS

The inner diameter for the carrousel is constrained by the pipes' minimum bending radius so the capacity is mainly decided by the outer diameter and carrousel height. Increasing the diameter increases the horizontal footprint of the barge which the requires a larger dock. Varying the height will increase the depth and draught of the barge and require an increased depth of the pipelayer and a higher water level in the dock.

Carrousel

For this first design iteration, the larger carrousel in the reference vessel will be used. The height is then lowered to achieve the desired capacity. The desired total capacity of the pipelayer is 4000t which is equal to the capacity of the reference vessel. This is split over two carrousels of 2000t so they are exchangeable which simplifies logistics.

This results in an inner diameter of 9.4m, an outer diameter of 22m, and a height of 5m. With the 9" pipe from Appendix B the design capacity of the carrousel is 2064t.

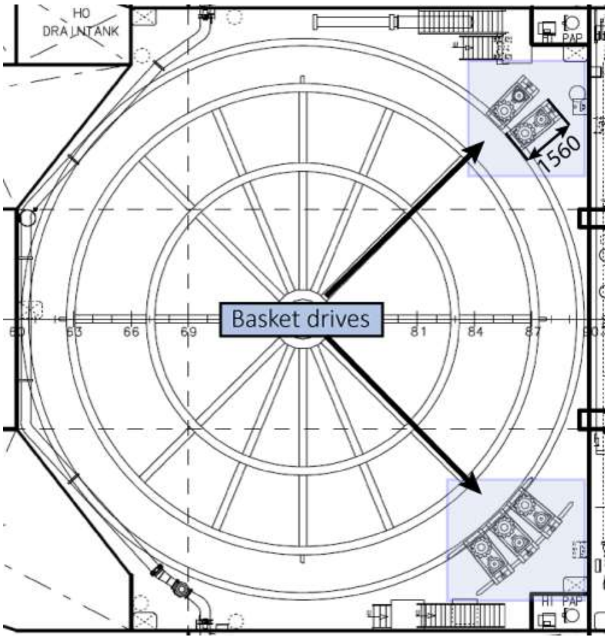


Figure 7.1. Traction drives around the carrousel used to keep control of its rotational momentum

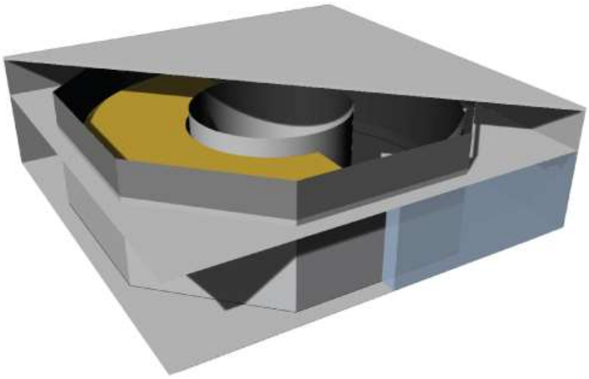


Figure 7.2. 3D impression of the barge illustrating both loaded and ballasted condition corresponding with the sideview on the next page

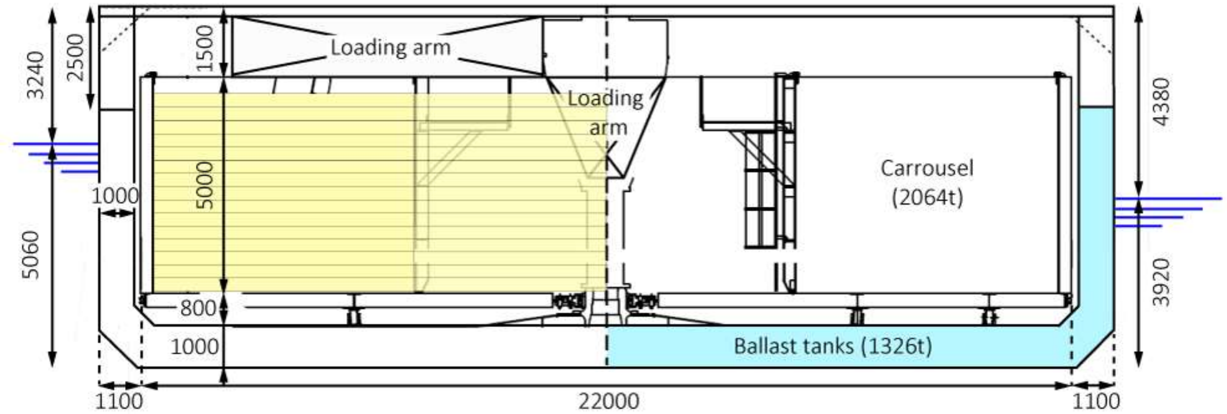


Figure 7.3. Sideview and draught of barge in loaded and ballasted condition

Barge

The barge is 1.1m wider on both sides of the carrousel and has a double bottom of 1m on which the carrousel is rested. This bottom is slanted in a 45° angle on the edges to allow easier positioning with guides that can be positioned in the docks.

The carrousel rests on rollers which allow it to rotate as the pipe (un)wound. This requires a space of 800mm between the carrousel and the double bottom. In addition, a clearance of 100mm is required between the carrousel and the wall. 5 traction engines in the reference vessel control the back tension on the pipe and the rotation of the carrousel. These 5 engines can be positioned in two of the corners of the barge as done in the reference vessel in Figure 7.1. The pipes have to be guided by a loading arm. To fit this arm over the carrousel, the deck is positioned 1.5m above it.

Ballast tanks

The barge has a larger freeboard when it is empty than when it's full. This could cause it to hit the deck above the dock as it gets filled with water. To mitigate this problem ballast tanks are placed to a distance of 2.5m from the top. Those 2.5m are reserved for the carrousel's control cabin, traction engines and walkways. A 3D-rendered impression is shown in Figure 7.2.

7.1.2 *WEIGHT ESTIMATION*

The lightweight of the barge is made up of the weight of the construction and the weight of the equipment. The deadweight is made up of the ballast and pipes. The values for these are shown in Table 7.1 and they will be briefly discussed below.

Lightweight

The construction is estimated to weigh 110t/m^3 based on ballpark figures in the company for the density of a standard barge [13]. The total lightweight is 968t of which 434t is a result of the equipment. The equipment is calculated based on weight estimations relating to the carrousel from documents of the reference vessel [18]. A breakdown of equipment is found in Appendix G.

Deadweight

The deadweight is based on the capacity of the carrousel (2064t) and the volume available for the ballast tanks (3049m^3) 2.5m below the upper deck.

7.1.3 *DRAUGHT AND STABILITY*

This subsection will cover the draught for three different loading conditions and the stability. First the different loading conditions will be mentioned which will be summarized in Table 7.1 and the stability will be covered.

Table 7.1. Weight, draught, and stability parameters for the three loading conditions of the barge concept.

Loading condition	**Weight**				**Draught**				**Stability parameters**		
	Ballast	Stores	Piping	Displ.	Draught aft	Draught for	Trim	List	KG	GM	G'Mliq
LC1: LSW only	0 t	n.v.t.	0 t	968 t	1.72 m	1.64 m	-0.08 m	-0.2°	1.13 m	30.33 m	30.33 m
LC2: Ballast	1326 t	n.v.t.	0 t	2294 t	3.86 m	3.82 m	-0.04 m	-0.1°	1.76 m	13.13 m	13.13 m
LC3: Loaded	0 t	n.v.t.	2064 t	3032 t	5.10 m	5.01 m	-0.09 m	-0.2°	3.28 m	9.10 m	9.10 m

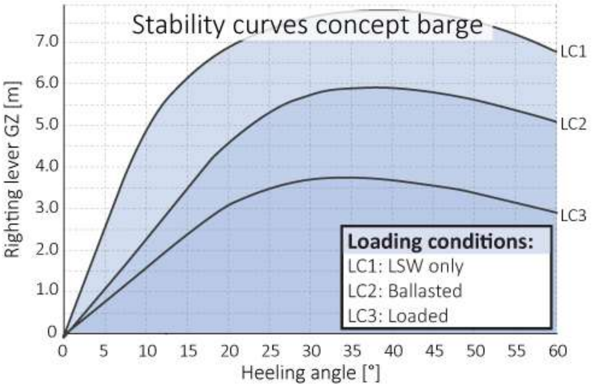


Figure 7.4. Righting lever of the barge versus heeling angle for the three loading conditions (LC) of the barge.

Draught

Three loading conditions will be examined for the barge. The first is the empty condition which only considers the lightweight of the barge. The second is the ballasted condition, and the third is the fully loaded condition. The draught for these loading conditions can be found in Table 7.1.

Stability

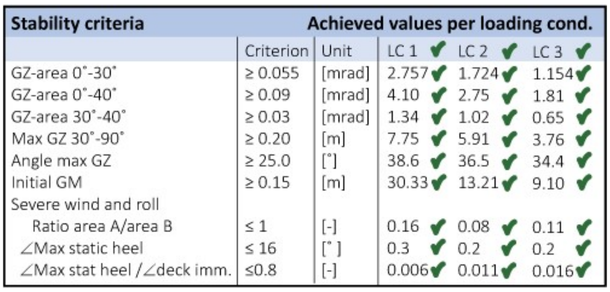
The intact stability calculation will be made with DELFTShip. To check if the barge complies to regulations, the 2008 International Code on Intact Stability is used [19]. The intact stability criteria that apply to the barge are the criteria that apply to all ships.

Figure 7.4 shows the righting lever curves (GZ) for the barge which is the horizontal distance between the upward buoyancy force and the downward gravity force for a vessel. These curves are the basis for most of the stability criteria which are listed in Table 7.2. In short, all three loading conditions comply with the intact stability criteria.

7.1.4 SECTION CONCLUSION

The barge will have a displacement of 3032t with a draught of 5.06m in loaded condition and will have a 24.2m beam and length, with a depth of 8.3m. It will hold a 5m-high carrousel which can contain 2064t pipe which is slightly more than the desired 2000t. In ballast condition, the barge will have a displacement of 2294t, a draught of 3.82m, and a freeboard of 4.48m. These measurements will influence the size of the dock which will be discussed in the following section.

Table 7.2. Stability criteria for the barge per loading condition. The criteria are based on the International Code on Intact Stability (2008) IMO MSC.267(85) - Minimum design criteria applicable to all ships.



Stability criteria			Achieved values per loading cond.		
	Criterion	Unit	LC 1 ✓	LC 2 ✓	LC 3 ✓
GZ-area 0°-30°	≥ 0.055	[mrad]	2.757 ✓	1.724 ✓	1.154 ✓
GZ-area 0°-40°	≥ 0.09	[mrad]	4.10 ✓	2.75 ✓	1.81 ✓
GZ-area 30°-40°	≥ 0.03	[mrad]	1.34 ✓	1.02 ✓	0.65 ✓
Max GZ 30°-90°	≥ 0.20	[m]	7.75 ✓	5.91 ✓	3.76 ✓
Angle max GZ	≥ 25.0	[°]	38.6 ✓	36.5 ✓	34.4 ✓
Initial GM	≥ 0.15	[m]	30.33 ✓	13.21 ✓	9.10 ✓
Severe wind and roll					
Ratio area A/area B	≤ 1	[-]	0.16 ✓	0.08 ✓	0.11 ✓
∠Max static heel	≤ 16	[°]	0.3 ✓	0.2 ✓	0.2 ✓
∠Max stat heel /∠deck imm.	≤0.8	[-]	0.006 ✓	0.011 ✓	0.016 ✓

7.2 VESSEL DESIGN

The reference vessels can be used as the basis for the implementation of this concept. This is done by replacing the two carrousels with two docks. This way, the pipelay tower, moonpool, deck house and engine rooms don't have to be redesigned from scratch. This design will also allow an operator to use the pipelay vessel in the traditional way for smaller projects that don't require resupply.

The pipelay vessel is dependent on the docks which hold the barges. The first subsection will cover the dimensions of the concept vessel. The second subsection will cover the resulting weight and draught. The final subsection will then use this information for the stability calculations. It is observed that the reference vessel can be used as a starting point for the design there is no need to design from scratch.

7.2.1 DIMENSIONS

The dimensions of the pipelay vessel concept are the result of the size of the docks around which a main deck will be raised and designed. The main deck and the length of the docks will in turn influence the main dimensions of the entire vessel.

Dock

The dock needs to be 12.47m in height to accommodate the barge in loaded and ballasted condition. This provides a 1m clearence below the barge in loaded condition and a 2m clearance above the barge in ballasted condition. For now these clearances are chosen arbitrarily untill later research and model testing can provide the actual required clearance in different situations.

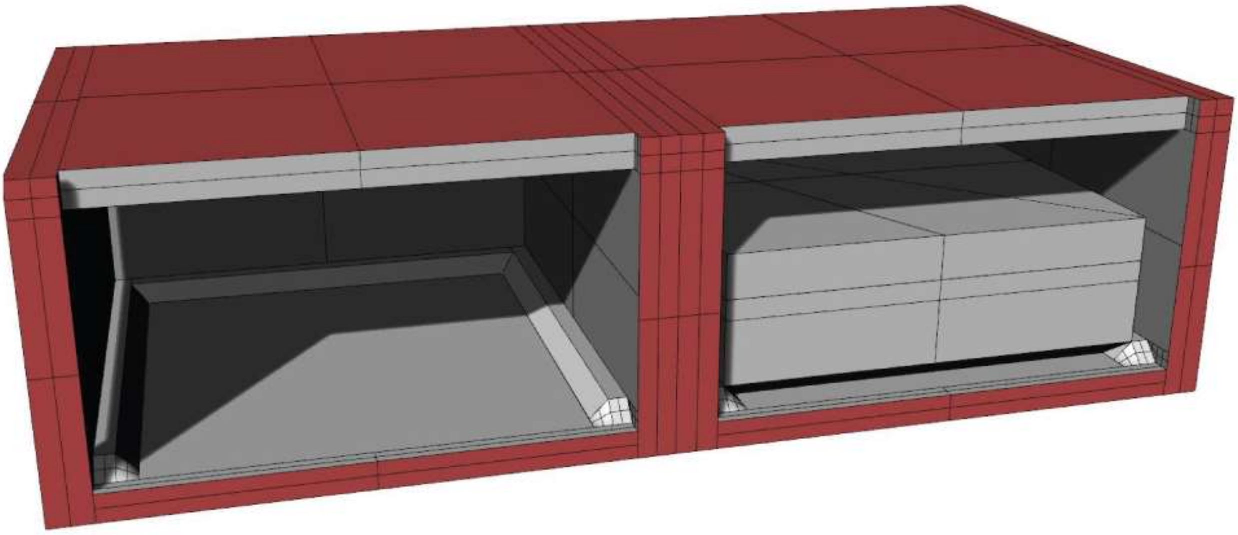


Figure 7.5. Docks with and without the barge. An indentation can be observed in the front where the dock door fits.

A clearance of 1m is taken around the barge. Though this is rather small, increasing it increases the horizontal footprint of the dock and in turn increases the size of the pipelayer. This increase lowers the draught and requiring more ballast capacity for the transshipment operation.

A space of six frames is kept between the two docks, derived from the reference vessel. This allows for fuel tanks on the lower level, a stairway higher up and access to the holds for personnel which have to operate the barges.

The barge can be pulled in with winches and controlled from the outside by a container tug that can be carried around by the pipelayer. It is assumed that the positioning inside the dock will be made easier with an indentation in the floor of the dock in which the barge can rest. This is a 1m deep indentation observable in Figure 7.5.

The dock is closed by large doors which allows for a watertight seal allowing the water in the dock to be drained. This way there is no free surface effect and the barge is not floating within the dock. The doors will be lifted up vertically which requires the installation of four large kingposts on the deck. Lifting the doors this way is the simplest solution because there are no large hinges required and no wave forces will be transferred to the doors. This would have been the case when the doors would have rotated upwards or sideways additionally taking up more space around the vessel.

To achieve enough weight for the door to sink below the waterline it can be ballasted. This requires pumps to drain it.

General vessel dimensions

The front is kept identical to the reference vessel as there is no need to alter this section. At mid-ship, the carrousels are replaced by the docks and the ship is elongated and the main deck heightened.

Due to the length of the two docks together and the required positioning from the keel up, the base of the ship needs to be longer by 18.72m, or 24 frames of 780mm. Most of this increase in length is caused by the size docks themselves, but 3m of empty space is created as a result of the shape of the stern. This empty space overlaps some of the reference vessels storage rooms and could be used for the required ballast pumps that will empty the docks. In addition, the door of the aft dock is curved with the shape of the stern to prevent the need for a further elongation of the vessel of 3 meters.

Main deck

When the dock was designed there was an option to remove the main deck above it to create more space for the motions of the barge. However, there are a few reasons for having a main deck.

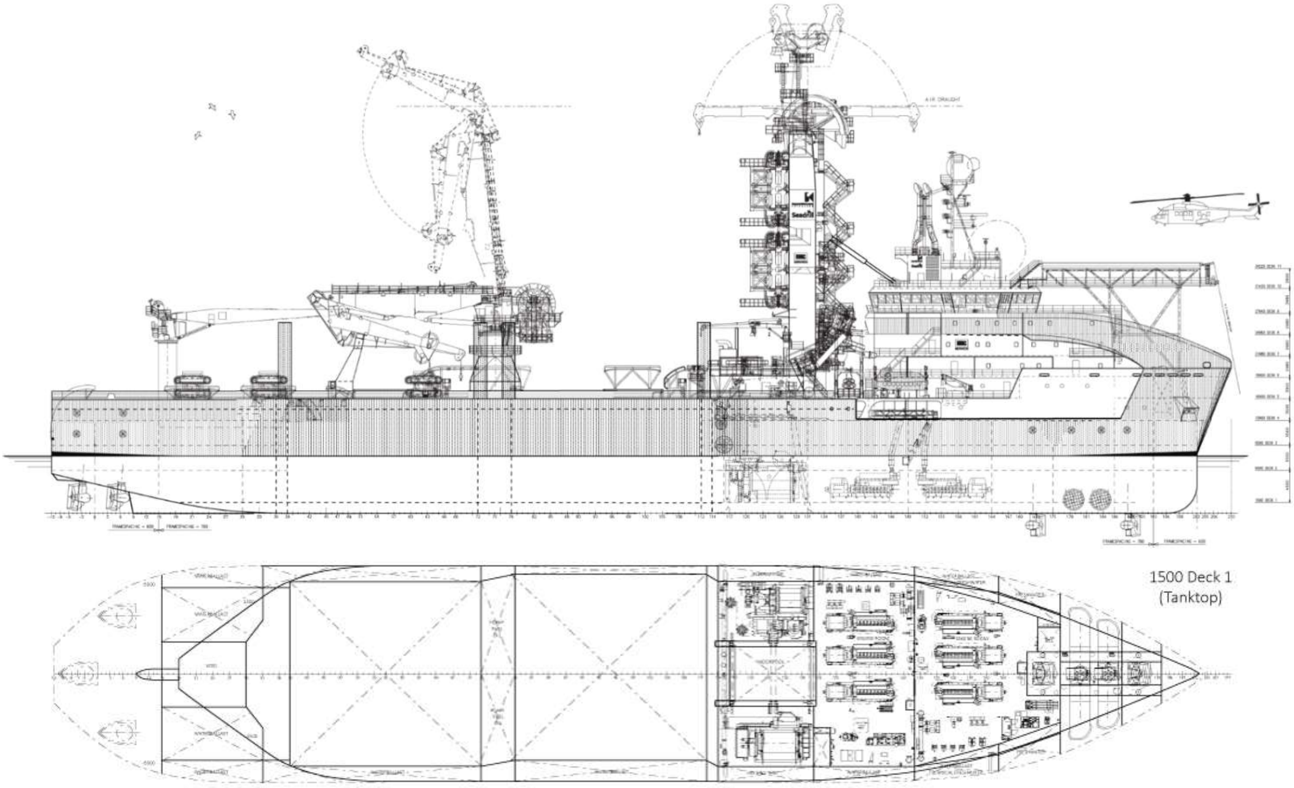


Figure 7.6. General arrangement of the concept vessel. What can be observed in the top view is the slightly moved hold which is done so it would be more central and further back in the pipelayer.

Figure 7.7. 3D DELFTShip impression of the concept vessel. The image is showing the portside with the doors. The starboard side contains the heave-compensating knuckle boom crane and the rails which guide the pipe to the pipelay tower.

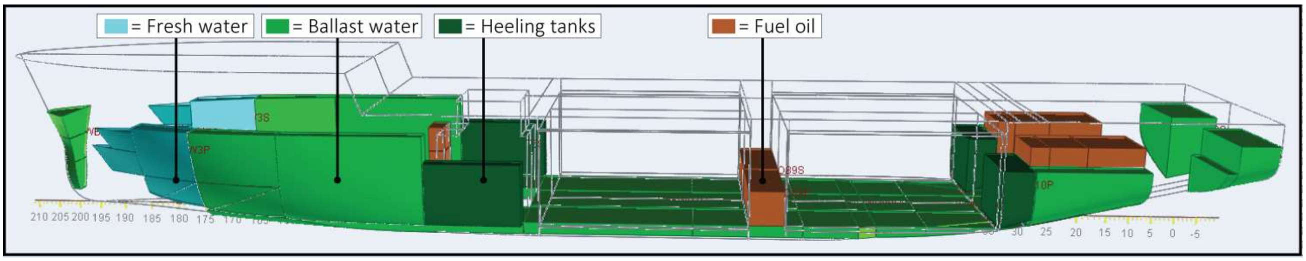


Figure 7.8. Tank arrangement for the concept vessel. Ballast tanks are used to bring the vessel to the correct draught for docking barges.

One reason is that extra equipment used in subsea construction is lifted by cranes onto the deck where it is stored. When needed it is moved by crane to the deck closer to the moonpool. Another reason for the deck is that having a closed main deck allows for a stronger, stiffer vessel. This is important because the doors in the side of the vessel are already spanning 52m, reducing the strength of the vessel. In addition, loading tensioners are position on the aft of the vessel and the guidance rails for the pipe between the tower and carrousels need a structure to stand on.

As a result of the high docks, the main deck needs to be raised above the docks by 2.77m. To allow the crew to move heavy objects to and below the tower, the deck around the moonpool and tower also needs to be raised.

Finally, raising the aft deck too allows the support crane to hover over the kingpost. This creates a continuous raised main deck from the moonpool up to the stern. For now, the deck will be kept at 13m around the deckhouse, but this could be changed during future design iterations.

A simplified general arrangement (without cranes and tensioners) from the side and the 1500 deck are shown in Figure 7.6 and the 3D impression is shown in Figure 7.7. The latter also includes the tank arrangement, further detailed in Appendix I.

7.2.2 WEIGHT ESTIMATION

This subsection will review the changes to the lightweight of the vessel and the changes to the draught in several loading conditions. This ensures the vessel can achieve enough draught to load the barges in any situation.

Table 7.3. Lightweight calculation for the concept vessel. Due to lengthening of the ship, sections are moved and steel and equipment is added and subtracted where needed. This causes the concept VCG and LCG to be higher than the original.

Lightweight	Weight	VCG	LCG
Modified reference vessel	13,686 t	14.43 m	83.00 m
Removed carrousels	-368 t	4.46 m	42.86 m
Removed equipment	-80 t	2.73 m	44.85 m
Extra steelweight	1941 t	10.88 m	73.24 m
Doors and kingposts	299 t	12.68 m	55.80 m
Concept vessel	15463 t	14.28 m	82.41 m

Lightweight

The lightweight is recalculated by using internal documentation of the reference vessel [18]. The forward part of the ship containing the deckhouse is moved further away from the centre, the deck is removed and added at a higher level, the carrousel and equipment belonging to it is removed, and the extra length for the vessel is added.

A summary of the calculations is shown in Table 7.3. While modifying the lightweight, the vertical centre of gravity (VCG) is also recalculated so that it can be used to check the stability of the vessel later. The changes heighten the VCG from 13.92m to 14.28m. A detailed calculation can be found in Appendix G.

Deadweight

The deadweight will be made up from several different components. These components are fresh water stores, fuel oil, mission equipment and food stores, the barges, and ballast water. For readability these items will be grouped under cargo and ballast. They are included in Table 7.4 for each of the different loading conditions which will be introduced in the next subsection.

Table 7.4. Displacement composition, draught and trim for several loading conditions. Lightweight can be derived from the displacement in the first loading condition. The draught margin is the smallest clearance between a barge and the respective open hold.

Loading condition	**Weight**			**Draught**					**Stability parameters**		
	Ballast	Cargo	Displ.	Draught aft	Draught for	Trim	List	Margin	KG	GM	G'Mliq
1: LSW only	0 t	0 t	15463 t	3.02 m	6.18 m	3.16 m	0.3°	n/a	14.27 m	4.63 m	4.63 m
2: Docking (10% stores)	1633 t	1871 t	17334 t	4.83 m	4.97 m	0.14 m	0.0°	n/a	13.47 m	4.88 m	4.77 m
3: Docking + aft open	7556 t	1871 t	23476 t	7.99 m	6.83 m	-1.15 m	0.0°	1.03 m	11.02 m	3.84 m	3.70 m
4: Docking + for open	7637 t	1871 t	23320 t	6.89 m	8.30 m	1.41 m	-0.1°	0.87 m	11.17 m	3.49 m	3.47 m
5: For load + aft open	4432 t	4903 t	23385 t	7.71 m	7.43 m	- 0.28 m	0.1°	1.05 m	10.65 m	4.03 m	3.93 m
6: Aft load + for open	4839 t	4903 t	23791 t	7.44 m	7.92 m	0.48 m	0.0°	1.06 m	10.64 m	4.02 m	3.94 m
7: For load + aft load	791 t	7935 t	22775 t	6.32 m	6.39 m	0.07 m	0.4°	n/a	11.40 m	4.51 m	4.38 m

7.2.3 *DRAUGHT AND STABILITY*

This subsection will cover the draught and stability of the pipelay vessel. Firstly, the different loading conditions will be introduced together with the required draught for transshipment activities. Secondly, the stability values will be discussed. The results from the draught and stability calculations per loading condition is summarized in Table 7.4. The ballast tanks used are shown in Figure 7.8.

Draught

The draught of the vessel is dependent on the loading conditions and the opened and closed docks. In addition, the trim of the vessel changes the draught locally which needs to be considered as barges need to be loaded into the docks.

Seven loading conditions will be evaluated. The first will be a lightweight only condition. The second will include ballast water and stores. The third and fourth will open one of the docks and let water in. Five and six will have one dock opened during a transshipment operation while the other dock will have a fully loaded barge. The seventh condition has two fully loaded barges with closed docks.

All the loading conditions with an opened dock will be ballasted such that the pipelayer achieves the required submerged draught of 7.56m for the transshipment activities. This way there will be a space of 1 meter between the barge and the dock. Conditions 2-4, which have closed docks, use minimum stores, which mean the fresh water tanks and fuel oil tanks are only filled for 10%. This also includes 220 ton of special cargo and general items on board, as used in the reference vessels docking condition [18].

In the different loading conditions the vessel will need to be ballasted in order to attain a trim where enough margin is available between the barge and the bottom of the docks. These margins can be found in Table 7.4. The lowest margin in condition 4 does not achieve the 1m desired distance. However, this is early stage design, and further iterations can include more ballast tanks, or decide to use more than the now 10% stores capacity.

Stability

To check if the vessel is still stable in different loading conditions, the intact stability is checked with the same 2008 International Code on Intact Stability for all ships as for the barge [19]. The checks are shown in Table 7.5. The vessel does not comply with two of the criteria in the lightweight only condition. However, this is not a sailing condition and the vessel will never be operated completely empty. Because the achieved value lies close to the required value this is acceptable [13].

Figure 7.9 shows the righting lever curves which are used in the calculation for most of the stability criteria. The pipelay vessel is less stable than a barge when it has a lower draught. This is the result of the lower waterplane area. For the conditions 3 to 7 the vessel has a draught of approximately 7.5m compared to the 5m draught in its empty state. In addition, the ballast water decreases the overall centre of gravity of the vessel. This effect is also visible for loading conditions 5 and 6, which have a fully loaded barge, with a lower centre of gravity than the ballast water for conditions 3 and 4.

Table 7.5. Stability criteria for the pipelay vessel concept per loading condition. The criteria are based on the International Code on Intact Stability (2008) IMO MSC.267(85) - Minimum design criteria for all ships

Stability criteria			**Achieved values per loading condition**						
	Criterion	Unit	LC 1 ✗	LC 2 ✓	LC 3 ✓	LC 4 ✓	LC 5 ✓	LC 6 ✓	LC 7 ✓
GZ-area 0°-30°	≥ 0.055	[mrad]	0.569 ✓	0.636 ✓	0.554 ✓	0.509 ✓	0.587 ✓	0.595 ✓	0.638 ✓
GZ-area 0°-40°	≥ 0.09	[mrad]	0.79 ✓	0.94 ✓	0.99 ✓	0.92 ✓	1.05 ✓	1.07 ✓	1.09 ✓
GZ-area 30°-40°	≥ 0.03	[mrad]	0.22 ✓	0.30 ✓	0.43 ✓	0.41 ✓	0.47 ✓	0.47 ✓	0.45 ✓
Max GZ 30°-90°	≥ 0.20	[m]	1.55 ✓	1.91 ✓	2.56 ✓	2.44 ✓	2.77 ✓	2.84 ✓	2.62 ✓
Angle max GZ	≥ 25.0	[°]	24.0 ✗	26.9 ✓	38.4 ✓	39.0 ✓	39.5 ✓	39.8 ✓	36.8 ✓
Initial GM	≥ 0.15	[m]	4.63 ✓	4.97 ✓	3.70 ✓	3.47 ✓	3.93 ✓	3.94 ✓	4.38 ✓
Severe wind and roll									
Ratio area A/area B	≤ 1	[-]	1.01 ✗	0.72 ✓	0.23 ✓	0.21 ✓	0.22 ✓	0.22 ✓	0.34 ✓
∠Max static heel	≤ 16	[°]	2.5 ✓	2.0 ✓	1.8 ✓	2.1 ✓	1.7 ✓	1.7 ✓	1.9 ✓
∠Max stat heel /∠deck imm.	≤0.8	[-]	0.086 ✓	0.07 ✓	0.09 ✓	0.11 ✓	0.09 ✓	0.09 ✓	0.08 ✓

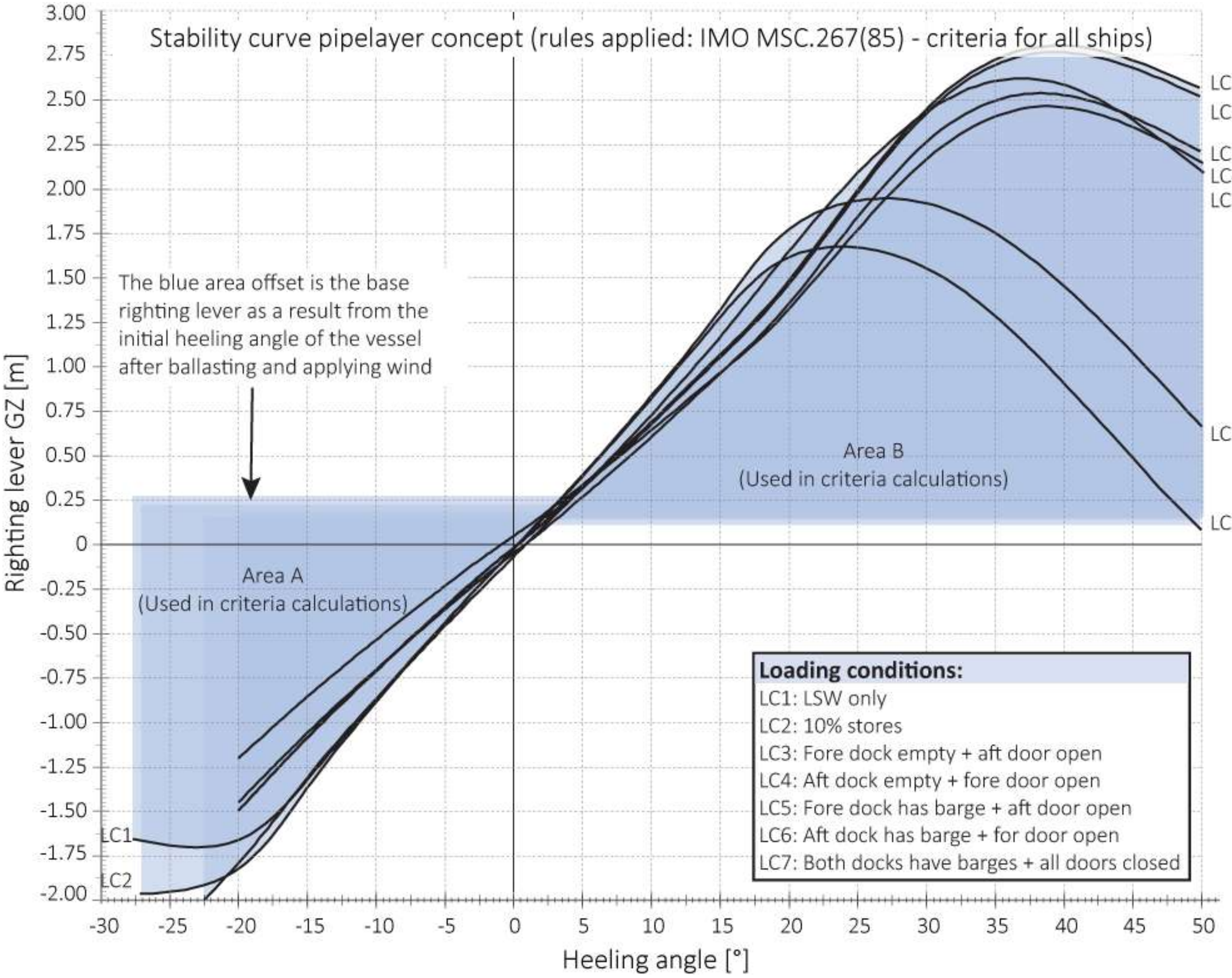


Figure 7.9. Righting lever of the pipelayer concept versus heeling angle for its seven loading conditions. The open dock conditions require a larger draught and thus have a significant lower centre of gravity and are thus more stable than the others

7.2.4 RESISTANCE AND SPEED PREDICTION

A Holtrop & Mennen calculation is used for the calculation of the ship's resistance and prediction for its speed. This is compared with the reference vessel calculation which have been adapted to match the model tests. The frictional resistance of the concept vessel has not increased proportionally to the increase in length, because the draught of the vessel in the sailing condition is only 6.35m whereas a draught of 7.2m had been used by IHC for the reference vessel. Although the frictional resistance of the concept vessel did increase with the increased length, its wave resistance is lower. This is the result of the elongation and the statistical approach of Holtrop & Mennen. The two resistances cancel each other out and the resulting predicted speed for the vessels is the same.

The available engine power is 85% of the total installed thruster power. This is the combined power of three 2950kW azimuth thrusters, which per contract requirement are run at 85%. The resulting vessel speed for the concept vessel with this power is 13.74kn. This is similar to the reference vessel at 13,71kn. Both are eventually higher than the target speed of 10kn which is the requirement from Petrobras for the Brazilian projects. The graphs can be seen in Figure 7.10.

7.3 CONCEPT VS REFERENCE COMPARISON

The final concept design is very similar to the reference vessel, but a few things have changed. Its length has been increased by 17m to gain the space along the tanktop to fit the docks. In addition, the lightweight has significantly increased because of the higher deck and increased length, though this was somewhat mitigated by the pipe carrousels that were removed.

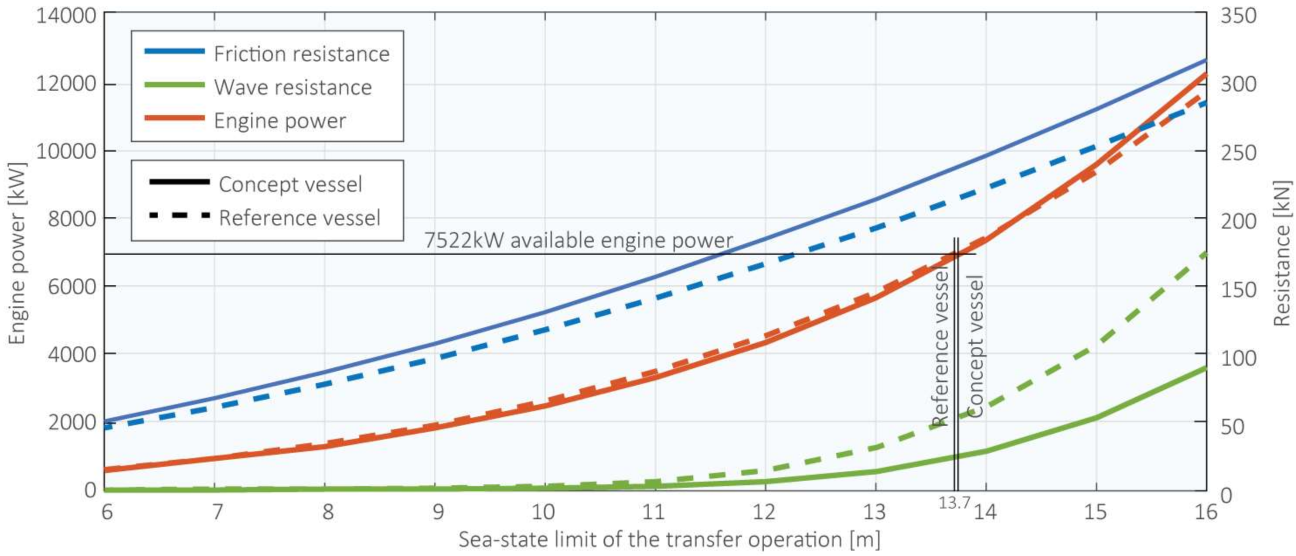


Figure 7.10. Speed prediction based on power and resistance graphs. The three 2950kW Azimuth thruster are used at 85% power. This is represented by the black horizontal lines.

Due to the changes the stability has of course changed somewhat, the metacentric height has somewhat decreased as the centre of gravity is now higher up due to the higher hold and pipelay tower. The need for a larger draught to load the barges, the size of the ballast tanks has been increased, this means that in ballasted condition, the vessel is deeper than the reference vessel. This is however, not a free sailing condition as is now used for the concept design. The general arrangement in Figure 7.6 can be compared with the reference vessel in Figure 2.1.

7.4 CHAPTER CONCLUSION

The pipe will be loaded onto the flexlay vessel by means of a large barge which contains a carrousel with a capacity 2064t pipes at a pipe diameter of 9”. This barge will be loaded into an enclosed dock in the side of the flexlay vessel and requires large ballast tanks to maintain enough draught when it is emptied and unloaded from the vessel so it doesn’t get stuck on the upper deck.

A new design was not required because the reference vessel lent itself to be modified to contain 2 side docks, without large modifications. The beam of the vessel is identical, and only depth and length needed to be altered in order to fit the docks. The vessel’s hold is heightened by 2.77m to 15.77m, which is almost one deck layer. The vessel is also lengthened by 17.94 meter to 152.94m.

Because of the large docks and the large amount of water entering the vessel when the dock doors are opened, a stability calculation is made to ensure the vessel is still stable in all conditions and the required submerged draught during loading can be achieved. This shows that all but one of the criteria are met and that it is possible to submerge to the correct draught. The only loading condition which does not meet the criteria corresponds to a lightweight only condition which is unlikely to happen in sailing conditions.

Table 7.6. Comparison of the main particulars of the reference vessel and the concept vessel to visualize the impact of the docks on the main dimensions.

Main particulars	Reference vessel	Concept vessel
Length waterline	135.00 m	152.04 m
Beam	29.94 m	29.94 m
Depth	13.00 m	15.77 m
Draught emtpy	4.65 m	4.90 m
Draught sailing cond.	7.20 m	6.30 m
Resistance	631 kN	632 kN
Thruster power (85%)	7522 kW	7522 kW
Vessel speed	13.71 kn	13.74 kn
Lightweight	13686 t	15463 t
Capacity	4000 t	4000 t
Centre of gravity (KG)	13.92 m	14.27 m
Initial GM (min-max)	3.78-5.52 m	3.47-4.77 m

8 CONCLUSIONS AND RECOMMENDATIONS

This chapter will summarize the main conclusions of the research. First the general conclusions from chapters 1 to 6 will be described briefly. Then the first and second sub-questions will be discussed followed by the case study and an answer to the main research question. This chapter is closed with recommendations for future studies.

8.1 GENERAL CONCLUSION

Flexible pipes come in small pieces of 200m and longer pieces of more than a kilometre. These are currently loaded by pipelay vessels in port which is essentially downtime for the pipelayer. It would be preferred if the pipelayer can stay on location and keep laying pipes all the time. This results in two possible logistic chains:

- Pipelay vessels return to port to get their own material and sail back to sea
- Supply vessels return to port and supply the pipelayer on site so it can stay on site

To find a solution, this thesis considers the effectiveness of the pipelayer in terms of the amount of pipe it lays per year because this is the main source of income for the vessel operator. This effectiveness is affected by the distance between the pipelayer and the spoolbase, the number of potential supply vessels and method of the transshipment they use. Logistical simulations lead to understanding of how this influences the pipelayer, and a lead to redesign the pipelayer to answer the main question: **“Is there a redesign of supply operations and a redesign of the flexlay vessel possible which uses supply vessels to improve the effectiveness of the pipelay operation?”**. As basis for these logistical simulations, the Brazilian field development of the Santos Basin is taken. This project lies 600km away from the spoolbase and uses pipes of on average 1000m. The seastate on which the logistics are dependent is based of Iceland.

Four transshipment methods are simulated:

- Spooling: This is dragging pipes out of one storage container and into the hold
- Lifting: Pipes are stored on reels which are lifted by a crane to the pipelayer.
- Floating: Pipes are stored in a barge, which is completely loaded into the dock
- Reference: The pipelayer sails back to the spoolbase to load pipes by spooling

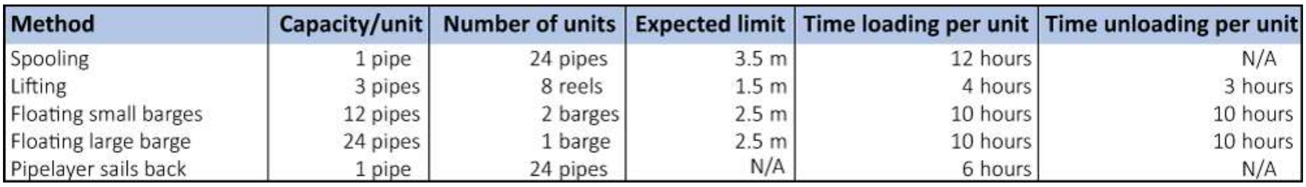
These methods are each distinct by the capacity of material that is transferred per move and the time required for it. A summary of the data can be found in Table 8.1.

8.2 FIRST SUB-QUESTION ANSWER

“What are the effects of distance and number of supply vessels on the effectivity of a pipelayer?”

For this evaluation of the distance and the number of pipelayers, the transshipment method is kept identical to the reference vessel. The analysis shows that it is possible to match the pipe demand of the pipelayer with two suppliers up to 1200km of shore. The gains from using suppliers become relatively larger for greater distances. These gains can be further increased when the pipelay vessel is able to lay pipes while simultaneously resupplied by a supplier. The gains are summarized in Table 8.2. These results are based on ideal weather scenario where transshipment is always possible to illustrate the relation to the reference vessel because pipelay activities are rarely interrupted in Brazil.

Table 8.1. Characteristics of the various transshipment and loading methods for pipelayers and suppliers in the logistical simulations



Method	Capacity/unit	Number of units	Expected limit	Time loading per unit	Time unloading per unit
Spooling	1 pipe	24 pipes	3.5 m	12 hours	N/A
Lifting	3 pipes	8 reels	1.5 m	4 hours	3 hours
Floating small barges	12 pipes	2 barges	2.5 m	10 hours	10 hours
Floating large barge	24 pipes	1 barge	2.5 m	10 hours	10 hours
Pipelayer sails back	1 pipe	24 pipes	N/A	6 hours	N/A

Table 8.2. First simulation set results based on ideal weather conditions. Transshipment is done by spooling pipes.

Distance	Simul. transfer	Effectiveness	Relative
600 km	yes	466 km/y	171 %
600 km	no	262 km/y	96 %
600 km	reference	272 km/y	100 %
1200 km	yes	465 km/y	211 %
1200 km	no	250 km/y	114 %
1200 km	reference	220 km/y	100 %

Another result is the confirmation that there is minimum effective distance. Closer to port it may be better, in terms of effectiveness, to sail back and forth with the pipelayer itself.

8.3 SECOND SUB-QUESTION ANSWER

“What are the effects of loading methods and seastate limits on the effectivity of the pipelayer”

Shown in Table 8.3 it is more effective to directly load barges with filled carrousels into the pipelayer than to transfer the material by the other methods. What can also be seen is that the transshipment wave height limit influences the effectiveness of the transfer. In weather conditions as found in Iceland, the operation should be possible up to limits of 1.75m to perform better than the reference vessel. This will change depending on the weather region, but shows that in harsh conditions, close to shore, activities with lower limits are no longer effective. Preferably, material should be transported in a barge which is docked into the pipelayer.

Like in the previous sub-question, results show that material should be transferred while pipelaying continues. Additionally, an evaluation is made of the cargo capacity of the pipelayer because the reference ship is currently used at 33% of its 4000t capacity. Simulations show that in the reference project a filling rate of 75% performs as good as when the vessel is filled to 100%. However, the capacity can directly affect the endurance of the vessel at greater distances.

Table 8.3. Second simulation set results based on Icelandic weather and expected operational limits in Brazilian projects.

Method	Simul. tran.	Effectivity	Relative
Spooling	yes	317 km/y	116 %
Lifting	yes	251 km/y	92 %
Floating small barge	yes	354 km/y	130 %
Floating large barge	yes	295 km/y	107 %
Reference vessel	N/A	191 km/y	100 %
Spooling	no	194 km/y	70 %
Lifting	no	303 km/y	71 %
Floating small barge	no	292 km/y	111 %
Floating large barge	no	295 km/y	107 %

8.4 RESULTING DESIGN

Based on the simulations the case study involves a design of a barge which can be loaded into a dock on the pipelayer. Both barge and vessel need to be designed for this purpose, the reference vessel is a good basis for the new concept.

The barge is designed with a 22m wide carrousel as in the reference vessel and is 24.2 x 24.2 x 8.3m. It contains the loading arm, control cabin and traction engines needed for operating the carrousel during loading and pipelaying activities. It has large ballast tanks in order to limit its draught when all the pipe is taken from the hold so it can leave the pipelayer without hitting the main deck.

The docks of the pipelayer are designed around the barge and are for now made 1m on the sides and below the loaded barge, and 2m above a ballasted barge. In between the docks 6 frames are reserved for walkways, the fuel tanks that were originally located between the carrousels, and potential access points into the dock. The docks themselves are closed by vertically moving doors, lifted up by kingposts on the main deck of the vessel.

The docks require the main deck to be raised by 2.77m to 15.77m. This is done from the aft to the deckhouse so that a continuous deck is created up to the pipelay-tower. This allows subsea structures stored on deck to be moved and installed above the moonpool. In additions the vessel needs to be elongated by 18.72m so that the docks can be placed at the level of the tanktop, and are deep enough for loaded barges to enter.

This increases the lightweight by 1800t to 15463t, and heighten the vertical centre of gravity from 13.92m to 14.28m. The draught and deadweight are calculated for seven loading conditions where the vessel is empty or loaded or has opened docks.

8.5 MAIN QUESTION ANSWER

“What is a possible redesign of supply operations and the flexlay vessel which uses supply vessels to improve the effectiveness of the pipelay operation?”.

The sub-questions showed that there is a lower limit of 600km from which the spooling concept has a better performance than the current reference vessels. It also showed that the percentual usage of the vessels’ capacity decrease its performance by more than 40% as shown in Table 8.4.

A final simulation for the concept vessel parameters shows that the concept vessel can operate close to shore with only one supplier or with two tugs. Both result in optimal effectiveness. The concept vessel can lay pipes up to 370 km/y when supplied. This is an increase of 47% compared to the reference vessel which lays 255 km/y. The performance of the concept vessel drops when the used capacity of the carrousels and/or barges is lowered to 50% and more transfers are needed per project. Many projects in Brazil use only up to 30% of the vessels’ capacity. This does affect the net gain of loading and unloading at sea. The project a ship is designed for should be kept in mind as it might not be able to perform at its best.

Table 8.4. Final simulation set results based on the Icelandic weather and expected operational limit of the concept vessel in Brazilian projects.

Method	Capacity	Effectivity	Relative
2 Supply ships	50%	310 km/y	122 %
1 Supply ship	50%	275 km/y	107 %
2 Tugs	50%	270 km/y	106 %
No supply (ref)	50%	230 km/y	90 %
2 Supply ships	100%	375 km/y	147 %
1 Supply ship	100%	367 km/y	144 %
2 Tugs	100%	362 km/y	142 %
No supply (ref)	100%	255 km/y	100 %

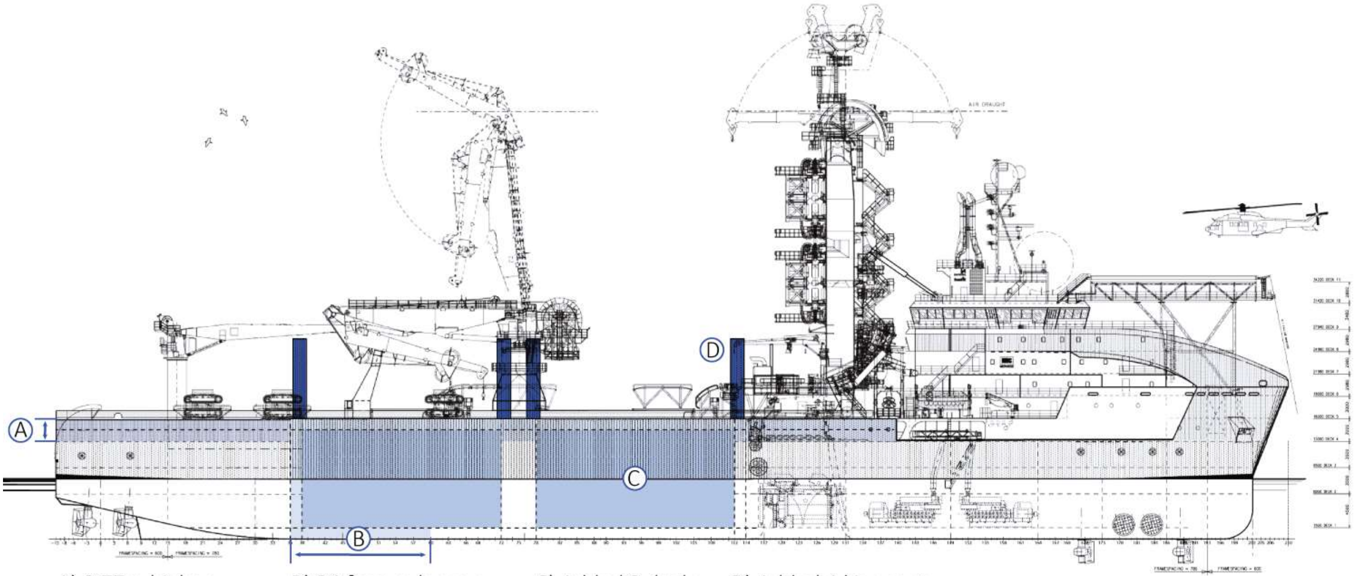
Table 8.5. Estimation of the profit that can be made based on rough estimations of the dayrate.

Composition	Pipe laid	Rate/km	Profit/km
Reference vessel (50%)	230 km	$ 428,478	$ 0
Concept vessel (50%)	270 km	$ 438,000	$ -9,522
Reference vessel (100%)	250 km	$ 386,470	$ 42,008
Concept vessel (100%)	367 km	$ 328,201	$ 100,277

The financial estimation shows that the costs per km pipe can be decreased from a worst case of $428,478/km to $328,201/km in the best case as visible in Table 8.5. The price per km pipe for the concept vessel results in losses when it is only loaded up to 50% of its capacity. A result that is subject to the weather conditions and an increase in the number of transshipment moves due to the smaller barges. This leads to increased waiting times for suitable weather conditions.

At greater distances the time travelled to port will start to add to the delays and performance starts to plummet. However, the effectiveness of the reference vessel drops more and the concept solution becomes a more attractive alternative.

The design of the pipelayer concept is shown below in Figure 8.1. The changes made to the original vessel are illustrated in blue in the sideview.



A) 2.77m higher B) 24 frames longer C) Added 2 docks D) Added 4 kingposts

Figure 8.1. GA sideview of the concept vessel.

8.6 RECOMMENDATIONS

During the thesis a couple of parts were not researched in detail after their importance became apparent. These parts are left for future research as they are outside of the scope of the study. Eight separate topics will be proposed for further studies.

Strength calculation

This aspect is the most critical open end to the research because of the added docks. A lot of open space is created around them and strength is lost with the replacement of part of the hull by the two large doors. The doors also need to be closed so a watertight hull is formed and need to resist the natural bending of the vessel.

Modelling the vessel-barge interaction

At the time of writing, diffraction performance on dockships is being researched at the MARIN, which states that this problem isn't yet solvable mathematically. This problem came up during the investigation of relative motions between the barge and vessel some limitations of diffraction software came to light as explained further in Appendix H.

Financial study in detail

A financial study should be linked to the workability and scenario simulation. The vessel passes through all the different states of activities, which should allow to link fuel usage to the different stages. This can be combined with initial capital investment into the larger, and more complex, pipelayer, the barges, suppliers, or the chartering of tugboats. Including these will provide insight in the financial feasibility of adding supply vessels to the logistics chain, potential gains, and return on investments.

This financial study will supplement the minimum distance at which the concept vessel becomes financially more stable. The existence of a minimum effective distance was already made clear when looking at the raw installed length of pipes per year, which illustrated that the relative gains of transshipment at sea decrease closer to the shore. This financial study needs to be combined with simulation results using applicable weather data.

Seastate region

The study should also be performed using the persistence or timeseries data from other regions where the pipelay vessel is expected to be operated, such as Brazil or the North Sea. This means that data from the actual relevant field development regions should be acquired.

Mission profile

The mission profile determines the sailing distance, water depth and other project characteristics. These in turn impact the number of trips a vessel needs to take. Different projects may have different gains from using supply vessels. For instance, a single trip project off the coast of Africa might be better performed by the reference vessel. This indicated the need for a case-based evaluation.

Persistence model

The persistence model is now based on the standard data format as mentioned by papers such as Hogben et al. [7] which only considers wave heights. However, it is for instance also possible to use a 3D matrix which contains the probability for a sea condition to change wave heights (Hs) in one direction and to a wave periods (Tp) in another.

Generalizing simulation models

Both persistence and logistical model are now built specifically for this thesis and might be useful for other studies after adjusting the code. Making the code more intuitive will open up more possibilities for new users and in new projects.

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APPENDICES

Appendix A BRIEF DESCRIPTION OF DIFFERENT PIPELAY SYSTEMS

This appendix serves as background information, providing a short introduction to oil and gas pipelay systems for readers who want to know more about this topic. Information in this appendix has been used as inspiration for the thesis proposal as well as for the final concept design in one way or another.

Different types of pipelaying methods are chosen for different projects depending on the type of pipe, the depth, and the preferences of the oil and gas company. Two types of pipe, rigid and flexible, are available to both of which come with their own specialized pipelay systems.

To illustrate how the different concepts have evolved, a brief summary of the advancements since the inception in the second world war will be made in the first section before continuing to the different systems used by modern day operators in the second and third section for rigid and flexible piping respectively.

A.1 HISTORY OF PIPELAYING

Starting in 1942 with a secret project meant to supply gasoline for the allies during the invasion of France inspired by cables that were laid over the seafloor. Oil and gas companies have moved their operations from the mainland to operating depths of up to 3000 meters under the ocean.

1942

The first instance of a vessel laying an underwater pipeline occurs in 1942 when the English support the invasion forces by laying a flexible pipeline with a soft lead core called HAIS [20]. This was quickly replaced by a rigid steel pipeline, called HAMEL, as a cheaper alternative to HAIS due to the high costs of lead. In total, thirteen flexible pipelines were laid over 130 kilometres between the Isle of Wight and Cherbourg and eight rigid pipelines over 50 kilometres between Dungess and Ambleteuse.

The lines were rolled on floating conundrums that would be either pulled by tugs or installed on a vessel as shown in Figure A.1. These reels had a capacity of 180 kilometres weighing about 6000 tons, about twice the capacity of most modern pipelay vessels which are shown in Figure A.2.

1950 to 1990

The first commercial offshore pipeline was laid in the Gulf of Mexico by the lay barge Herman B [21]. In the following decade, extra equipment such as stingers and tensioners were introduced to support the pipes during pipelaying. These allowed moving to deeper waters. Barges were inefficient due to the reliability on favourable weather conditions and were slowly replaced by dedicated pipelay vessels able to work in the harsher North Sea. As companies ventured to deeper waters and the depth limit of S-lay was reached, the J-lay concept grew in popularity for its ability to lay pipes in waters up to 2000 meter.

Figure A.1. The Pipe Lines Under the Ocean project (P.L.U.T.O.), to the left the large conundrum to which the pipe was wound, to the right the tugs which were used to roll out the pipe as it was laid across the English Channel (Source: [15])

Figure A.2. The Lewek Constellation and the Saipem Castorone are two of the largest pipelaying vessels today. Both vessels can be resupplied with new pipes at sea (Images from: [27] [28])

Present day technology

Today's vessels are in increasing amount designed for working in icy condition and use dynamic positioning. The vessels can be equipped both J-lay and S-lay configurations for extra flexibility and can as such lay both flexible pipelines and rigid pipelines of increasing diameters.

The Lewek Constellation and Saipem Castorone, shown in Figure A.2, are amongst the largest pipelay vessels today. Both are capable of laying pipes in waters more than 3000 meters deep and illustrate how pipelaying has advanced. They are equipped with large cranes so new pipes can be loaded onto the vessel in parallel to pipelaying activities. This capability allows the operator to reduce the pipelay vessels' transit times.

A.2 RIGID PIPE SYSTEMS

There are four main systems for rigid pipelaying: S-lay, J-lay, Reel-lay and towed pipelay. These will be discussed in the following subsections together with their advantages and disadvantages.

S-lay

The S-lay system derives its name from the shape of the pipe during the pipelay operation as illustrated in Figure A.3 on the right. With this system, the pipe starts from a horizontal position form the vessel. On the deck, the generally 12m-long pipes are welded together, checked by x-ray and then coated [22].

During the continuous assembly, the pipelines are led through tractions units which control the tension in the pipeline. From here the pipe is guided onto a large ramp, the stinger, which restricts the bending of the pipe as it leaves the vessel. This prevents buckling in the upper section of the pipeline [23].

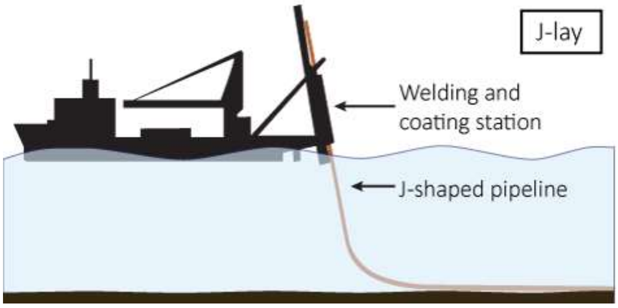
The advantages of the S-lay system are the fast installation time, the wide range of diameters that can be handled and the large range of water depths [24]. In addition, the short pipe-sections are easy to transship at sea, allowing the pipelayer to stay on site. Vessel motions and tension in the pipe are the main limiting factors and the maximum project depth is limited by the bend in the pipe.

J-lay

The J-lay system derives its name from the J-shape of the pipe during the pipelay operation as illustrated Figure A.3 on the left. It can lay pipes up to a depth of 3.350 meters [23]. The pipe is assembled in a vertical position in the J-lay tower which includes welding and coating, and checking. This tower's angle may be aligned with the pipe to reduce the bending forces at the seabed [22].

Four pipe lengths of 12 meters may be pre-welded together to create a piece of 48 meters, before being lifted into the tower. A clamp raises the pipe, and positions it over the assembly station where the previous pipe is held, suspended in a tensioner.

Like in the S-lay system, the small pipes allow for easy restocking at sea and the vessel does not have to return to port. The tension exerted on the pipe can be lower than in S-lay systems because there is no need for a horizontal component to prevent the buckling in the pipe as it leaves vertically. This also decreases the amount of bending and fatigue the pipe experiences due to ship motions. Finally, the vessel requires less power to maintain position.



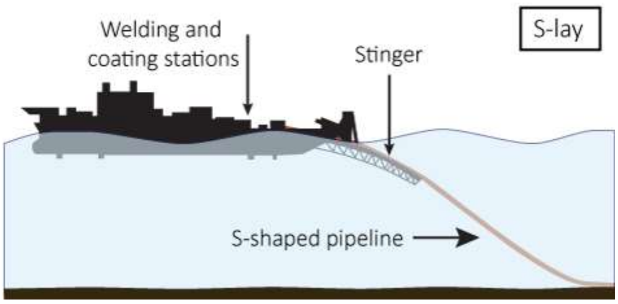


Figure A.3. The S-lay system (left) and the J-lay system (right)

The most important limitation is the single welding position in the tower, compared to multiple welding stations in the S-lay system. To mitigate this, up to four sections can be pre-welded [23].

Reel-lay

Reel-lay systems store long lengths (multiple kilometres) of pre-welded steel pipe on large reels. The pipe is plastically deformed in the process and needs to be straightened when unspooled.

The reel is oriented either horizontally or vertically as illustrated in Figure A.4. In the horizontal case, the pipe will leave the vessel supported by a stinger after being straightened as in an S-lay type vessel. In the vertical case, the pipe will often be led through a tower like in a J-lay type vessel. The horizontal reel design leads to a lower centre of gravity, but is more difficult to keep in place during loading and laying. In addition, the pipe bends more often before leaving the vessel.

The reel-lay system combines the precise J-lay method with a higher effective lay rate as the pipe pieces don't have to be welded on the pipelayer. This also means that the welding, coating and control can take place onshore in a better environment.

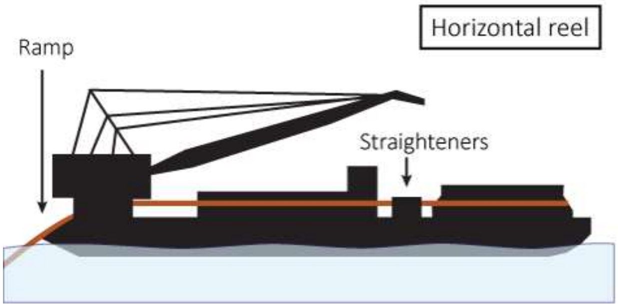
The biggest disadvantage is that the vessel needs to return to port to restock after expanding its storage. Another is the plastic deformation of the pipe when it is loaded onto the reel, reaching up to a strain of 2% [25]. This gives the pipe an oval shape, causes permanent elongation and reduces the resistance to external pressure. The deformations can also influent welds, initiate cracks and reduces the fatigue resistance.

Towed pipelay

In towed pipelay short pre-welded, checked, and coated pipes are transported by tug to their destination. The disadvantage of towed pipelaying is the limited length of the pipes and the sensitivity to the weather. It is often used in shore approaches where pipe is towed from the shore into the water and sometimes in smaller production systems. There are four different types of towed pipelay: surface, subsurface depth, off-bottom and bottom tow each illustrated in Figure A.5Figure A.. These methods are described in Mechanics of Offshore Pipelines [23] and Tow Techniques for Marine Pipeline Installation [26] and will be discussed briefly below.

Surface tow

Surface tow is mainly used in shallow waters up to 50m deep. The pipeline is connected to buoys that provide enough buoyancy for the pipe to stay at the



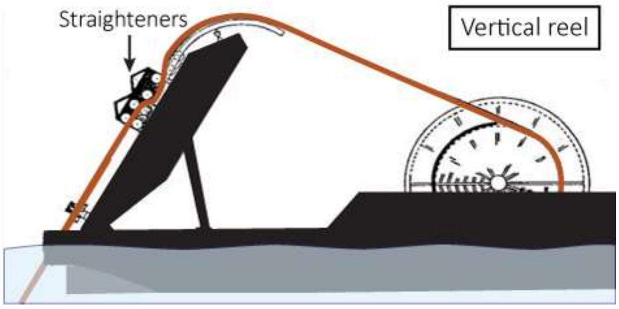


Figure A.4. Two variations of reel lay vessels [23].

surface. The pipes will be transported to the location and welded together on a barge before being lowered to the seabed. The advantage of this method is that during favourable weather circumstances, heavy pipelines can be installed without experiencing high tension forces. The main disadvantage is however the sensitivity to wind and waves. This causes oscillations and fatigue at the trailing end.

Subsurface tow

The pipe is towed below the surface at a fixed depth by two tugs required for the transport for lateral stability. It is supported by buoyancy modules with chains that act as counterweights and prevent oscillations. The chains and buoyancy modules are removed on location before the pipes are lowered onto the seabed. With this method, the pipe experiences less disturbances of the weather. The tension keeps the end from oscillating. The operation is dependent on the bollard pull of the tugs, their coordination in different sea states and the limits to the tension.

Off-bottom tow

Similar to the constant depth tow method the pipeline lateral stability and buoyancy are ensured by buoyancy modules and chains, but it is towed by a single tug. The chains act as both weights and springs, ensuring that the pipe stays at a constant depth. From this position the buoyancy modules can be released or filled with water, allowing the pipe to sink to the seabed. This method is more complicated than the bottom tow but there is no interaction with the soil and still little influence of waves and currents.

Bottom tow

In this method the pipe is dragged over the seabed weighed down by a sled. When necessary, the sled is pulled from the sea bottom lowering friction forces and increasing control of the pipe. This makes the pipe the least susceptible to currents, waves, and fatigue than from all the towed systems. The route needs to be cleared of obstacles and holes and the type of soil needs to be known to calculate tension in the pipeline and prevent damage to the pipe and its coating.

A.3 Flexible pipe systems

There are three major flexible-pipelay systems, these are the J-lay like flexlay method, the s-lay like horizontal-lay method and the triple lay methods.

Flexlay

The pipes are stored on the ship in continuous lengths of generally 1000m in length. The vessels are most often loaded in ports alike reel-lay vessels. They are then taken out from the hold lifted to the top of a pipelay tower and then lowered vertically to the seabed alike the J-lay system for rigid-lay vessels. This method removes the need for welding station on board of the vessel as separate parts are bolted together. The disadvantage of the method is the need to travel back to port once the holds have been emptied. In addition, the pipe itself is complex and more expensive to fabricate than steel.

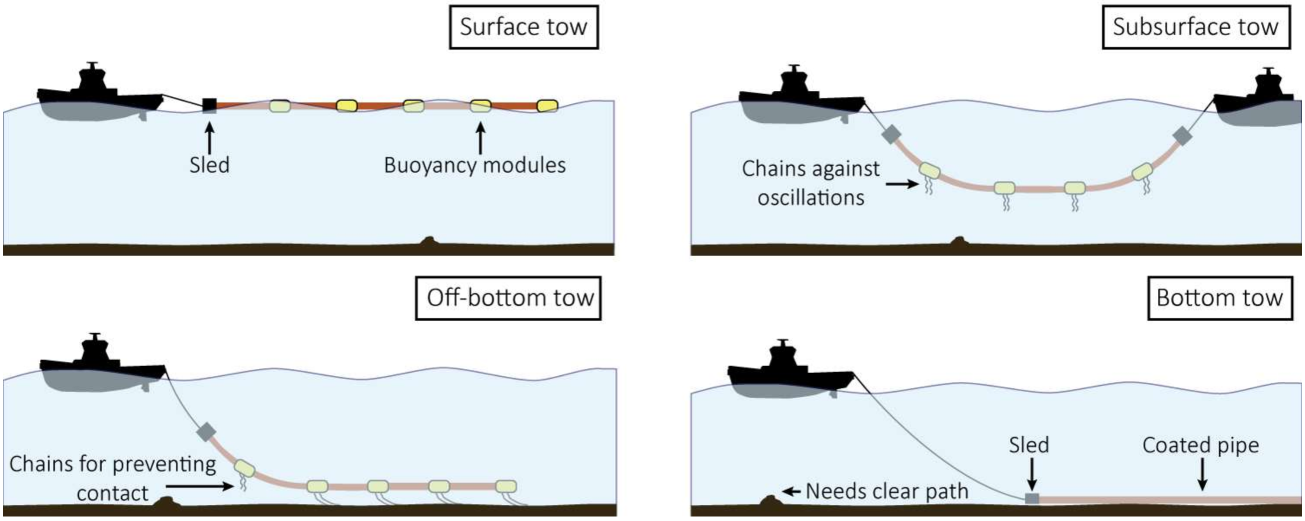


Figure A.5. Four different methods of towed pipelay [25]

Horizontal lay

Horizontal lay is similar to the S-lay system for rigid-lay vessels. The pipe is led through tensioners on the deck to the rear of the vessel where it leaves the vessel from a small ramp. The advantage of this system is that it does not require a pipelay tower or a moonpool and any subsea structure can easily be lifted over the side of the vessel. The disadvantage is the bending forces on the pipes when it moves through the ramp, and the sensitivity to ship motions in heavy weather. In addition, bigger tensioners are needed to handle larger tension.

Triple lay

Triple lay is a name for a system which lays all three pipes that run from wells to FPSO's at the same time. These pipes are the umbilical, annular and flowlines. The pipes are stored in separate locations on the vessel in either carrousels or on reels. The pipes are then led from the rear of the vessel similar to the horizontal lay method. The pipes are then either connected to each other as they leave the vessel or laid independently.

The advantage of the triple lay system is that only one pass has to be made to connect the flowline, annular and the umbilical to the well and to the FPSO. The disadvantage is that all the structures from the wellheads to the FPSO have to be designed specifically for triple lay. In addition, the entire field has to be laid out to support this which is not always favourable.

Appendix B FLEXIBLE PIPING AND PROJECTS

This appendix provides background information on flexible piping in offshore projects. It is generally used for the upper part of riser systems, where the pipe experiences a lot of motion and requires regular replacement. In some rare cases, this flexible pipe is also used for flowlines on the seabed.

First the composition of the flexible piping will be discussed, followed by common components which are frequently installed together with the pipes by the same vessel during projects. A brief description of the various projects will close this appendix.

B.1 FLEXIBLE PIPE AND COMPONENTS

Flexible piping is generally installed together with large components that connect the pipe to wellheads and manifolds where smaller pipes come together and are combined into larger ones.

Flexible piping

Flexible pipes are made up of different layers to prevent leaking and corrosion, provide tension resistance and protect against outside pressure. These layers make the pipe both flexible and expensive and are illustrated in Figure B.1.

The flexibility of the pipe prevents some common problems in rigid piping where large lengths could be unsupported on an uneven seabed, as it bends along with the soil. This means less bridges and supports have to be constructed below the water. The flexibility also allows the pipe to be stored in a carrousel or on a reel in long continuous lengths. This length varies from smaller pieces of 200m to several kilometres depending on its function and the project. Inner diameters range from 4” to 20”, but bending radii decrease as the diameter gets larger. This type of piping enables routing at the sea bottom in complex subsea layouts, and because it does not deform during the construction it may be later retrieved and reused in other projects.

Layer compositions differ depending on the depth of the subsea network and the inner diameter of the pipe required for the transport of the product.

Figure B.1. Composite layers of a flexible pipe [31]

The properties of some representative flexible pipes are shown in Table B.1. The 9” pipe mentioned in that table has been used as reference during the thesis research.

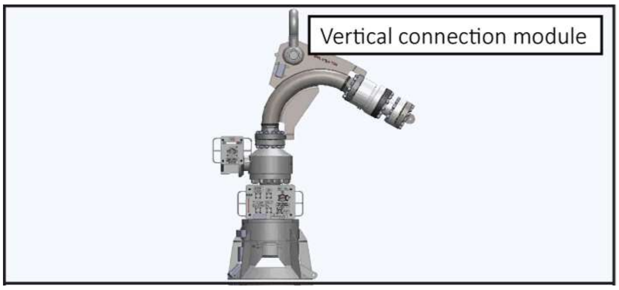
The life expectancy of a pipe is 25 years. However, the top part of a riser (a pipeline going from the seabed to an FPSO on the surface) is in almost constant motion, and needs regular replacement.

Common subsea components

Two subsea components in particular are regularly installed together with flexible piping, vertical connection modules and pipeline end terminations. Both items are illustrated in Figure B.2.

Table B.1. Flexible pipe properties for several diameters. the 9" diameter pipe is the reference used throughout the thesis. [18]

Flexible pipe properties							
Pipe size	Layers	Design pressure	Design temp.	Int. diameter	Ext. diameter	Weight (empty)	Min. bend radius
4 inch	7	207 bar	65 [°C]	101.6 mm	158.7 mm	46.7 kg/m	1.1 m
6 inch	7	207 bar	45 [°C]	152.4 mm	229.8 mm	84.9 kg/m	1.6 m
7 inch	8	207 bar	65 [°C]	177.8 mm	280.4 mm	125.0 kg/m	1.8 m
7 inch	18	207 bar	70 [°C]	177.8 mm	426.9 mm	209.8 kg/m	2.8 m
9 inch	10	310 bar	65 [°C]	228.6 mm	374.5 mm	222.2 kg/m	2.4 m



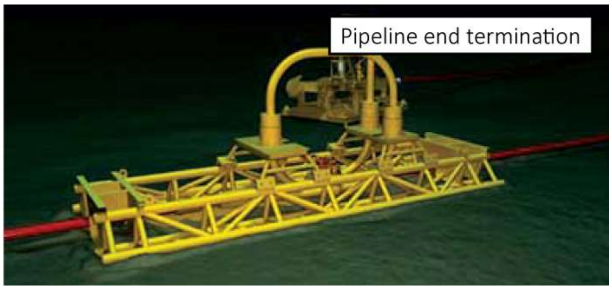


Figure B.2. Two common flexible pipe components. On the left a vertical connection module is being connected to the flexible pipe. This is hard to see because offshore regulations require everything is yellow for safety. To the right a pipeline end termination is

The vertical connection modules connect the flexible pipe to wellheads and connection hubs. The structure consists of a hydraulic connector which has to be operated by a remotely operated underwater vehicle (ROV). These modules are used at the start and end of most flexible pipe projects.

Pipeline end terminations are used where the line on the seabed stops and transfers in a vertical pipe that goes to a FPSO. The end terminations may reach lengths of up to 12m and weigh between 40t and 200t.

B.2 DESCRIPTION OF PROJECTS

This section will be primarily focused on the characteristics of the Brazilian project. The research is based on Brazilian projects because the most information is available here and because it is the main operating region for the reference vessel.

Brazilian projects

Field development in Santos Basin of Brazil consists of 24 planned FPSO's planned each servicing 30 wells with most of the piping made up of flexibles. Petrobras prefers this type over rigids because of flexibility in laying activities and the reusability of the pipe. Petrobras even imported the pipe from Europe's spoolbases at the start of the field development until Technip erected a spoolbase in Vitória. The 10 times higher price of the pipe compared to rigid steel piping has not returned them to using rigids. The fields are located at the current limits of flexible pipes on record depths of up to 3000m.

The Vitória spoolbase has only 2 quays however, and together with the weather, tide, and daylight restrictions on entering the harbour, large queues appear now and then. On occasion vessels have to wait a couple of days in front of the harbour with extreme cases of up to 20 days. To reduce the capacity bottleneck at the spoolbase, smaller vessels are asked to lay pipe at shallow waters (100m) outside the port for temporary storage during quiet moments as a way of peak shaving. The pipe marked with a buoy making it possible for the next vessel to pick it up a later time without having to enter the spoolbase. This is only possible because of the reusability of the piping.

A Technip pipe production facility at Acu, between Rio and Vitória, supplies the current spoolbase with extra material, which is transported over land by trucks for now while a new port is being constructed here. This port will reduce the sailing distance from 600km to 200km and increase the number of vessels that can be loaded at the same time. GE Oil & Gas - Wellstream has a spoolbase at Niterói, a port near Rio de Janeiro, but this became too small for the newest generation of pipelayers.

Due to choices in project planning, the vessels are generally filled up to a third of their capacity this takes three days. Loading one pipe takes usually 12h regardless of the length. Two pipes can be loaded at the same time to speed up this process.

Pipelaying

Before the pipelaying can commence, surveys are made of the pipe route. As wellheads may be constructed years before the exploitation of the field the connection hubs are covered to prevent dirt and rust of making it inoperable. ROV's are used to remove the cover of the manifold or wellhead hub and clean the connection point in advance.

The actual pipelaying starts often with placing a VCM on either a wellhead or a manifold. The pipe and VCM are first lowered to 3000m within close proximity of the connection hub, where the VCM is connected to the heave compensated crane and lowered onto the connection hub.

The pipe is routed along a predetermined route, as shown in Figure B.3 and fixed with chains to anchor torpedo's or suction anchors. Provisions to connect the anchors to the pipe are installed at the moonpool during the laying procedures, but the physical connection is made by ROV at the seabed. Contracts demand an average lay-speed of 200m/h [27] but peak speeds of 600m/h are possible if delays need to be made up. At the end of a project it may be necessary to pass over the line to make sure everything is in order.

Three different types of pipe are connected to wellheads, and can all be laid by a pipelay vessel. These are a flowline through which the oil or gas will be transported, an umbilical containing electrical cables for power and control of the wells and an annular which has the function of pumping waste material such as mud back into the well. The umbilical is the stiffest of pipes and comes into very long continuous lengths ranging from a few to more than 100km [28] as any connection will lower the efficiency of the cable. The cables are, however, less heavy than the flexible piping ranging between 40 and 150kg/m.

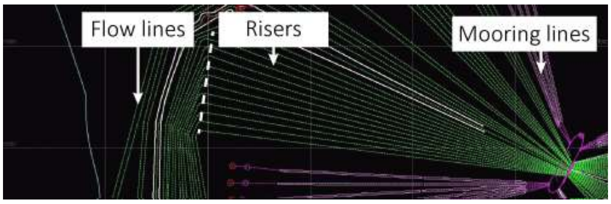


Figure B.3. Subsea configuration of pipes showing risers, flowlines and mooring lines near the FPSO

Appendix C VERIFICATION OF OPERATOR DATA

It is good practice to compare the different data sources from interviews and online documents and check them for consistency and reliability. This is important because the results of the simulations are dependent on their input. A few different variables, such as project size, laying speed and sailing times will be verified below.

Project size and carrousel capacity

Based on the performance of pipelay vessels from Sapura [5], four vessels performed a total of 336 projects laying 1566km pipeline. This results in an average of 4.66km per project. This value should match the expected used carrousel capacity.

During interviews [1] it was stated that the largest carrousel of the vessel has not been further filled than 1/3rd of its capacity. To verify if this matches with the project size, the calculation below assumes the reference 9” pipe from Appendix B with an outer diameter of 374.5mm. For ease of computation, and because the pipes will not be perfectly rolled together, 400mm is assumed in Figure C.1.

With a height of 6.750 meter in the carrousel, it is possible to create 18 layers of piping, each with a length of about 725m. After six layers the vessel carrousel is filled for one third. This is equal to 4.80km. This value matches the project size of about 4.66km. These values are assumed reliable.

Duration for loading and transit

The loading time for the vessels is based on the number of pipes to be loaded onto the vessel. Filled only for one 1/3rd of the capacity, this means that approximately 6 pipes of 800m are loaded into each carrousel. The same sources state that loading takes 12h per pipe as the loading time is not dominated by the length of the pipe, but the handling and preparations. Because two pipes can be loaded into the two carrousels at the same time, 5 passes need to be made. This adds up to 3 days of loading. This matches the operator estimation that the vessel spends in general 3 days in port.

The operator estimates the time to get from the port to the offshore field is about 1.5 days. There is a clear relation to the average speed of the vessel. With the Santos Basin field development at 600km (320 mile) from the Vitória spoolbase and a design speed of 10 knots this trip takes 32 hours.

Project duration and mean lay-speed

The Petrobras contracts demand that the average lay-speed cannot go below 200m/h on punishment of not being paid. There are a few ways to check whether this value is useful for the simulation model. The Petrobras definition for a project is everything between two port visits. However, the activities could range from just some delivery to full pipelaying activities and some flexible thinking is required during this validation to find a ‘standard project’ definition which can be used in the logistical model.

With a minimum laying speed, and activities that continue 24 hours per day, the estimated time to lay 4.6km flexible piping (assumed one complete

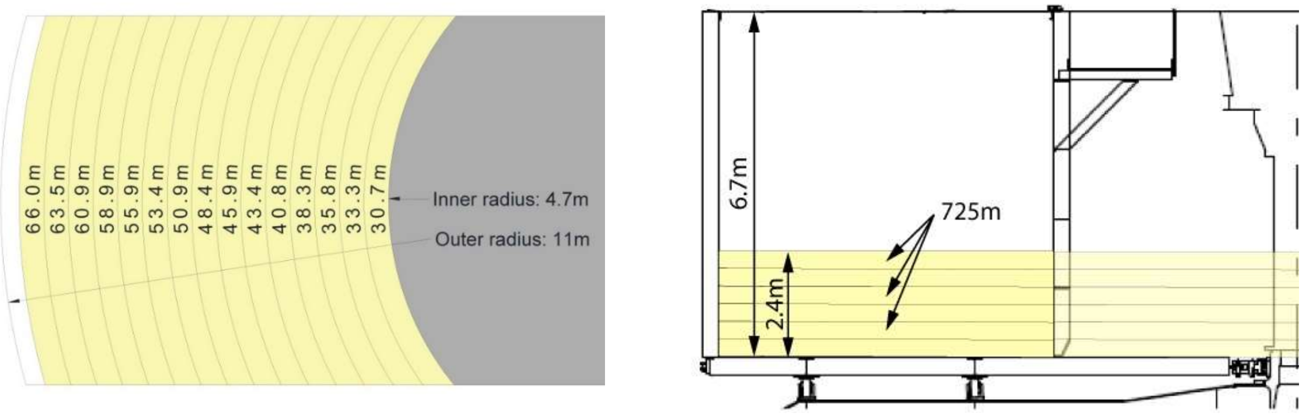


Figure C.1. Lengths of a layer of 9-inch piping in the carrousel with a 400mm outside diameter project) is 23 hours. In reality, total time on site is much larger due to a large overhead of supporting activities. The operator suggests that the time between port visits is approximately two weeks. It takes on average 6.5 days per roundtrip. This leaves only 12 hours for the entire pipelaying operation.

However, if both holds are loaded for one third of their capacity then 9.6km of pipe is loaded with which 2 ‘projects’ can be done in a row. This is the first discrepancy between the definition of a project (all the work between 2 port visits) and the time required for a project: 2 weeks as indicated by the operator. Taking the 2 partially loaded holds results in a 13-day roundtrip. The calculation in Table C.1 gives an overview of the numbers mentioned in Figure C.2. It also shows the relation to the average, which illustrates that there is a lot of variation in the same field for the sister ships.

The loading and transit data, and estimations on different activities by the operator is used as input for the logistical model. Multiple runs result in a roundtrip of 13 days for 2 projects of 4.8km, each consisting of 6 pipe segments of 800m. The results from the simulation coincides with figures from the operator.

Table C.1. Average project size and duration per reference vessel. The average values are adjusted to 365 days for this calculation

Vessel	Duration	Projects	Total pipe handled	Project dur.	Project size	Rel. dur.	Rel. hand.
Sapura Diamante	731 days	123	560 km	5.9 d/prj	11.9 km	91%	99%
Sapura Topazio	727 days	82	438 km	7.9 d/prj	15,8 km	121%	78%
Sapura Jade	364 days	54	270 km	6.7 d/prj	13.5 km	104%	96%
Sapura Esmeralda	364 days	67	360 km	5.4 d/prj	10.9 km	84%	128%
Average	365 days	56	272 km	6.5 d/prj	13.0 km	100%	100%

Figure C.2. Sapura performance figures [5]. The averages of these figures were used to set up and validate the logistical model.

Appendix D SEASTATE PERSISTENCE ALGORITHM VALIDATION

To validate the seastate pattern resulting from the persistence algorithm of Chapter 5, three approaches are taken. The first is a visual validation. The second a persistence graph validation by plotting the persistence data to find the perceptual deviation from the original data. The third validates if the seastates match on a scatter diagram basis. And the fourth is a validation by comparing simulation results between the algorithm timeline and the original weather data by running the logistical model with both timeseries.

Visual validation

The main goal of the algorithm is to include the time aspect of persistence of seastates, in order to remove the statistical simplification of scatter diagrams, which is the standard route to workability analysis. The timelines are shown in Figure D.1 where the improvement of the persistence model over a "scatter diagram approach" can be easily observed when compared to original timeseries. The visible ranges are selected from autumn and are to contain seastates up to 6m.

Persistence graph validation

A variation on the persistency graphs is used for this comparison which uses cumulative occurrences of the seastates. This integral can be interpreted as the probability of exceeding a seastate [29]. In addition, two graphs are shown: one for storms, and one for the calms. Storms are occurrences during which the significant wave height (Hs) is equal to or higher than a threshold, while calms are the opposite. Both are shown on the next page in Figure D.3. Two runs will be evaluated. The first is a testcase with a regular wave pattern of 0, 1 and 2m occurrences as shown in Figure D.2. The second is based on the actual timeseries data [30].

In the creation of persistence data, the source time series is cut up into four seasons. At the transition between seasons occurrences are cut in two. This results in more occurrences as can be observed in

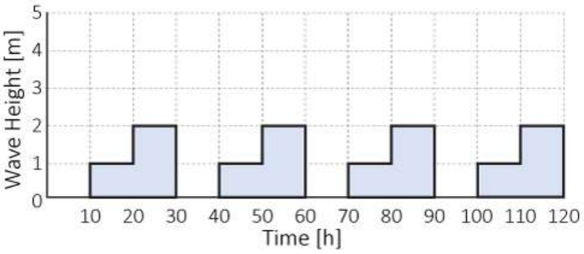


Figure D.2. Test input for the persistence algorithm validation

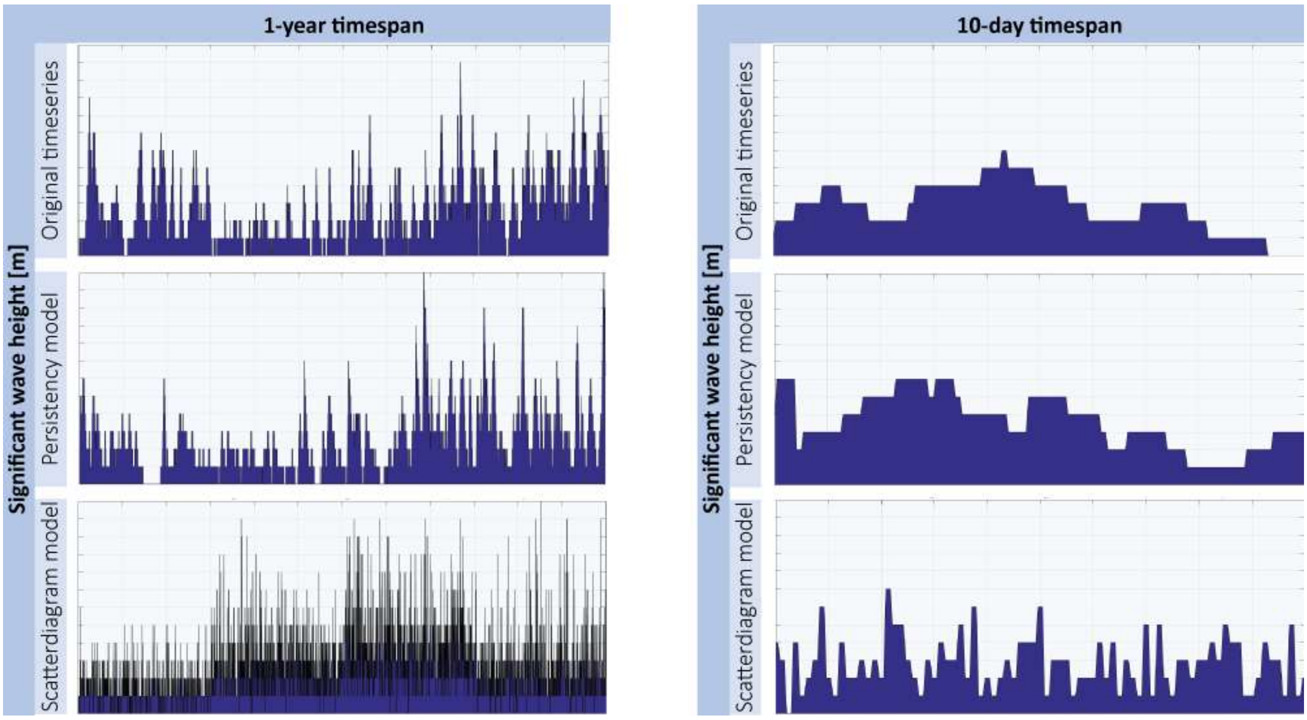


Figure D.1. Visual comparison of the algorithm results with the original timeseries and a timeseries based on scatterplot data. The images are taken from autumn and are selected to have wave heights up to 6m.

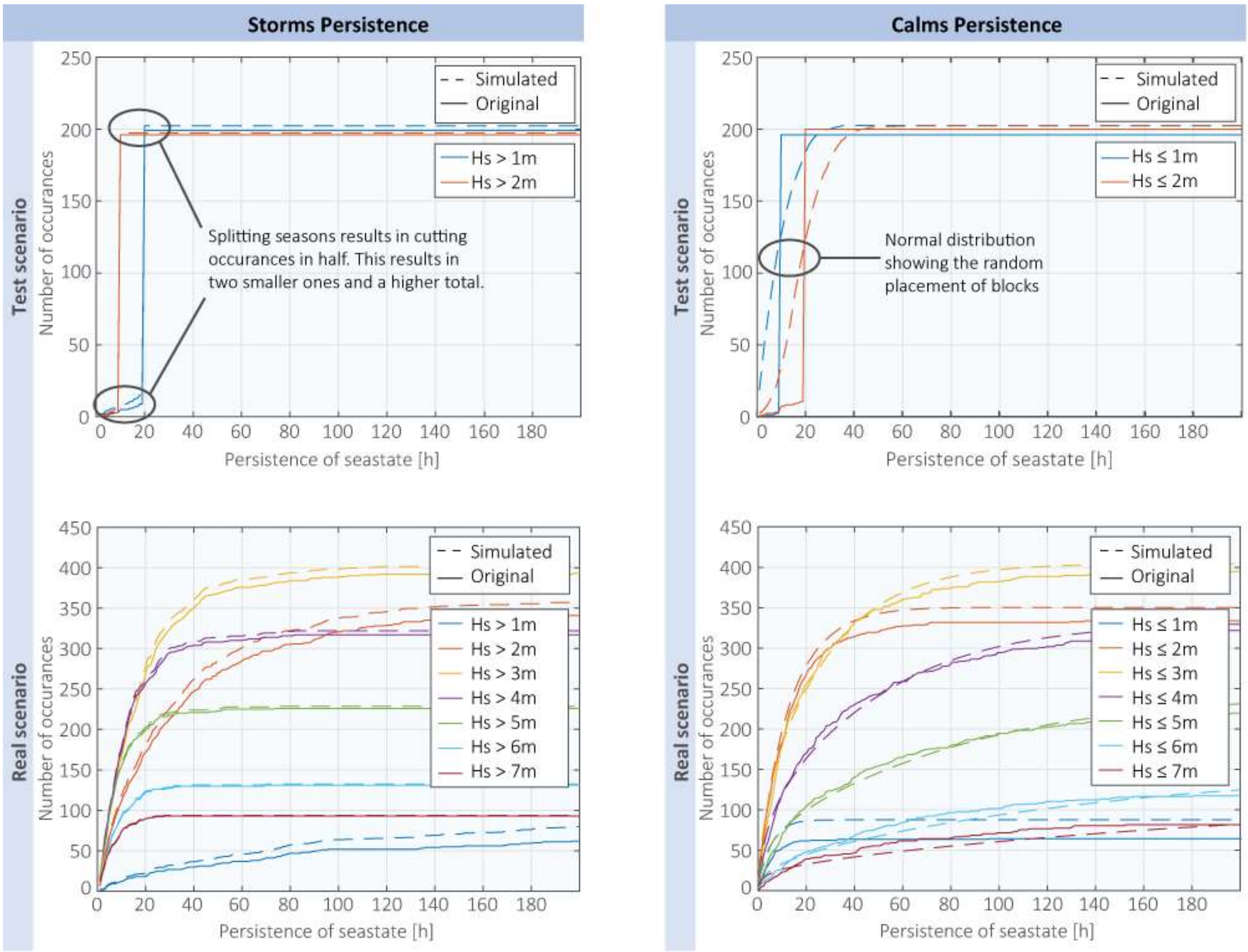


Figure D.3. Calms and storms persistence validation between simulated and original data. Both test data and real time data is used as an input for this validation. In addition, all graphs represent the average results of 1000 simulations.

Figure D.3. In the testcase an additional effect occurs due to the random placement of storms. The calms are no longer of a fixed duration of 10 or 20h, but instead have random lengths mostly between 1 and 40h. However, the persistence data from the simulated timeseries matches the original data.

Scatter diagram statistics validation

The scatter diagram graph in Figure D.4Figure D. is made from the simulated timeseries to check if wave heights are properly distributed. Lower wave heights are more persistent and rarely interrupted. This creates an issue with the way in which the algorithm places blocks, causing some blocks to no longer fit and to be discarded. This is visible in autumn and winter.

Simulation run validation

The final validation runs the logistical model with both the original and simulated timeseries. For the evaluation the amount of pipe laid and the time spend waiting on weather are plotted. Two different plots are made to evaluate this performance in relation to the logistical model. The first is the effect over the number of simulations on the result. The second is the spread of the results. Both are shown in Figure D.5. The mean result stabilizes after seven simulations. The boxplots show that both the original and simulated timeseries produce similar results and that the spread for both is limited to less than 10%.

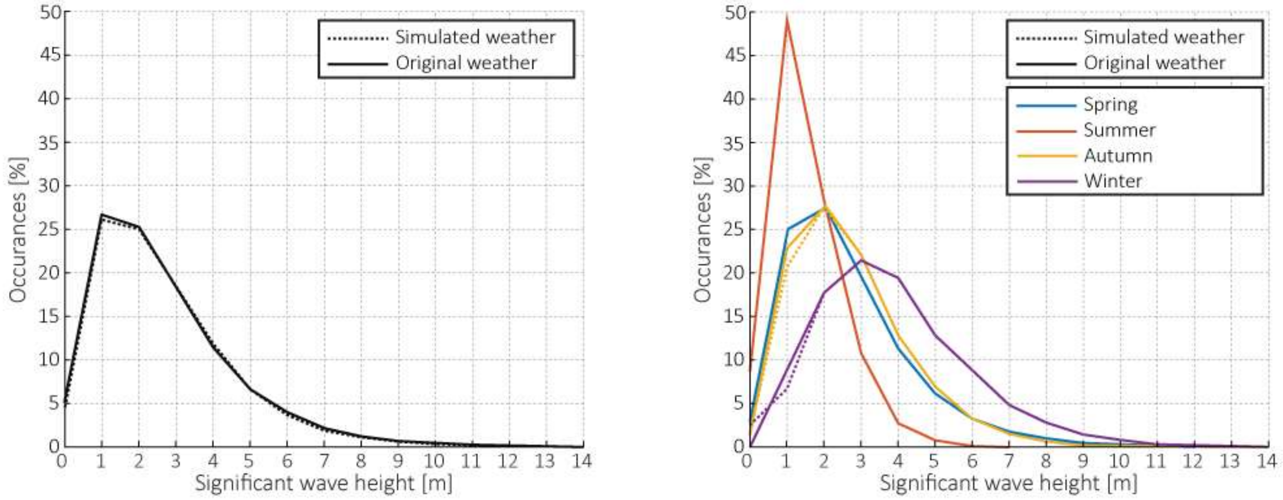


Figure D.4. Scatter diagram comparison of different methods per year (left) and per season (right). Only the wave height is plotted as wave period is not part of the persistence model and data.

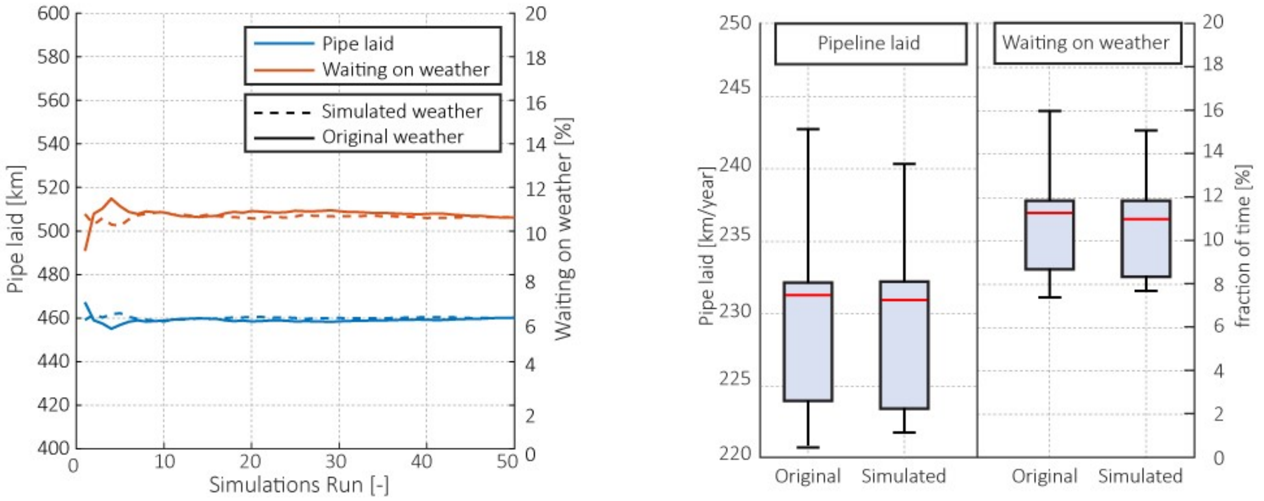


Figure D.5. Performance of the logistical model based on original and simulated timeseries over 50 simulations.

Appendix E FLOWCHARTS OF INDIVIDUAL LOGISTICAL MODEL SECTIONS

This appendix goes into detail of the logistical model described in Chapter 4. It will describe the four different parts of the model: loading, transit, transshipment and pipelaying. Although the flowcharts are a relatively simplified version of the actual MATLAB code, main characteristics will be covered.

Loading

Two important assumptions define the loading and unloading operation shown in Figure E.1. The first is that the material for the reels and barge will be prepared before the vessel arrives at location. The second is that the spoolbase has an infinite production capacity of flexibles. Production and performance parameters of the facilities are unknown but the spoolbase in Brazil supplies multiple fleets of flexlay vessels.

The term "container" will be used to represent an object which holds pipes. It can be either a single pipe (when spooling), a reel, a barge or another medium one might want to use. This allows the logistical model to handle all transshipment methods in the same way.

All activities except for transfer by spooling require the unloading of empty containers. The times for both are kept the same as the loading times, so in some cases the code instantly proceeds to loading the vessel.

The tide is set to twice 6 hours. This is an oversimplification and is dependent on the draft of the vessel. Therefore, this will slightly restrict the speed of loading and slightly slow down supply by at most 6 hours on a return-trip of 9 days.

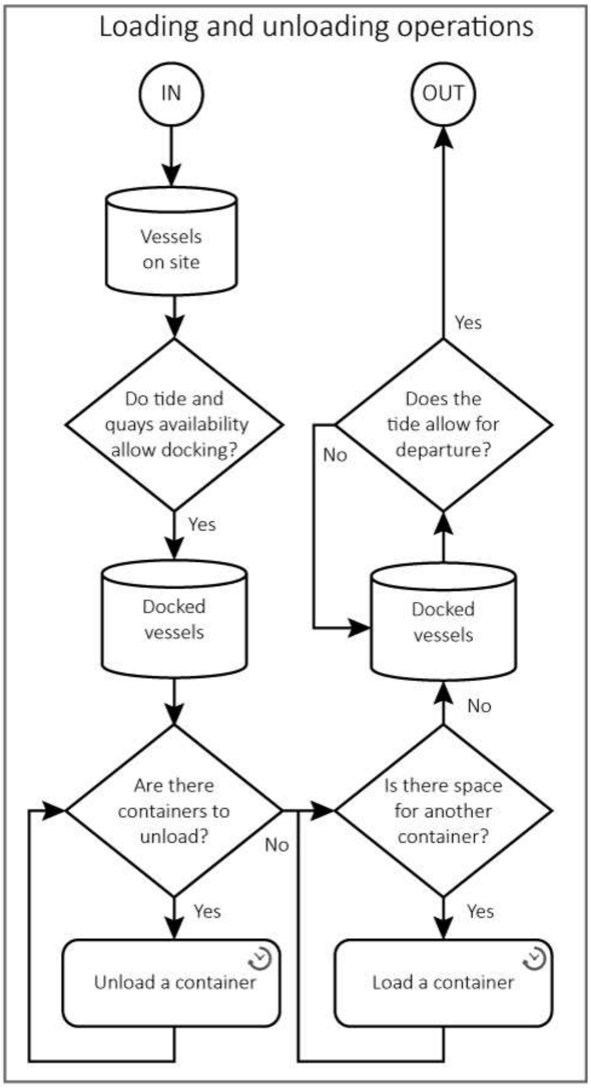


Figure E.1. Flow-chart of the loading and unloading operations at the spoolbase

Transit

The transit in Figure E.2 is a simple system that works the same for both to and from the offshore location. It is a countdown of the distance a vessel has to sail which decreases by the speed of the vessel. Varying vessel speeds due to seastates are not taken into account because that depends on the ship design which isn't known at this stage.

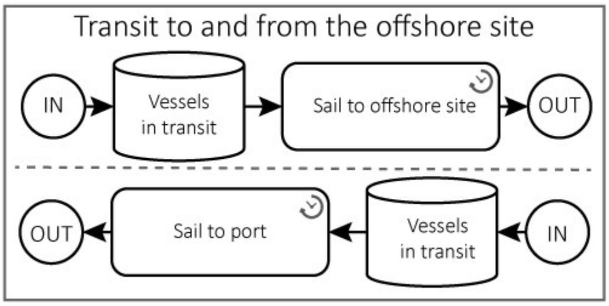


Figure E.2. Flow-chart of transit between locations.

Some logistical simulation programs take into account routing around storms. This and routing to other vessels for supply operations is not included. The projects under investigation are simplified to pipelaying only at the same constant distance from port, as a yearly average is desired, opposed to the performance on a specific project.

Transshipment

The transshipment flow is shown in Figure E.3. When a supply vessel arrives to the pipelayer, it will check if the pipelayer has a hold it can load in. If this is possible it will check if the seastate allows it. This check uses the seastate timeline created by the persistence model of Chapter 5.

As a simplification, the weather window is for both unloading and loading as a set requiring a double time window. This may result in a worse performance because larger weather windows are needed, but it is assumed to be preferred over frequent interruptions of the transshipment. In the case of non-simultaneous transshipment it is possible for the pipelayer to continue laying after transshipment is interrupted by high seastates. However, it cannot use the partly loaded hold.

Transfer of fuel and personnel is handled by tankers and helicopters like in the Brazilian projects and does not have to be included in the model as it can be planned to take place when there is no transfer.

Pipelaying

Pipelaying is the main purpose of the pipelayer. Of the four models this is the most complex model as visible form the flowchart in Figure E.4.

The first step is to check if an idle hold contains pipes that can be laid, the second check is if it's the start of a project. If it is the start there needs to be enough time to reach the seabed, which requires 4 pipes of 800m, to reach the water depth of 3000m. If it is not the start, pipe may be suspended from the pipelayer after heavy weather, or it may be that the pipelayer is in the midst of pipelaying. If that is the case activities can just continue where they left off. If pipe needs to be recovered from the seabed time needs to be spend on recovery first.

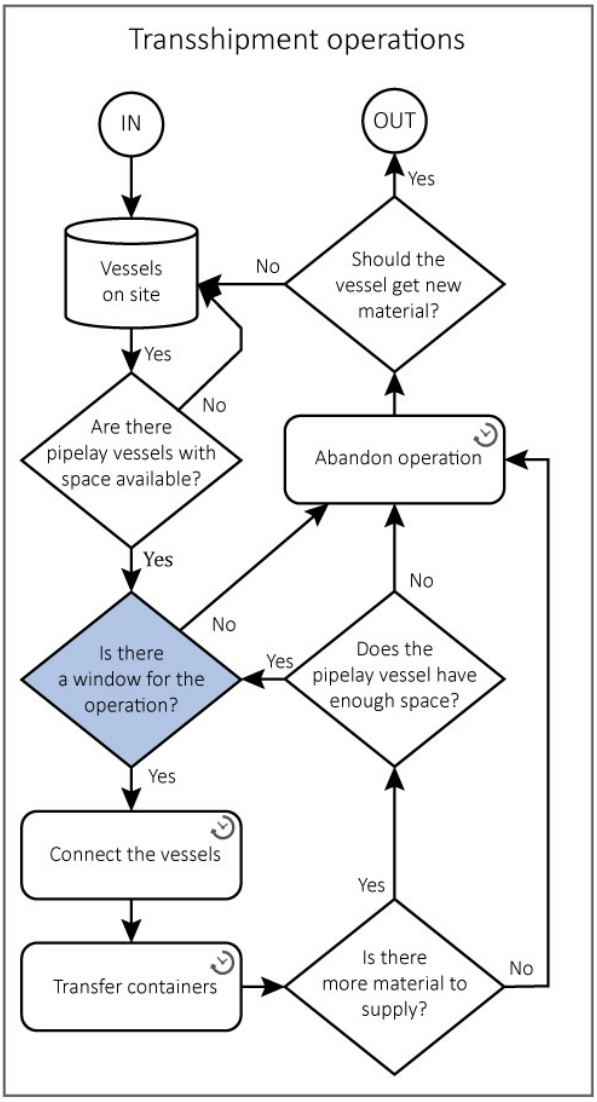


Figure E.3. Flow-chart of transshipment operations. The blue section is dependent on the weather persistence model.

Pipelaying continues until a project is done. During this section of the code the vessel will loop through a sequence of initiation and pipelaying until the project is done. Initiation consists of lifting the pipe into the pipelay tower and connecting it to previous pipes. Pipelaying is the lowering of the pipe down the moonpool. At the end of the project pipe is lowered to the seabed (abandonment).

Good weather is required for abandonment, recovery, initiation, and pipelaying. This is checked against the persistence model timeseries in the same way it was checked during transshipment.

The individual steps in the pipelaying process each take up a certain amount of time which is not discussed in other chapters. They are listed in Table E.1 together with potential formula's and a brief explanation at the end. The durations for the various procedures mentioned in the table are based of operator estimations [1].

Table E.1. Various constant durations used during pipelay operations which influence the pipelaying speed depending on the situation

Pipelaying activity	**Duration**	**Formula**	**Explanation of constants**
Initiation base (recovery)	5 h	= 5	*3h to get pipe over tower + 2h connecting pipes*
Initiation aided by previous pipe	6 h	= 6	*3h to get pipe over tower + 2h connecting pipes*
Initiation first project pipe	17 h	= 17	*3h new pipe over tower + 5h bend restrictors + 3h connecting VCM* *...to pipe + 1h overboarding + 5h wellhead connection*
Initiation last project pipe	18 h	= 18	*2h new pipe over tower + 5h bend restrictors + 3h connecting VCM* *...to pipe + 1h overboarding + 7h wellhead connection*
Abandonment	16 h	= Waterdepth / Layspeed+6	*2h old pipe over tower + 3h instal. retrieval head + 1h retrieval ROV*
Recovery	9 h	= 2·Waterdepth / Cranespeed +3	*1h overb. ROV and 2h connecting recovery cable to pipe at seabed*
Pipelaying	3 h	= Pipelength / Layspeed	

**Where: Waterdepth = 3000m, Layspeed = 300m/h, Cranespeed = 1200m/h, Pipelength = 800m*

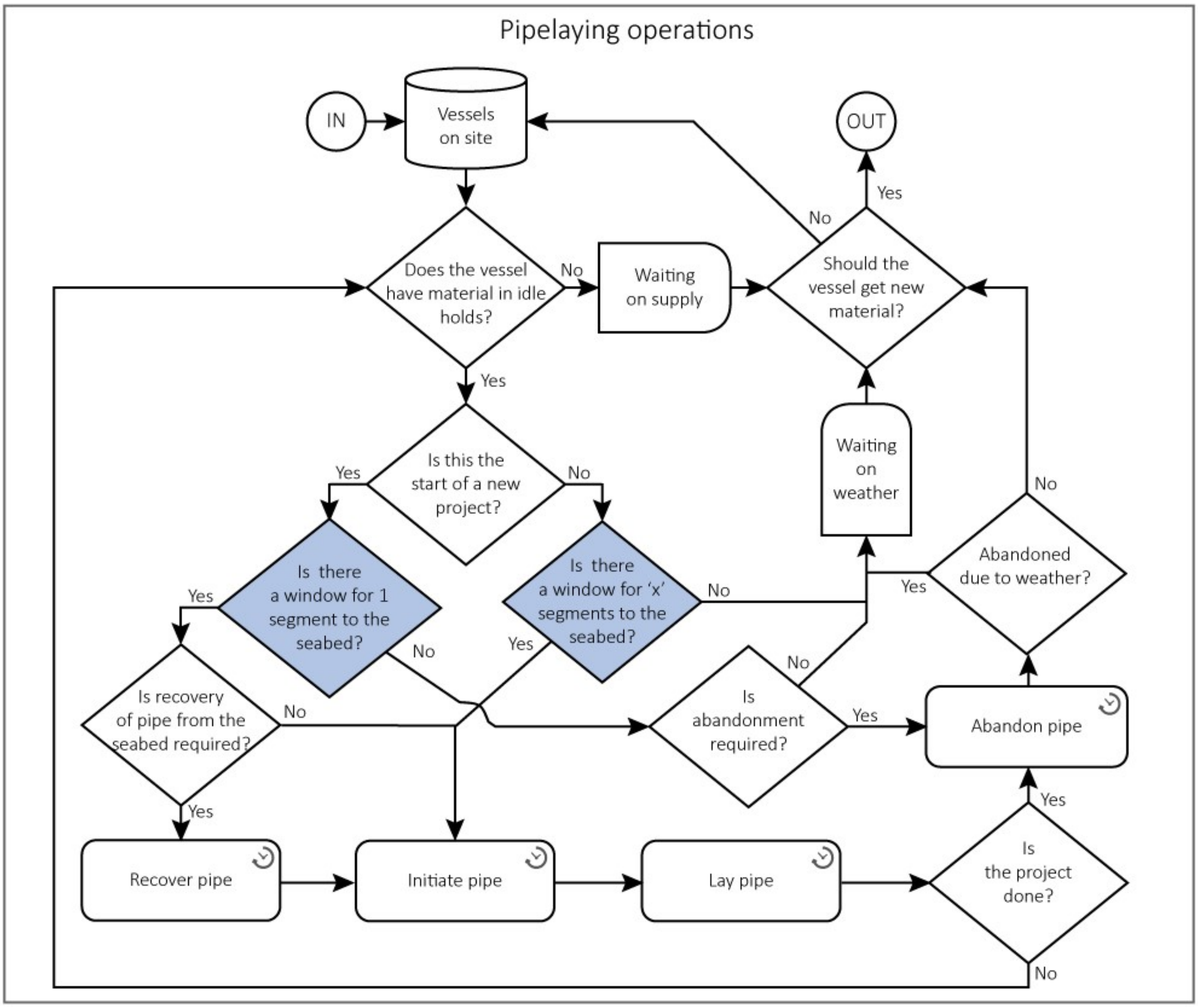


Figure E.4. Flowchart of the pipelaying process. The blue sections are dependent on the timeseries made by the weather model.

Appendix F REFERENCE VESSEL INFORMATION

This appendix covers the main dimensions and parameters for the reference vessel in this thesis. This is the flexlay vessels of which seven were built for two operators, Subsea7 and Sapura Navegação Marítima. These vessels are operating mainly in Brazilian waters for Petrobras projects and have seen consistent use during their charter contracts. Most of the work on the vessels consists of laying the flexible pipe, but also delivering material to other vessels, replacing risers at FPSO's, installing flexibles with other purposes such as cables, surveying routes and installing subsea structures.

One of the reference vessels is shown in Figure F.1. Distinct are the large pipelay tower centred above the centre of gravity and hovering over a moonpool, and two offshore cranes at the aft of the vessel, the largest one equipped with heave compensation. The material is stored in large carrousels below deck as shown in Figure F.2. The main dimensions and parameters of these vessels are included below in Table F.1.


Figure F.1. Reference vessel - Sapura Diamante


Figure F.2. Pipe stored in large carrousels below deck

Series	IHC PLSV Type 550-30
Flagstate	Panama
Classification	Lloyd's Register of Shipping +100A1 WDL (5t/m2 Fr.-10 – 119), Heli Landing Area, +LMC, UMS, DP(AA), CAC (3), ECO, ICC, NAV-1, IBS, *IWS
Regulations	Code of Safety for Special Purpose Ships 2008

Table F.1. Main dimensions and parameters for the reference vessel

Main dimensions	
Length over all	145.95 m
Length between perpendic.	135.22 m
Breadth (moulded)	24.94 m
Depth main deck	13.00 m
Design draught (moulded)	7.60 m
Scantling draught (moulded)	8.50 m
Deadweight	
Deadweight at des. draught	9375 t
Deadweight at sca. draught	12819 t
Speed	
Trial speed at des. draught	13.6 kn
Payload capacities	
Deck loads for local strength	10 t/m^2
Helideck	
Helicopters	S92 Heli
Diameter	22 m
Pipelaying equipment	
Tensioners	550 t
A&R system	610 t
Aux. A&R system	220 t
Skidable Hang off clam	610 t
Carroussels	2500 t
	2150 t

Tank capacities	
Marine gas oil	2075 m^3
Fresh water	1010 m^3
Water ballast	5050 m^3
Heeling tanks (50%)	1050 m^3
Technical fresh water	620 m^3
Thrusters	
Azimuth thruster (x3)	2950 kW
Retr. Azimuth thruster (x2)	2400 kW
Bow thruster (x2)	2200 kW
Lifesaving appliances	
Davit launched lifeboat (x2)	60 pers.
Lifting gear	
Offshore knuckle boom crane	
Safe working load	250 t
Radius	12 m
Knuckle boom crane	
Safe working load	20 t
Radius	15 m
Provision crane	
Safe working load	1 t
Radius	12 m

Complement		
Captain class	5 cabins	5 persons
Crew (single)	31 cabins	31 persons
Crew (double)	42 cabins	84 persons
Public spaces		
Messroom		60 seats
Recreation room (non-smo)		29 seats
Recreation room (smoking)		10 seats
Internet room		6 seats
Library		16 seats
Offices		13 seats
Conference room		10 seats
Gymnasium		
Machinery		
Main engines- diesel gen. (x6)		
Maximum output	3840 kW	
Engine speed	720 rpm	
Generators - emergency/harb.		
Output	1500 kW	
Engine speed	1800 rpm	
Voltage	440 V	
Frequency	60 Hz	

Appendix G LIGHTWEIGHT ESTIMATION

This appendix contains the weight calculations made for the barge and the pipelay vessel. The first section for the barge will briefly describe the calculation of the weight of the pipe in relation to the size of the carrousel and pipe and follow with the weight calculation for the barge itself. The pipelayer section will show the reference sections used and continue with a more detailed estimation for the new weight of the pipelayer. The longitudinal and vertical centre of gravity will be calculated too and shortened to LCG and VCG respectively.

Barge lightweight

The weight calculation for the barge is directly related to its dimensions which are derived from the type of pipe to be loaded, the size of the carrousel, and its required capacity. The input parameters, resulting dimensions and lightweight distribution are shown in Table G.1.

The first step in calculating the dimensions of the barge and the weight, is setting the height and diameter of the carrousel. This leads to the available capacity. Pipe is stacked in layers, with the following formula the weight per layer is calculated:

$$W_{layer} = \sum_{rings}^{n} SW_{pipe} \cdot 2\pi(4.7 + n \cdot OD_{pipe})$$

Where:

$W_{layer} = total\ weight\ of\ the\ pipe\ in\ t\ per\ layer$
$SW_{pipe}\ = pipe's\ specific\ weight\ per\ m.$
$OD_{pipe}\ = outer\ diameter\ of\ the\ pipe$
$n\ = number\ of\ rings\ per\ layer\ of\ pipes$

This can then be multiplied by the number of layers to get the total capacity of the carrousel. For this research the outer pipe diameter for a regular 9” pipe is 374.5mm. Due to the filling efficiency of the carrousel this is rounded up to 400mm.

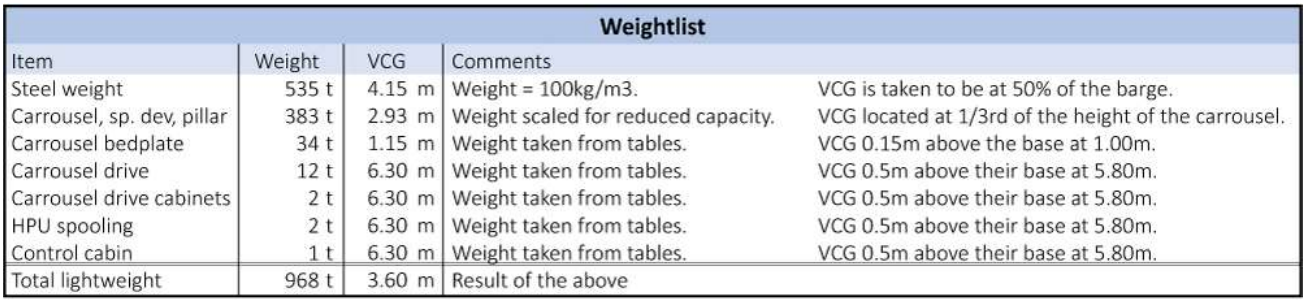
The dimensions of the barge were discussed in Chapter 7, and are based on the dimensions of the carrousel. The weight is based on its dimensions and industrial ballpark figures [13]. The steel weight of the barge is 110 kg/m^3 along the entire volume of the barge.

The weights for the bedplate, spooling device, internal pillar and other equipment related to the carrousel, are taken from the weight calculation for the reference vessel [18]. The centres of gravity are based on the geometrical shape in the sideview of the barges GA. For most items the centres of gravity are assumed to be located at 50% of their height. The carrousel, spooling device (arm), and pillar have their centre of gravity at 1/3rd of the height.

Pipelayer concept lightweight

The lightweight of the pipelayer is based on the calculations of the reference vessel and adapted to match the new concept. To do this, all the equipment related to the carrousel is removed from the calculation, and existing material is moved upwards or forwards with respect to the stern of the vessel due to the elongation. Then the voids are filled with hull based on a reference block. These adaptations are visualized in Figure G.1. The reference block is taken from the carrousel region of the reference vessel, which is also hollow. Its weight and sections are shown in Table G.2. To calculate the new vessel lightweight the carrousels and their equipment are removed from the reference vessel, as are the hulls where the doors will be placed. The deck is also removed and afterwards placed back on the higher position. The doors are placed back and all the gaps that result

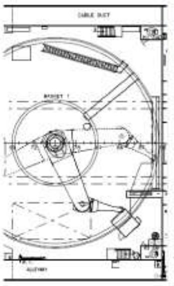
Table G.1. Detailed weight calculation for the barge. Due to the dependence on the pipe and dimensions, these are included.



Weightlist

Item	Weight	VCG	Comments	
Steel weight	535 t	4.15 m	Weight = 100kg/m3.	VCG is taken to be at 50% of the barge.
Carrousel, sp. dev, pillar	383 t	2.93 m	Weight scaled for reduced capacity.	VCG located at 1/3rd of the height of the carrousel.
Carrousel bedplate	34 t	1.15 m	Weight taken from tables.	VCG 0.15m above the base at 1.00m.
Carrousel drive	12 t	6.30 m	Weight taken from tables.	VCG 0.5m above their base at 5.80m.
Carrousel drive cabinets	2 t	6.30 m	Weight taken from tables.	VCG 0.5m above their base at 5.80m.
HPU spooling	2 t	6.30 m	Weight taken from tables.	VCG 0.5m above their base at 5.80m.
Control cabin	1 t	6.30 m	Weight taken from tables.	VCG 0.5m above their base at 5.80m.
Total lightweight	968 t	3.60 m	Result of the above	

Table G.2. Lightweight data per section of the reference block around the carrousel. This block is shown to the left. The density in this table is used as a benchmark figure for the weight of additional hull material in the new design concept vessel.



Denisity of reference vessel block sections around the carrousels

Section	Weight	Length	Width	Heigth	Volume	VCG	Density
110-04 (Double bottom mid)	52 t	11900 mm	9200 mm	1500 mm	164 m^3	0.73 m	0.318 t/m^3
110-12 (Double bottom SB)	50 t	11900 mm	10370 mm	1500 mm	185 m^3	0.78 m	0.271 t/m^3
110-13 (Double bottom PS)	50 t	11900 mm	10370 mm	1500 mm	185 m^3	0.78 m	0.271 t/m^3
110-22 (Hull SB, tanktop to maindeck)	62 t	11900 mm	3940 mm	11500 mm	539 m^3	8.66 m	0.114 t/m^3
110-23 (Hull PS, tanktop to maindeck)	63 t	11900 mm	3940 mm	11500 mm	539 m^3	8.71 m	0.117 t/m^3
110-36 (Maindeck PS, excl hull)	62 t	11900 mm	11030 mm	1800 mm	236 m^3	12.30 m	0.262 t/m^3
110-37 (Maindeck SB, excl hull)	54 t	11900 mm	11030 mm	1800 mm	236 m^3	12.35 m	0.230 t/m^3
Total	394 t				2085 m^3	6.69 m	0.189 t/m^3

from this movement are filled with sections whose weight is based on the density of corresponding sections from the reference vessel. This is shown in Table G.3.

To calculate the weight of the door, the kingpost lifting the door and the support structure for the kingposts, data is used from the Juttlandica. This is a Ro-Ro vessel with a similar vertical lifting door. The weight is scaled with the size of the door for both the supports and the kingposts.

The outer walls of the dock are estimated by assuming a 20mm thick steel plate with a factor of 1.5 for stiffeners and frames. These walls replace the existing walls around the carrousels.

With these new figures it is possible to estimate the new longitudinal and vertical centre of gravity. The lightweight of the concept is estimated to be 1,808t larger than the reference vessel, and totals 15,494t. It's vertical centre of gravity rises by 38cm

Table G.3. Detailed weight calculation for the pipelayer vessel concept. This is based on the weight estimation tables for the reference vessel. Section numbering in this table refers to numbers of the reference block sections in this chapter.

Weightlist

Weight item	Volume	Density	Weight	VCG	LCG	Ref. sections
Reference vessel weight	-	-	13686 t	13.92 m	71.84 m	Predetermined by weight tables
- Deck over original length	-5096 m^3	0.245 t/m^3	- 1254 t	12.10 m	41.28 m	110-36 & 110-37 (ref deck)
- Carrousels and equipment	-	-	- 446 t	4.23 m	43.12 m	Predetermined by weight tables
- Hull where doors come.	-1808 m^3	0.116 t/m^3	- 209 t	7.76 m	55.80 m	110-22 & 110-23 (ref hull)
+ Height for frames between docks	396 m^3	0.220 t/m^3	87 t	6.69 m	55.80 m	Heeling tank density
+ Deck over new length and height	6063 m^3	0.246 t/m^3	1492 t	14.93 m	50.25 m	110-36 & 110-37 (ref deck)
+ Aft belowdecks	2790 m^3	0.116 t/m^3	323 t	3.23 m	3.72 m	110-22 & 110-23 (ref hull)
+ Main hull extension (forw. docks)	6730 m^3	0.116 t/m^3	778 t	6.35 m	78.03 m	110-22 & 110-23 (ref hull)
+ Double bottom ext. (forw. docks)	806 m^3	0.287 t/m^3	231 t	0.75 m	78.03 m	110-04 & 110-12 & 110-13 (ref DB)
+ Doors for the docks	652 m^3	0.199 t/m^3	130 t	7.76 m	55.80 m	Heeling tank density
+ Thicker walls for the docks	-	-	51 t	7.76 m	55.80 m	Scaled up from weight tables
+ Kingpost and support	-	-	170 t	18.21 m	55.80 m	20mm thick walls, appendage factor 1.5
+ Moonpool extra height	1850 m^3	0.246 t/m^3	455 t	7.10 m	95.58 m	110-22 & 110-23 (ref hull)
Concept vessel weight			15494 t	14.30 m	82.36 m	

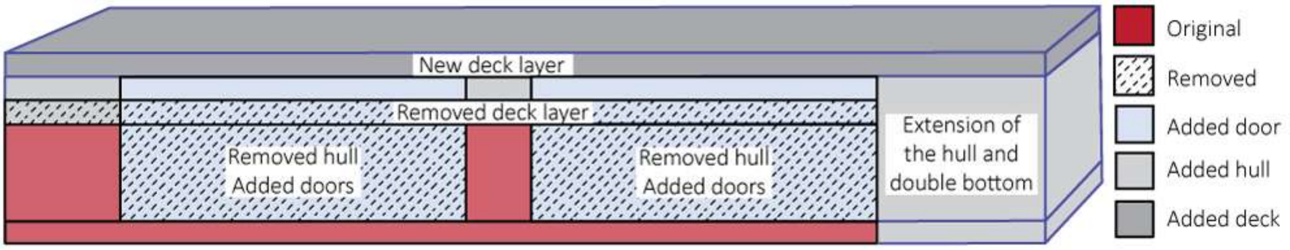


Figure G.1. Visualization of the removal and addition of steel parts to the concept vessel design to support the weight calculation table. The dimensions in this figure are not to scale. The image shows the doors on the starboard side for visibility. In the actual concept models these are located on the portside of the vessel.

Appendix H MOTION ANALYSIS WITH DIFFRACTION SOFTWARE

When loading the floating cargo into the vessel, it is important to know if the relative motions are within the boundaries for safe operations. These boundaries are defined by the vertical motions of the vessel and the size of the hold. The barge should not hit the bottom or the ceiling of the hold. The relative motions then also indicate the required depth of the water in the hold, which is directly related to the draught of the vessel during loading and unloading activities.

Modelling open holds & software limitations

The mesh is created via a tool that's developed in DELFTShip. At the time of researching this, the tool would only create a symmetrical mesh, despite DELFTship functionality allowing to model asymmetric vessels. When trying to piece together an asymmetric shape as shown in Figure H.1, however, it proves difficult to tell Diffrac that the combined shapes are part of the same body, and errors arise where the two objects touch. In an attempt to mitigate this a symmetrical shape is made which assumes the dock is opened on both sides as shown in Figure H.2. The mesh of that vessel can be taken straight from the 3D model made in DELFTShip. The mesh loaded into Diffrac to calculate the ship motions in various conditions.

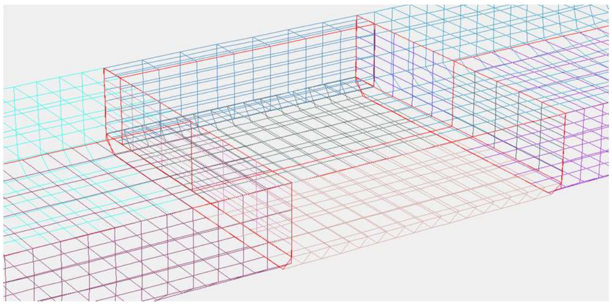


Figure H.1. Asymmetry due to opened hold

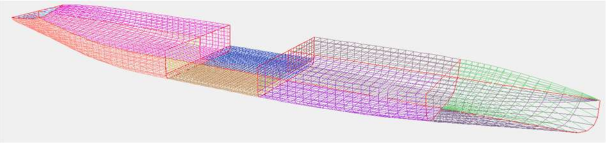


Figure H.2. Hull with open hold on both sides

Effect of the hold on diffrac results

The erratic results when solving the diffraction problem are especially visible in the responses for surge, heave and pitch as shown in Figure H.3. The same calculation was run for a mesh with completely closed dock, and with an opened moonpool. In those two cases results showed frequency responses at specific points, but overall the results were valid. This can clearly not be said for the results with an open dock. There are two possible causes: Firstly, the thin walled double bottom may create interference between the pressure sources on the top and bottom of the dock floor, effectively cancelling each other out. Refining the grid was tried but did not yield a better result. Secondly, the software calculates the wave motions from the seabed, and the waves inside the dock are not calculated from the bottom of the dock.

The creator of the software, the maritime research institute (MARIN) has recognized this problem for dock ships in general and started a multi-year research project on tackling this issue.

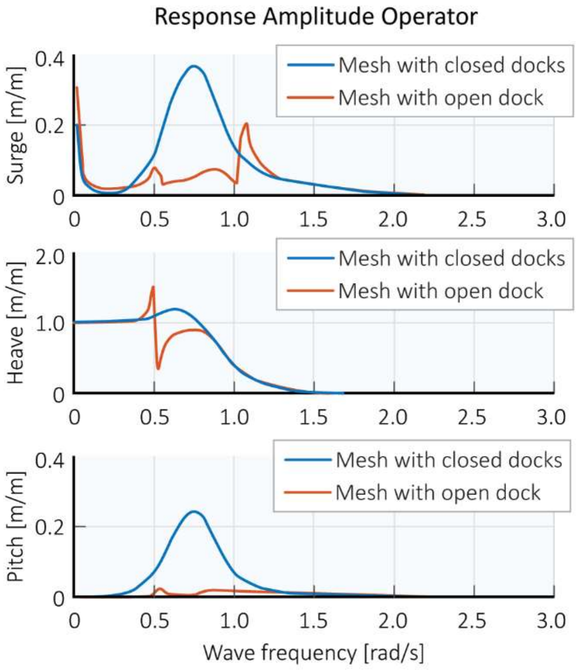


Figure H.3. Response amplitude operators for the hull with open hold compared to the same hull but closed. The result shows that Diffrac is unable to properly work with the open hold as both lines are expected to be at least somewhat similar.

Appendix I STABILITY BOOKLET FOR THE CONCEPT VESSEL

This appendix will cover a brief version of the stability booklet. The purpose is first to visualize the locations of the ballast, fuel, heeling, and fresh water tanks. And secondly include how full the tanks have been filled for each loading condition used in the determination of the vessels' stability in chapter 7.

Tank arrangement

The arrangement of the tanks is based on the layout used in the reference vessel. The main changes consist of straightening the fuel oil tanks between the two docks, and elongating the ballast tanks below the docks. The former was needed because the ballast tanks can't be fitted around the circular carrousel anymore. The visualization is shown below in Figure I.1. All the larger tanks are modelled. This includes are ballast tanks, heeling tanks, fresh water tanks and the fuel oil tanks.

Tank filling rate.

The tanks are filled to ensure that there is enough draught at the docks for a barge to enter with enough clearance. This means that in different situations a different trim is desired. Getting the opened dock to the correct draught over its entire is essential for the transshipment activities. The filing rates and the weight of the contents of the tanks are shown in Table I.1.

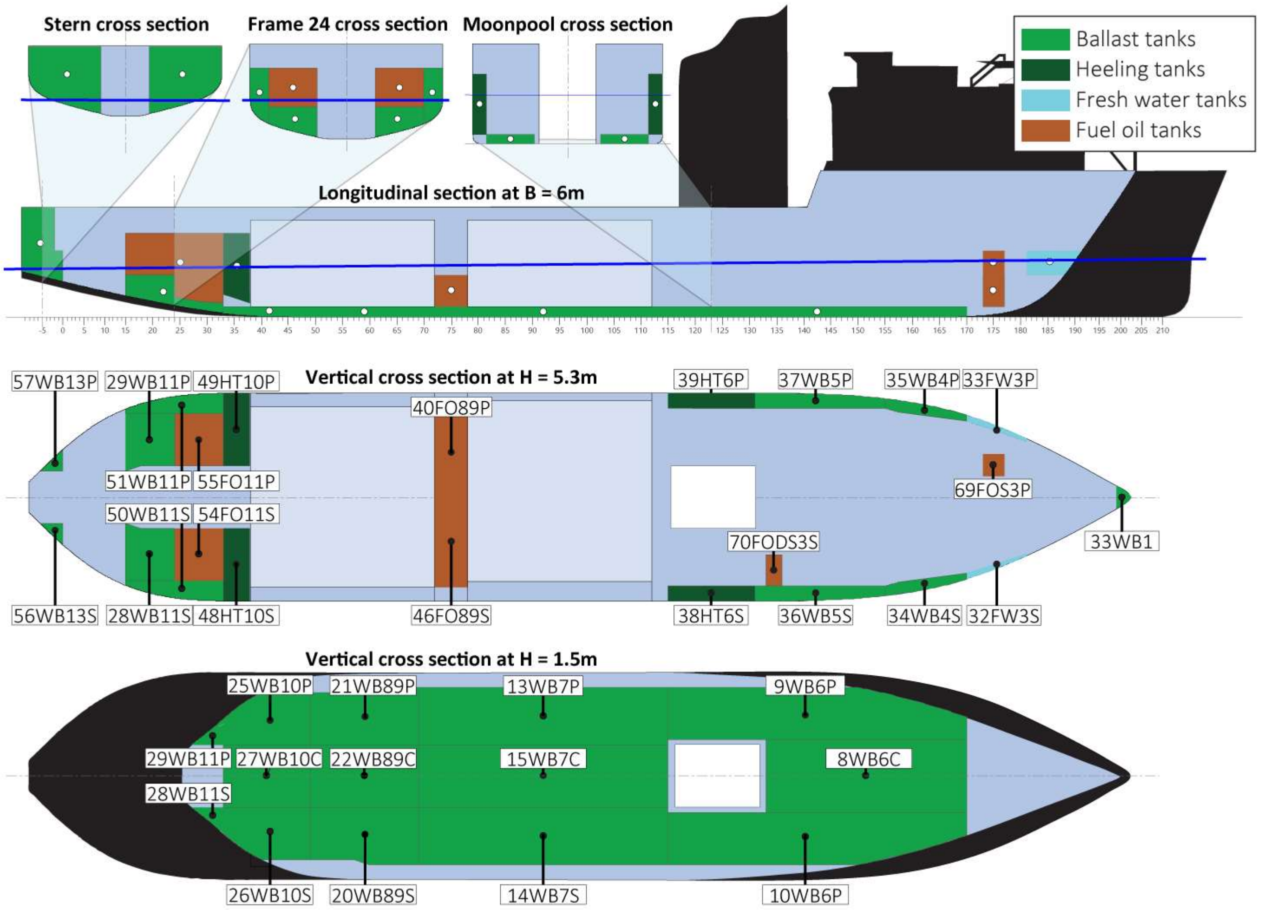


Figure I.1. Visualization of the location of the various tanks aboard the vessel which were used during the stability calculations for the various loading conditions in order to keep the vessel at the correct draught and trim.

Table I.1. Filling rate per tank for the various loading conditions. Subtotals are included and added to the lightweight to the lightweight to retrieve the total weight of the vessel in a certain condition.

Weight and filling rate of onboard tanks per loading condition														
Weights	LC1		LC2		LC3		LC4		LC5		LC6		LC7	
Special cargo	0 t	-	0 t	-	190 t	-	190 t	-	190 t	-	190 t	-	190 t	-
General	0 t	-	0 t	-	30 t	-	30 t	-	30 t	-	30 t	-	30 t	-
Barges	0 t	-	0 t	-	0 t	-	0 t	-	3032 t	(< for)	3032 t	(< aft)	6064 t	(< both)
subtotal		**0 t**		**0 t**		**220 t**		**220 t**		**3252 t**		**3252 t**		**6284 t**
Ballast														
31WB1	0 t	(0%)	0 t	(0%)	78 t	(98%)	78 t	(98%)	0 t	(0%)	0 t	(0%)	0 t	(0%)
34WB4S	0 t	(0%)	0 t	(0%)	224 t	(98%)	224 t	(98%)	0 t	(0%)	0 t	(0%)	0 t	(0%)
35WB4P	0 t	(0%)	0 t	(0%)	224 t	(98%)	224 t	(98%)	0 t	(0%)	0 t	(0%)	0 t	(0%)
36WB5S	0 t	(0%)	0 t	(0%)	414 t	(98%)	414 t	(98%)	63 t	(15%)	400 t	(95%)	0 t	(0%)
37WB5P	0 t	(0%)	0 t	(0%)	414 t	(98%)	414 t	(98%)	0 t	(0%)	0 t	(0%)	0 t	(0%)
9WB6P	0 t	(0%)	0 t	(0%)	408 t	(98%)	408 t	(98%)	408 t	(98%)	408 t	(98%)	0 t	(0%)
95 WB6C	0 t	(0%)	0 t	(0%)	437 t	(98%)	437 t	(98%)	437 t	(98%)	437 t	(98%)	0 t	(0%)
10WB6S	0 t	(0%)	0 t	(0%)	408 t	(98%)	408 t	(98%)	408 t	(98%)	408 t	(98%)	0 t	(0%)
13WB7P	0 t	(0%)	0 t	(0%)	426 t	(98%)	426 t	(98%)	426 t	(98%)	426 t	(98%)	0 t	(0%)
14WB7S	0 t	(0%)	0 t	(0%)	426 t	(98%)	426 t	(98%)	426 t	(98%)	426 t	(98%)	0 t	(0%)
15WB7C	0 t	(0%)	0 t	(0%)	466 t	(98%)	466 t	(98%)	466 t	(98%)	466 t	(98%)	0 t	(0%)
20WB89S	0 t	(0%)	0 t	(0%)	176 t	(98%)	176 t	(98%)	176 t	(98%)	176 t	(98%)	176 t	(98%)
21WB89P	0 t	(0%)	0 t	(0%)	176 t	(98%)	176 t	(98%)	176 t	(98%)	176 t	(98%)	90 t	(50%)
22WB89C	0 t	(0%)	0 t	(0%)	202 t	(98%)	202 t	(98%)	202 t	(98%)	202 t	(98%)	202 t	(98%)
25WB10P	0 t	(0%)	0 t	(0%)	102 t	(98%)	102 t	(98%)	102 t	(98%)	102 t	(98%)	52 t	(50%)
26WB10S	0 t	(0%)	0 t	(0%)	102 t	(98%)	102 t	(98%)	102 t	(98%)	102 t	(98%)	102 t	(98%)
27WB10C	0 t	(0%)	0 t	(0%)	156 t	(98%)	156 t	(98%)	156 t	(98%)	156 t	(98%)	156 t	(98%)
28WB11S	0 t	(0%)	229 t	(100%)	225 t	(98%)	225 t	(98%)	225 t	(98%)	225 t	(98%)	0 t	(0%)
29WB11P	0 t	(0%)	229 t	(100%)	225 t	(98%)	225 t	(98%)	0 t	(0%)	225 t	(98%)	0 t	(0%)
50WB11S	0 t	(0%)	209 t	(67%)	306 t	(98%)	306 t	(98%)	0 t	(0%)	306 t	(98%)	0 t	(0%)
51WB11P	0 t	(0%)	209 t	(67%)	306 t	(98%)	306 t	(98%)	0 t	(0%)	200 t	(64%)	0 t	(0%)
56WB13S	0 t	(0%)	401 t	(69%)	468 t	(80%)	573 t	(98%)	0 t	(0%)	0 t	(0%)	0 t	(0%)
57WB13P	0 t	(0%)	355 t	(71%)	326 t	(65%)	491 t	(98%)	0 t	(0%)	0 t	(0%)	0 t	(0%)
subtotal		**0 t**		**1633 t**		**6690 t**		**6961 t**		**3996 t**		**4839 t**		**3996 t**
Heeling tanks														
38HT6S	0 t	(0%)	0 t	(0%)	252 t	(98%)	252 t	(98%)	252 t	(98%)	0 t	(0%)	0 t	(0%)
39HT6P	0 t	(0%)	0 t	(0%)	252 t	(98%)	26 t	(10%)	0 t	(0%)	0 t	(0%)	0 t	(0%)
48HT10S	0 t	(0%)	0 t	(0%)	362 t	(98%)	362 t	(98%)	185 t	(50%)	0 t	(0%)	0 t	(0%)
49HT10P	0 t	(0%)	0 t	(0%)	0 t	(0%)	37 t	(10%)	0 t	(0%)	0 t	(0%)	0 t	(0%)
subtotal		**0 t**		**0 t**		**865 t**		**676 t**		**436 t**		**0t**		**436 t**
Fresh water														
52FW2S	0 t	(0%)	6 t	(10%)	6 t	(10%)	6 t	(10%)	6 t	(10%)	6 t	(10%)	6 t	(10%)
53FW2P	0 t	(0%)	6 t	(10%)	6 t	(10%)	6 t	(10%)	6 t	(10%)	6 t	(10%)	6 t	(10%)
32FW3S	0 t	(0%)	14 t	(10%)	14 t	(10%)	14 t	(10%)	14 t	(10%)	14 t	(10%)	14 t	(10%)
33FW3P	0 t	(0%)	14 t	(10%)	14 t	(10%)	14 t	(10%)	14 t	(10%)	14 t	(10%)	14 t	(10%)
subtotal		**0 t**		**42 t**		**42 t**		**42 t**		**42 t**		**42 t**		**42 t**
Fuel oil														
46FO89S	0 t	(0%)	23 t	(10%)	23 t	(10%)	23 t	(10%)	23 t	(10%)	23 t	(10%)	23 t	(10%)
47FO89P	0 t	(0%)	23 t	(10%)	23 t	(10%)	23 t	(10%)	23 t	(10%)	23 t	(10%)	23 t	(10%)
54FO11S	0 t	(0%)	68 t	(10%)	68 t	(10%)	68 t	(10%)	68 t	(10%)	68 t	(10%)	68 t	(10%)
55FO11P	0 t	(0%)	68 t	(10%)	68 t	(10%)	68 t	(10%)	68 t	(10%)	68 t	(10%)	68 t	(10%)
69FOS3P	0 t	(0%)	4 t	(10%)	4 t	(10%)	4 t	(10%)	4 t	(10%)	4 t	(10%)	4 t	(10%)
70FODS3S	0 t	(0%)	4 t	(10%)	4 t	(10%)	4 t	(10%)	4 t	(10%)	4 t	(10%)	4 t	(10%)
69FOS3P	0 t	(0%)	4 t	(10%)	4 t	(10%)	4 t	(10%)	4 t	(10%)	4 t	(10%)	4 t	(10%)
70FODS3S	0 t	(0%)	3 t	(10%)	3 t	(10%)	3 t	(10%)	3 t	(10%)	3 t	(10%)	3 t	(10%)
subtotal		**0 t**		**196 t**		**196 t**		**196 t**		**196 t**		**196 t**		**196 t**
Deadweight		0 t		1871 t		8013 t		7875 t		7922 t		8328 t		7312 t
Lightship		15463 t		15463 t		15463 t		15463 t		15463 t		15463 t		15463 t
Displacement		15463 t		17334 t		23476 t		23338 t		23385 t		23791 t		22775 t