Feasibility study of *Solitaire's* aftship retrofit

A Systems Engineering approach

F. Aguilar Tejero

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by

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A mis padres,
sin vosotros esta tesis
no hubiese sido posible.

Abstract

Solitaire is a DP positioned pipelay vessel capable of laying pipe up to 3000 meters. Currently, *Solitaire* is more than 40 years old. Although it has been upgraded multiple times, it has been identified that certain improvement can be achieved by retrofitting just the aft of the vessel. The purpose of the research is to evaluate the feasibility of improving *Solitaire* by retrofitting it with a new aftship, by exploring the different design possibilities, including the different stinger support configurations. To this end, an analysis of alternatives has been done and the preferred options have been implemented into a concept design.

The use of Systems Engineering (SE) has been motivated by the need to establish a clear structure to guide the design due to the complexity of the problem. This methodology allows to keep a good overview of the requirements and constraints involved in the design.

An operational analysis was carried out to identify the operational deficiencies of the design. This lead to four main areas of improvement. i.e, Longitudinal strength, Stinger and Stinger handling system (SHS), Resistance and Deck space. By addressing these operational deficiencies, the operational time of the vessel can be improved. Either by reducing the theoretical peak cycle time, decreasing the downtime or a combination of both. Based on the operational analysis a set of requirements has been compiled and a functional definition of the design has been made.

With all the insight obtained through the operational analysis, the design requirements and the functional definition; an analysis of alternatives has been carried out. For each of the operational deficiencies, multiple alternatives are analysed. Local optima are found for each of the deficiencies although, if each of these local optima is implemented in the design, the global performance of the vessel is compromised. Therefore, a holistic design is proposed to integrate all the solutions into one preferred concept design.

The new design adds 1000 m^3 of buoyancy at the aft for the same draft (8.5 m) and the increase in transit speed is approximately 0.3 knots. A wide base stinger is designed with the main hinge being located at frame 0. The Stinger handling system (SHS) is simplified by supporting the stinger with two tackle wires and the Stinger handling frame (SHF) spreads the loads at the aft. Due to the new buoyancy distribution and the new weight distribution, the longitudinal strength of the design is improved. However, the shear forces in certain sections become relevant. Since the stinger is moved further aft, the workability of the design is decreased slightly. Although, this modification do es not affect the DP capability. The total cost of the retrofit is approximately 55 million euros.

Overall, the findings of the research suggest that the retrofit of the aft is technically and economically feasible. Nevertheless, a design validation needs to be carried out to better quantify the total improvement of the new design.

Acknowledgements

As with most things in life, it is due to the people around us that we are able to achieve great things. Therefore, here are my acknowledgements to those of you who have helped me along the way.

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Teresa, thank you because "*... you are the rock upon which I stand...*"

A mis padres, por el empeño y la dedicación que han puesto en mi formación. Pero sobre todo por apoyarme en todos los sentidos. Y a mis hermanos, por todos los momentos juntos. Gracias por vuestro cariño y paciencia.

Fernando
Delft, November 2019

Contents

List of Figures

List of Tables

Acronyms

GM_L Longitudinal metacentric height.

GM_T Tranversal metacentric height.

A&R Abandonment & recovery.

CoC Condition of Class.

CoG Centre of Gravity.

DJF Double joint factory.

DP system Dynamic Positioning system.

FiFi Fire Fighting.

GA General alarm.

HFO Heavy Fuel Oil.

KFFP Keel flow fairing plate.

LO Lube Oil.

LR Lloyd's Register.

MASWBM Maximum Allowable Sill Water Bending Moment.

MDO Marine Diesel Oil.

MGO Marine Gas Oil.

NDT Non destructive test.

OD outside diameter.

PA Public announcements.

PLEM Pipeline end manifold.

PLET Pipeline end termination.

RAO Response Amplitude Operator.

ROV Remote Operated Vehicle.

SE Systems Engineering.

SHF Stinger handling frame.

SHS Stinger handling system.

SPC Special purpose crane.

SWBM Sill Water Bending Moment.

VMT Vessel Management Team.

WoW Waiting on Weather.

1

Introduction

In this chapter, the thesis and research is introduced. First, the background of the research is given. Thereafter, the problem statement is explained, followed by the research question and the scope of this thesis. The last section describes the outline of this thesis, linking research questions with chapters.

1.1. Background

The Swiss-based Allseas Group, hereinafter Allseas, owns seven ship-shaped pipelaying vessels. *Solitaire* is one of the largest pipelaying vessels in the world and has been developed for installation of large diameter pipelines. The pipes are welded on the ship in a horizontal working plane causing the pipeline to leave the vessel horizontally. To prevent the pipeline from bending or breaking due to its weight, the pipeline is guided by an outrigger called, "stinger".

Solitaire was built in 1972 as a bulk carrier, under the name of *Trentwood*. It was converted to a pipelaying vessel between 1996 and 1998. After entering into service in 1998, there have been several upgrades in the structure and equipment, the most important one being in 2005. During this upgrade, the stinger was changed and elongated, and the cantilever beam was installed. To counteract the extra weight in the aft, block-shaped sponsons were installed in the aft. See Figure 1.1

Existing aged ships are often required to extend their service life because of the direct and indirect costs associated with new ship acquisition programs. With proper maintenance and safety measures via life-cycle management, aged ships can effectively serve years beyond their designed service life. In this regard, the decision as to which point in time the ship should retire has traditionally been an economic one. Rise of ship acquisition costs makes the service life extension an attractive alternative to shipowners. However, operating aged structures beyond their service life also involves a decrease in the reliability and an increase in their maintenance and failure costs. [4]

Due to increasing pipelay requirements and ageing of existing equipment, Allseas would like to investigate if a more efficient ship design could be achieved by replacing the aftship of the *Solitaire*.

Systems engineering provides a base to solve problems and track requirements throughout the design process. Due to the complexity of this problem Systems Engineering would be used as a design methodology.

1.2. Objective

The objective of this thesis is to evaluate the feasibility of retrofitting a new aftship, by exploring the different design possibilities, including the different stinger support configurations. Strength crite-

Figure 1.1: Starboard side sponson. ©Allseas B.V

ria, re-utilisation of already existing equipment and cost must also be considered.

1.3. Research questions

The prime research question of this thesis is:

What is the feasibility of improving *Solitaire* by retrofitting a new aftship?

Which can be broken down in the following sub-questions:

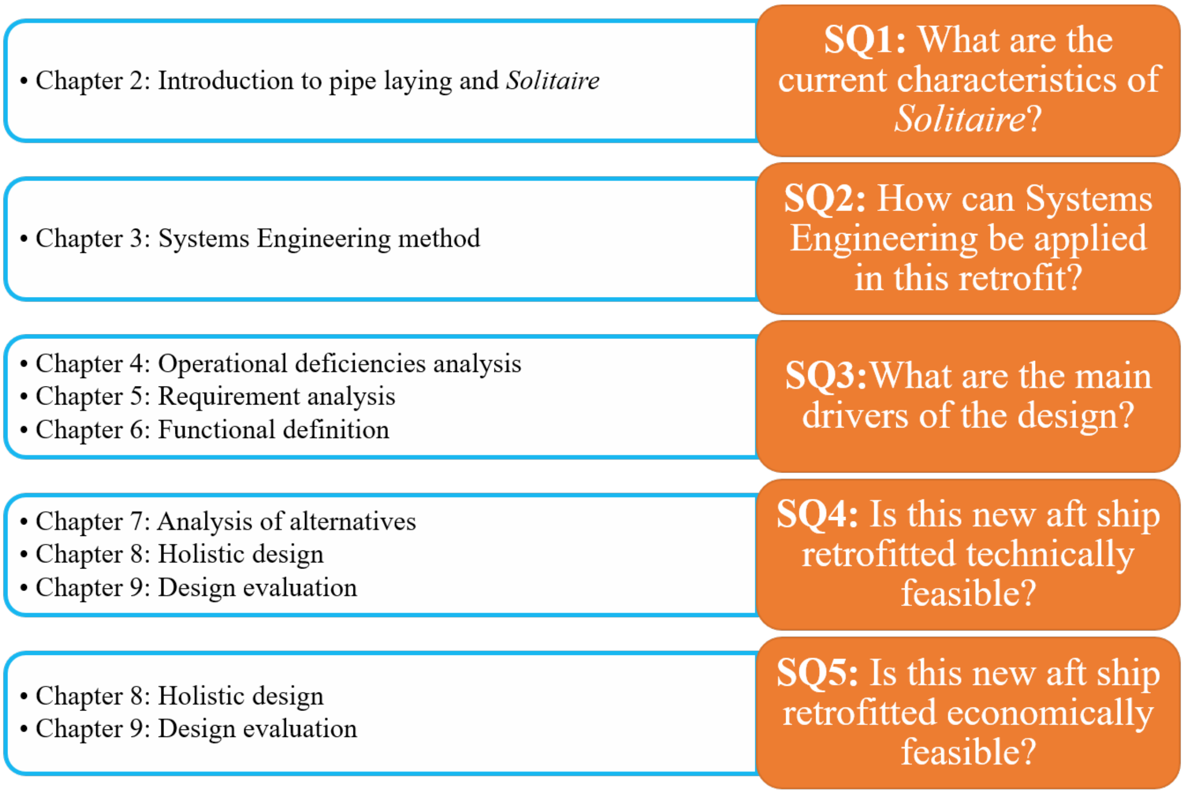
1. What are the current characteristics of *Solitaire*?
2. How can Systems Engineering (SE) be applied in this retrofit?
3. What are the main drivers of the design?
4. Is this new aftship retrofitted technically feasible?
5. Is this new aftship retrofitted economically feasible?

This research questions and sub-questions consist of different words which are clarified below.

- Feasibility: the state or degree of being easily or conveniently done. [5]
- Feasibility study: An assessment of the practicality of a proposed plan or method. [6]
- Retrofit: to add (a component or accessory) to something that did not have it when manufactured. [7]

1.4. Report structure

Due to having selected Systems Engineering as the design method, the report structure will also follow the different chapters. In Figure 1.2, the different chapters that answer the aforementioned sub-questions is shown.



2

Introduction to pipelaying and *Solitaire*

The aim of this chapter is to provide the necessary background information to understand the rest of the thesis. First, it looks at the main features of the *Solitaire*, followed by an explanation of the S-lay technique. This technique is used to perform the main function of the ship, pipelaying. Therefore, it is important to understand all the processes, equipment and phases of this technique in order to comprehend part of the decisions made in this report.

2.1. *Solitaire*[1]

Solitaire is a pipelaying vessel (formerly a 125,000 t bulk carrier), that uses the S-lay technique (section 2.2). It is able to lay pipelines in deep waters thanks to her Dynamic Positioning system (DP system). It features the *Phoenix* automatic welding system, developed in-house. This system improves the welding quality and obtains higher welding rates.

The main characteristics of the *Solitaire* are, Table 2.1

Vessel particulars	Dimension
Length overall (excl. stinger)	299.85 m
Length between perpendiculars	248.65 m
Breath moulded	40.60 m
Depth moulded	24.00
Service draught	6.50-9.23 m (excl. thrusters), 14.37 m (incl. thrusters)
Displacement	83428 t
Maximum speed	13.5 knots

Table 2.1: Main particulars *Solitaire*

The vessel is able to lay pipelines between 2" and 60" in outside diameter (OD), being able to carry up to 22,000 t, dependent on the pipe characteristics.

Due to the large length and high roll period, it has excellent pitch and roll behaviour. Therefore, it is able to work in waves up to 4 - 4.5 m of significant height at a TZ of 7-9 s (depending on angle of attack) with an associated wind speed of 30-40 knots. This feature, the high pipe carrying capacity together with the DP system enables *Solitaire* to obtain high workability. The maximum water depth that has been achieved is 2775 m. Being able to install up to 8 km of pipeline a day. To be able attain

[1] Mainly from [8]

such high workability, the firing line design and configuration is of great importance. The firing line, Figure 2.1, has a length of 225 m. And it consists of the following main components:

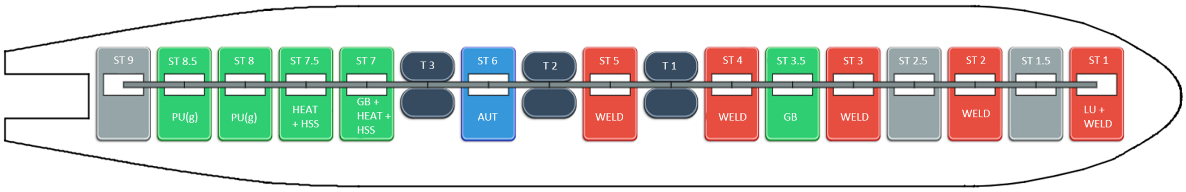


Figure 2.1: Schematic of firing line configuration for Nord Stream II. ©Allseas B.V

- 9 workstations, spaced 24.4 m
- 5 intermediate workstations to complete the double joint field joint coating
- Non destructive test (NDT) station
- 3 tensioners, 350 t each
- Track type roller supports between workstations
- Roller supports after coating stations

As it can be seen in Figure 2.1, stations coloured in red are used for welding (in station 1, the line up of the pipes is also carried out), stations in green are used for applying the necessary coating, stations in blue are for NDT and stations coloured in grey are not being used, in the current configuration.

Figure 2.2: Firing line. ©Allseas B.V

2.2. S-lay technique [2]

Even though there are multiple pipelaying techniques, the S-lay method is used across Allseas fleet. This method provides fast installation for all pipe diameters over a large range of water depths. This

[2] Mainly from [9]

is possible because the pipes are assembled in an horizontal plane, the firing line. This means that the pipeline leaves the vessel horizontally. To prevent the pipeline from bending or breaking due to its weight, the pipeline is guided by an outrigger called "stinger". The stinger introduces the necessary bend to direct the pipeline to the seafloor while supporting it. Figure 2.3

Figure 2.3: S-lay diagram. ©Allseas B.V

In order to explain the process, the route that a joint covers is followed. *Solitaire* can load joints with her two pipe transfer cranes, from supply vessels or from shore, while in port. These joints can then be stored in the holds or taken directly to production. *Solitaire* has two factories where the joints are welded: the Double joint factory (DJF) and the firing line. First the single joints (12.2 m) enter the DJF in order to weld two together and obtain a double joint (24.4 m). Then, this double joints are fed to the firing line to be welded to the pipeline. By using double joints the production is generally increased.

Before a joint can be welded, the edges have to be prepared by bevelling. It is done onboard to make sure there is no corrosion, damage and to make sure the shape of the bevel is correct ensuring that a good quality weld is obtained. After the bevelling, the ends of the joints are preheated and aligned with the pipeline, so that the welding can start. Allseas uses the "Phoenix" welding system. This system is automatic, having multiple heads, and has been developed in-house.

Usually, the wall thickness of the pipes is thick enough that the welding process must be completed in several steps. Usually it consist of:

1. Root pass
2. Hot pass
3. Several fillers passes
4. Cap pass

The first layer of deposited weld metal is called "root pass" or "bead". Therefore, this station is called "beadstall". This weld must have enough strength to move the pipe to the next station. Also, in this station the pipe has to be lined up with the pipeline.

After the root pass and hot pass, depending on the wall thickness, a certain amount of filler passes are done, followed by the cap pass, which finishes the weld. For this purpose, the pipelay vessel pulls forward one pipe length after a root pass, in this case 24.4 m.

When the cap is finished, the weld is checked in the NDT station. The checks can be done by ultra sound or X-ray depending on the pipe. If the weld is not of good quality it can be repaired or the joint has to be cut and the process has to start all over again (bevelling, preheating, line up, etc).

Once the weld is finished and accepted, it is cleaned (grit blasting) and heated to allow for good bonding of the coating with the pipe. This coating prevents the pipe to be corroded. On top of the anti-corrosion coating, a protective or infill coating is applied for pipes with concrete weight coating.

Finally, the pipeline is lowered to the seafloor by means of the stinger. The stinger is fitted with roller boxes. These boxes have rollers placed in a V-shape that provide vertical and horizontal support. Also, they control the bend of the pipe. Different configurations can be applied in order to adapt the radius of the bend, adjusting for different water depths.

During the whole pipelaying process, the pipeline should be kept under tension to prevent buckling. As is known, buckling is the phenomena in which a structural element collapses under a compression force. In this process, buckling mainly occurs at two points: when the pipeline leaves the stinger or when it touches the ground. It is caused due to bending by excessive underwater weight. Thus, by applying tension to the pipeline, the bend is reduced. *Solitaire* is equipped with a tension capacity of 1050 t (3 x 350 t).

This tensioners also maintain the pipeline in place since, when the pipeline is lowered to the seafloor the ship is pulled backwards. Therefore, the DP system is continuously working.

2.2.1. Influencing factors [3]

There are several influencing factors to determine the pipeline laying capacity of a vessel. The main two are:

- Production speed
- Maximum water depth

The **production speed** is driven by several factors. These factors are mainly due to how the welding process is designed, Figure 2.1.

- **Double joint factory:** Using double joints has a few advantages. There is less line-up of joints in the pipeline as well as less work in it. Therefore, this results in less breakdown and repair work in the pipeline. Also, joints can be rotated while welding, allowing quicker welding.

- **Pull time:** Once the double joint is welded to the pipeline it can not move freely anymore. This implicates that all stations have to be ready before the vessel can move and lay pipeline (this is called a "pull"). This movement has to be carefully timed with the vessel to keep the pipeline under constant tension and prevent buckling. Also, when a pull is underway welding can not be done therefore, if the pull is as fast as possible more welding time is available, increasing the production speed.

- **Work division between stations:** As explained in section 2.2 to complete the weld different passes have to be done. Thus, each station is in charge of different passes. Also, the NDT

[3] This factors are general knowledge within Allseas. Reflected in [1] and [10]

and the coating can be split up throughout different stations. Ideally, work should be equally divided across all the stations, meaning the bottle neck is form by all stations. This would mean all stations finish at the same time and no work capacity is wasted by having to wait for the bottle neck. Generally, the bottle neck is station 1, the reason for this is the need to line up the double joint and also do the root pass.

Therefore, generally the lead time of the process is given by the time that it is spent in the "bead-stall". For example, if we have a big diameter but a small wall thickness. The bead pass will take time. But the number of filler passes will be small, since the wall is thin. In the case of a small diameter but thick wall, the root pass will take less time. But the number of filler passes will be higher.

An increase in water depth requires more tension to carry the larger length of suspended pipeline. Furthermore, the wall thickness has to increase to withstand the increasing external pressure. On the other hand, using a larger departure angle reduces the need for extra tension. Since, the vertical component of the tension equals the weight of the suspended pipeline and, since the pipeline leaves the vessel at a steeper angle, the suspended length is smaller, resulting in less weight.

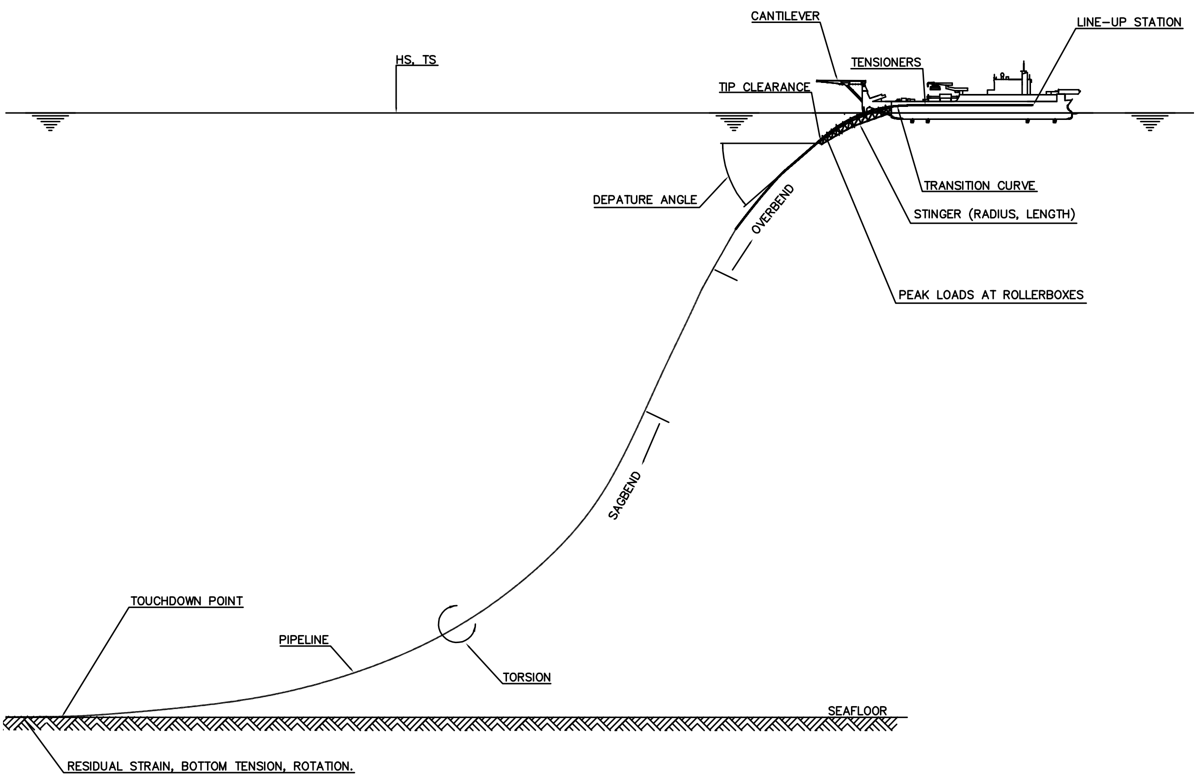


Figure 2.4: Schematic of S-lay. Adapted from [1]

Therefore, the **maximum water depth** is a function of two factors.

1. Departure angle, which is dependent on the stinger length and radii
2. Tension capacity

The **Radii of the stinger** is dependent on the diameter of the pipeline, because a smaller radii leads to larger deformations in the overbend.

The **tension capacity** is critical to prevent buckling of the pipeline. To limit it, pipelines are installed with a minimum radii and a maximum length of the stinger, which results in a maximum departure angle.

Also, it is important to note that to keep the pipeline in tension, the DP system has to be powerful enough. If not, the vessel would be pulled by the weight of the suspended pipeline.

2.3. Chapter conclusions

Solitaire has been in operation since 1972 as a bulk carrier, and converted to a pipelay vessel between 1996 and 1998. It has undergone an important retrofit in 2005 to extend its capabilities. Therefore, there is a lot of ageing of equipment and the pipelaying requirements are increasing. A lot of processes are integrated together to fulfil the mission of the vessel, which translate into a complex system integration. Although the design and integration of systems is complex the S-lay technique enables *Solitaire* to achieve high workability. Different design factors influence the performance, such as, double joint factory, firing line configuration, tensioner capacity, etc. Therefore, *Solitaire* is considered a complex vessel.

3

Systems Engineering method

Dynamic positioned pipelaying vessels are considered complex vessels, due to high number of integrated systems, the high degree of requirements and restrictions and the demanding of the operational profiles. Due to the nature of this project, a retrofit, the restrictions are even higher becoming a more complex problem. Therefore, it is of utmost importance to understand the problem and how the different parts relate to each other and impact the outcome of the design, but also to use a logical and structured approach. As a results of the aforementioned reasoning, a Systems Engineering (SE) approach is used.

3.1. Systems Engineering (SE)

As defined in [11], "systems engineering is a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect. Systems engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system."

The increasing complexity of engineering projects has encouraged the establishment of systems engineering as a standalone discipline. Systems engineering provides a base to solve problems and track requirements throughout the design process. Thus, the design associated risks are mitigated, lowering the amount of rework and keeping the budget on check.

The well known "V-model" (Figure 3.1) illustrates the key steps of a systems engineering process. It provides an overview of life cycle development and the relation between requirements, systems definition, the end product and its validation. [2]

3.2. Systems Engineering Life Cycle Stages [1]

The systems engineering life cycle, defines the different stages from idea, passing thought the development, production and operation till the ultimate disposal. The system life cycle model consists of three stages, as depict in Figure 3.2

- The **concept development** stage, integrates the formulation and definition of the system, the feasibility of its realisation, and the specific system architecture to best satisfy the costumer needs.

[1] Mainly from [2]

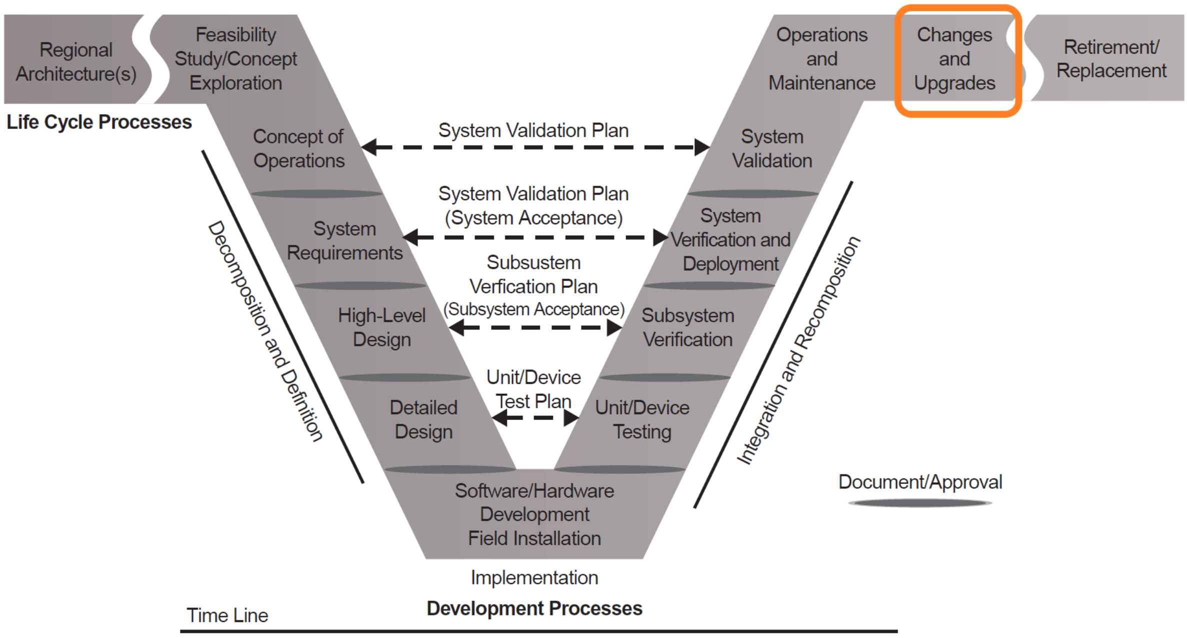


Figure 3.1: V-model, from [2]

- The **engineering development** stage, translates from concept to a validated physical system design.

- The **postdevelopment** stage, includes the production, deployment, operation and support of the system during its life.

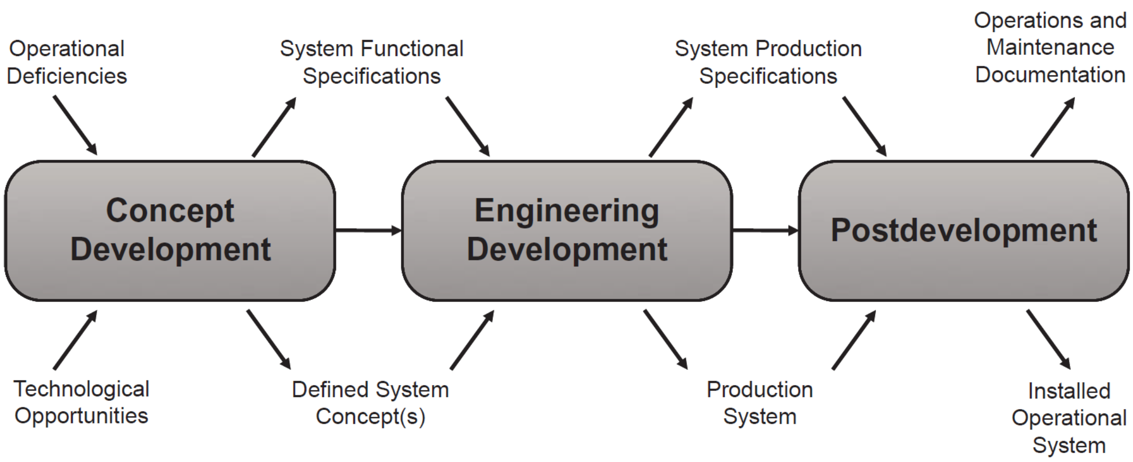


Figure 3.2: Main stages in a systems life cycle , from [2]

Feasibility studies usually extend to the concept development phase. If the outcome of the study is positive, then further investment can be sourced and the project can be continued to the following stages, engineering development and postdevelopment.

Taking into account the aforementioned reasoning and the nature of this thesis with its own limitations, mainly time. Only the first stage, concept development, is carried out.

3.2.1. Concept development stage

The concept development stage encompasses three phases, as shown in Figure 3.3.

- **Needs analysis:** in this phase a description of the capabilities and the operational effectiveness is made, which define the need for the system.
- **Concept exploration:** during this phase a set of requirements is created as well as a series of candidate system concepts.
- **Concept definition:** in this phase, the preferred concept is selected, and a set of functional specifications that describe the concept is outputted. This description should be functional and physical.

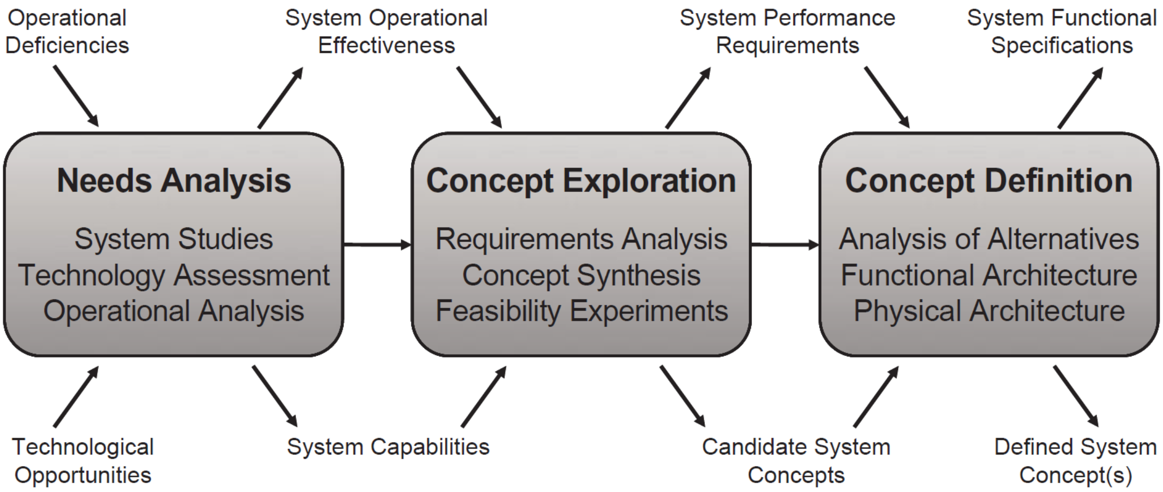


Figure 3.3: Phases of concept development stage , from [2]

The SE method involves four steps. These four steps are applied repetitively in each phase during development. Application of the systems engineering method evolves over the life cycle, as the system progressively materialises, the focus shifts from system level during needs analysis down to component and part levels during engineering design.

- **Requirement analysis (Problem definition):**
  - assembling and organising all input conditions, including requirements, plans and models;
  - identifying the operational need, constraints, environment, or other higher-level objectives;
  - clarifying the requirements of what the system must do, how well it must do it, and what constraints it must fit; and
  - correcting inadequacies and quantifying the requirements wherever possible.
- **Functional definition (Functional Analysis and Allocation):**
  - translating requirements (why) into functions (actions and tasks) that the system must accomplish (what)
  - partitioning (allocating) requirements into functional building blocks, and

  - defining interactions among functional elements to lay a basis for their organisation into a modular configuration.

- **Physical definition (Synthesis, Physical Analysis, and Allocation):**
  - synthesising a number of alternative system components representing a variety of design approaches to implementing the required functions, and having the most simple practicable interactions and interfaces among structural subdivisions;
  - selecting a preferred approach by trading of a set of predefined and prioritised criteria (measures of effectiveness (MOE)) to obtain the best "balance" among performance, risk, cost, and schedule; and
  - elaborating the design to the necessary level of detail.

- **Design validation (Verification and Evaluation):**
  - designing model of the system environment (logical, mathematical, simulated and physical) reflecting all significant aspects of the requirements and constraints;
  - simulating or testing and analysing systems solutions against environmental models; and
  - iterating as necessary to revise the system model or environmental model, or to revise system requirements if too stringent for a viable solution until the design and requirements are fully compatible.

3.3. Modernisation of systems: retrofit

New system development is usually driven by new technologies and competition, spurring new needs and technical opportunities. Comparatively, during the life time of a system the aforementioned factors continue to have an impact, which lead to a relative decrease of the system effectiveness in comparison with the possible advances of competitors [2]. However, in a large and complex system not all the components become obsolete. Since, technological advances do not occur simultaneously across all of them. Therefore, modernisation or retrofit only involve certain number of components.

This makes it possible to obtain equal or more effectiveness with a fraction of the cost and time instead of replacing the total system. Especially, in the offshore industry were assets are quite big investments, in terms of money and time from concept to operation.

Within the V-model, upgrades and changes (retrofits) are at the end of the main life cycle (complete system), marked with orange in Figure 3.1. If you zoom in on this "Changes and Upgrades" block, a smaller life cycle is found. This mini life cycle has similar stages as the main one.

As reasoned in section 3.2 only the *Concept Development* stage is considered in this thesis. As with the concept development of a new system, similar steps are followed. The main difference is the scope of the project, which is limited to designated portions of the systems and to the components that contain the part of the system to be retrofitted. Therefore, a great effort is required to obtain compatibility with the unmodified parts of the system.

Since the subject of the retrofit is the aft ship, two different scopes can be taken:

1. To the whole vessel
2. To the aft ship

One problem with focusing on the aft ship is the definition of the interface, between the aft and the rest of the vessel. Defining an interface could lead to a fix boundary, which would lead to fix solutions. Also, if there is an incompatibility with the interface, it will involve design adjustments on both sides leading to major technical difficulties [2]. Therefore, at the beginning the focus is open to the whole vessel. The reason to do it this way is to be able to capture how the aft ship design affects the whole vessel. Thus, you ensure the overall performance of the vessel is not compromised by the new design. But also, change at any level (function, system, subsystem, etc) should be such that none of the higher-level requirements are affected [12].

Therefore, the current specifications that are not going to change in the new design will be imputed as requirements instead of being constraints. Thus, the design space is less constrained.

Once there is enough understanding of the problem the interface can be defined. Therefore, the design space is reduced, which simplifies the search for a solution.

3.4. Chapter conclusions

Dynamic positioned pipelaying vessels are considered complex vessels. The retrofit of a complex vessel is a challenging problem as the constraints increase due to the interfaces with the existing design. Therefore, it is of importance to define the interface properly.

Systems Engineering (SE) provides a good methodology to solve logically a complex problem. Providing a good structure to breakdown the problem into smaller blocks and documenting all the process.

In a large complex system, not all the components become obsolete at the same time. Thus, a retrofit only involves certain parts. This allows expending little resources to obtain the same or higher performance than before.

4

Operational deficiencies analysis

In this chapter, the mission and operational profiles of the vessel are described. Furthermore, the operational deficiencies[1] of *Solitaire* are addressed and analysed. These deficiencies have been identified by the Technical Department and the Crew on-board. From this analysis a set of requirements can be compiled in the following chapter.

4.1. Mission

Solitaire's mission is to execute pipelaying and associated work, such as installation of risers and subsea structures. This mission is already fulfilled by the current design although it can be improved. Therefore, the current design has to be analysed in order to address the operational deficiencies.

4.2. Operational modes

For the aforementioned mission different Operational modes are described in detail. [13]

- **Normal pipelay:** The stinger is in the water supporting the pipeline. The DP system is in use, keeping *Solitaire* in position and well as compensating for the horizontal force due to the pipes weight. When a pipe double joint is welded to the pipeline, the vessel moves forward, while the tensioners lay the pipeline. Usually pipe is being supplied by a vessel or barge at the same time.

- **Abandonment & recovery (A&R) condition:** When the weather conditions deteriorate, it may be decided by the Vessel Management Team (VMT) to abandon the pipe. The pipeline will be lowered to the seafloor by means of an A&R cable, attached to a lay down head which is welded to the end of the pipeline. Depending of the conditions, the A&R cable can be cut and recovered, by means of attaching it to a buoy, allowing the stinger to be lifted out of the water, and to sail to sheltered waters. Or it can stay attached to the vessel.

- **Standby and Waiting on Weather (WoW):** *Solitaire* is on standby when the pipeline is abandoned, but remains connected via the A&R cable. The stinger remains in the water, ready to resume operations when possible, or can be rotated up. In this condition the vessel is able to do weathervaning.

- **Special installation:** *Solitaire* is also capable of installing special structures that are part of the pipeline infrastructure, e. g. PLETs, PLEMs, in-line structures, subsea templates.

[1] It is important to note the operational deficiencies are mainly focused on the aft, since is the scope of this thesis.

- **Adjusting stinger angle and radius:** Depending on the pipelay depth the stinger radius will be adjusted either by changing the stinger sections or by adjusting the height of the roller boxes. Configuration changes and roller box adjustments are carried out in sheltered areas, stinger rotations can be carried out in-field by means of the stinger winches and the Stinger handling system (SHS).
- **Transit conditions:** All thruster conditions are running. During transit the stinger is always in its higher position, on the survival pins.
- **Survival condition:** In survival condition the pipeline is abandoned and the stinger is rotated out of the water.

4.3. Operational analysis

An operational analysis was carried out to better understand the time that *Solitaire* expends in each activity. It was found that by changing the design, the duration of pipelaying can be decreased by a reduction of the peak cycle time, downtime or the combination of both.

- **Reduction of peak cycle time:** The fastest time to produce a joint would be decreased. While the downtime is kept the same. Thus, the timeline would be shifted to the left.
- **Reduction of downtime:** The hap between the actual and peak cycle time would decrease
- **Combination of both**

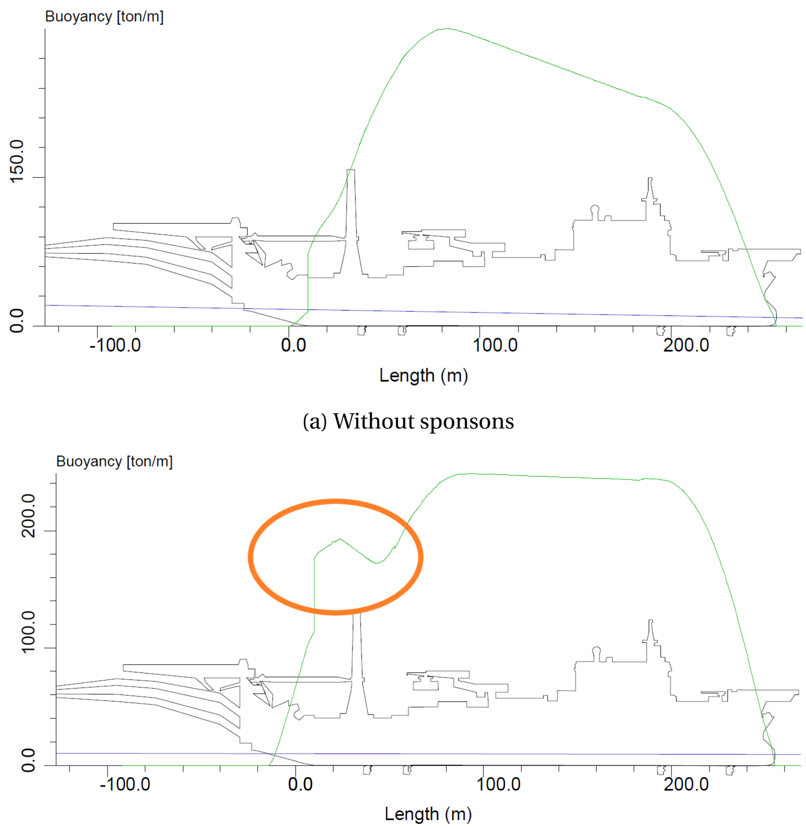
4.4. Longitudinal strength

It is well known that a ship structure can be modelled as a girder. The global forces acting on it come from the distributed hull weight, cargo weight, buoyancy and the waves loading. These forces all together compose the sectional loading, resulting in strains and stresses in the hull structure. *Solitaire* is always in hogging, due to the high weight in the hull ends, especially in the aft.

During the big upgrade in 2005, new equipment was installed, which increased the weight in the aft. Mainly, a new stinger, the cantilever beam and the heels that support the stinger. These created a need for more buoyancy, to not exceed the still water bending moment as imposed by the classification society Lloyd's Register (LR). This was solved by installing sponsons as mentioned in chapter 1. This increase of buoyancy can be seen in Figure 4.1b marked in orange.

During an inspection in 2015, heavily corroded plates were found in the main deck. The compromise solution was to lower by 8% the Maximum Allowable Sill Water Bending Moment (MASWBM) to obtain Condition of Class (CoC). Thus, the MASWBM is close to the limit but within. In addition to this, a new stinger section 1, has been designed which increases even further the weight at the aft. All these lead to a need to decrease the hogging moment of the vessel. In the current situation, the loading condition that has the highest Sill Water Bending Moment (SWBM) is "arrival ballast", it is characterised by:

- 30% consumables
- 0% pipes
- Stinger in survival position
- Special purpose crane (SPC) stored in position

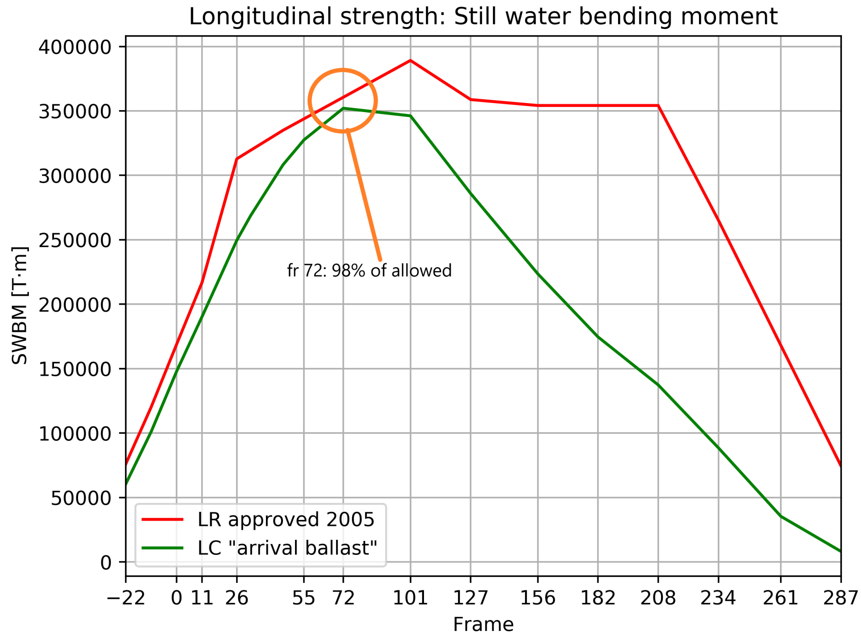


(a) Without sponsons

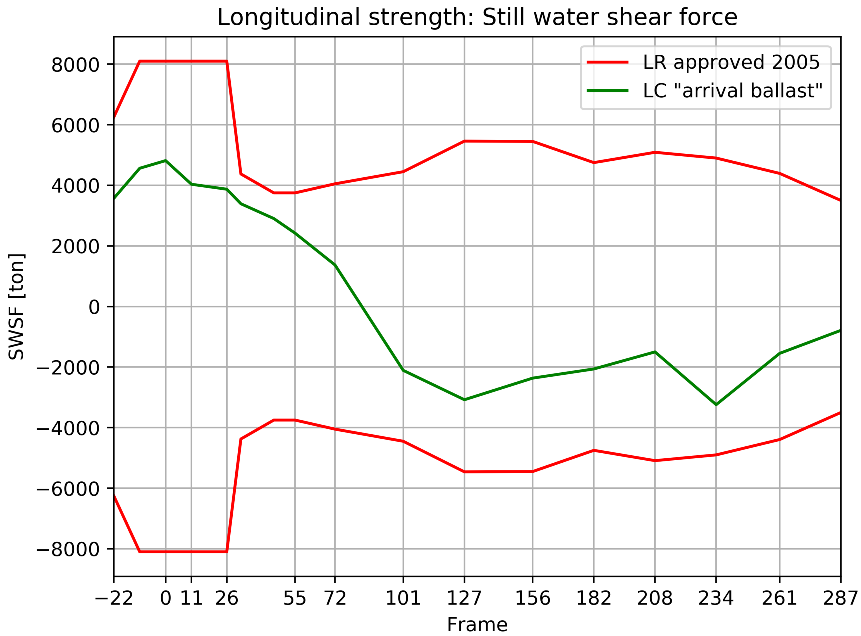
(b) With sponsons

Figure 4.1: Buoyancy curves of *Solitaire* [ton/m].

This issue with the longitudinal strength should be solved as soon as possible, if not the class can be revoked and it will not be able to operate.



(a) Bending moment along the length



(b) Shear force along the length

Figure 4.2: Loading condition 20: "arrival ballast"

4.5. Resistance

In 1996, a test campaign was conducted at MARIN to determine the bare hull resistance. Due to the addition of the sponsons during the 2005 upgrade, the resistance increased, drastically. This increase is due to the odd shape of the sponsons which leads to more wave-making resistance and the increase of wetted area, which increased the frictional resistance. Also, frame 11 is completely vertical (Figure 4.3) creating important flow separation. For this reason, a Keel flow fairing plate (KFFP) was installed to improve the flow between the sponsons, also known as a spoiler. This flow separation, increases the resistance, as a lot of vortexes are being shed, creating a big backwash, Figure 4.4.

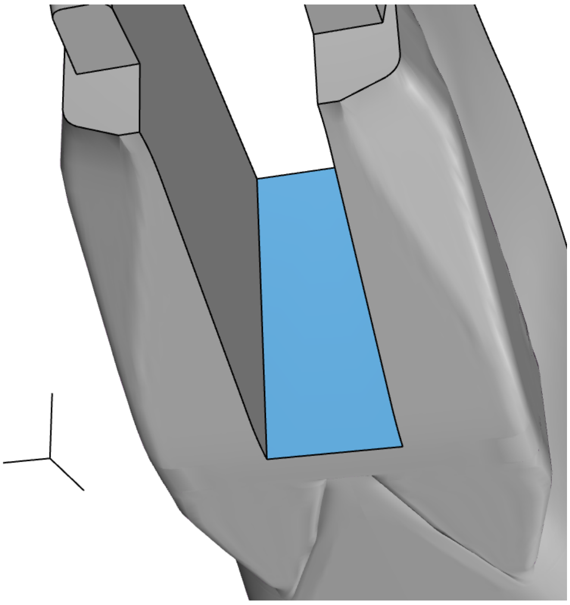


Figure 4.3: Bottom view of the aft, frame 11 in blue

Figure 4.4: View (looking aft) of the Stinger slot backwash. ©Allseas B.V

During 2009, speed trials were conducted to estimate the required power during transit, and determine possible solution to either decrease the fuel consumption and/or decrease the resistance [14]. Which lead to different concepts to lower the resistance.

In 2010, different aft designs were tested at TU Delft towing tank (Table 4.1) and compared to obtain the decrease in required power.

Hull form	Description
1	Original 1996 hull form
2	Original sponsons, no spoiler
2A	Original sponsons, spoiler **[Current]**
2B	Original sponsons, half infill
2C	Original sponsons, full infill
2T1	Like 2A, with 1 m trim forward (equal displacement)
2T2	Like 2A, with 2 m trim forward (equal displacement)
3A	Faired sponsons, with spoiler
3B	Faired sponsons, half infill
3C	Faired sponsons, full infill

Table 4.1: Different tested hull forms

If the stinger slot is completely closed, then the aforementioned vortex has a much smaller volume or even not created anymore. The aft designs with less resistance are the ones with the full infill, 3C and 2C.

Solitaire spends some time sailing. Therefore, Allseas would like to improve the transit speed, which would allow her to have more operational days. [2]

4.6. Stinger

4.6.1. Stinger configuration

The stinger is connected to the vessel by means of two hinges, close to the centre line, marked with orange in Figure 4.5. The stinger hinge position can be set at three different heights. While laying pipe in deep water configuration, the stinger radius is 110 m, Figure 4.7. Thus, most of the stinger is submerged. If it is loaded by lateral waves, then most of the load is taken by the heels and the hinges.

In this situation, the operational limit is lowered, impacting the workability of *Solitaire*. The main reasons [3] are the low stiffness of the lateral support structure (heels) and the small lever arm between the stinger centre line and the hinges.

4.6.2. Stinger handling system (SHS)

The stinger handling system Figure 4.7 is located on top of the outriggers, and consists of two hydraulically operated skids which can be locked in a range of positions. The skids are connected to the stinger employing a rigid fixing frame. The hang-of cables are suspended from wires that hang from the cantilever which connects to the top of the cross-over. These wires are connected to the stinger winches on the cross over. [8]

The reason to have in place a rigid fixing frame instead of having the stinger suspended by cables is the fact that in certain situations the stinger can experience uplift.

4.6.3. Roller boxes

On top of the stinger roller boxes Figure 4.7 support the pipe. All roller boxes are fitted with load cells. The height of the roller boxes is set up depending on the project/pipeline characteristics. Each

[2] Allseas views transit days as lost days of operation.

[3] Joris van den Boomen, technical superintendent of *Solitaire*, interviewed on March 13^{th} 2019 in Delft, Netherlands.

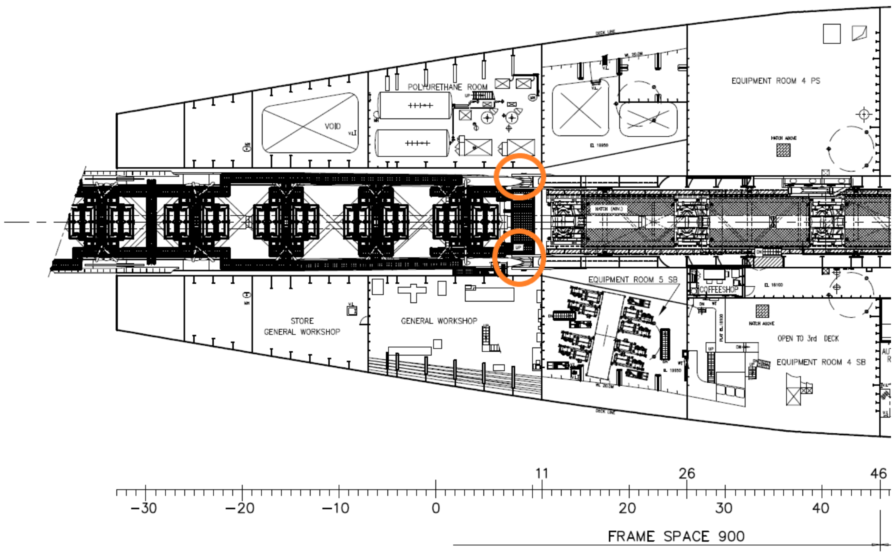


Figure 4.5: Hinge location

of the roller boxes has to be adjusted separately. Thus, if the height has to be adjusted, the stinger has to be lifted out of the water to be able to access them. This adjusting can not be performed at high sea states and is time consuming.

4.7. Deck space

The general firing line configuration has up to 2 stations dedicated to field joint coating. This coating varies per project. The whole workload, as with the welding, has to be spread out throughout the stations as explained in section 2.2. For some projects, an extra station at the end of the firing line will be useful to divide more the workload, footnote 3. Furthermore, it would provide with more flexibility to configure the firing line stations if needed for a certain project. For example, if the pipe thickness is big, it might be necessary to have an extra welding station to divide the welding workload. Thus, the rest of the stations would be shifted to the end of the firing line. Also, more equipment could be stored on deck.

4.8. Aft ship mooring system

Due to the large area of the stinger and SHS structure (Figure 4.7), wind forces create high loads that need to be compensated by the aft mooring system, Figure 4.6. Therefore, a minimum of two breast lines and two longitudinal lines on one side of the vessel are installed to cope with the wind loads. Some of these lines can not be handled by the existing mooring winches so they are attached in bollards. They are also not able to use the winches to adjust or tighten these lines.

When the 'heels' are stowed they are in the way of stern lines. Which interfere with each other. Thus, there is a risk that the lines or the structures get damaged.

Lastly, due to the high freeboard of the ship, aft breast lines acquire a steep angle at the quay, reducing the effectiveness of the line. Which might result in the snapping of the lines due to exceeding their limit.

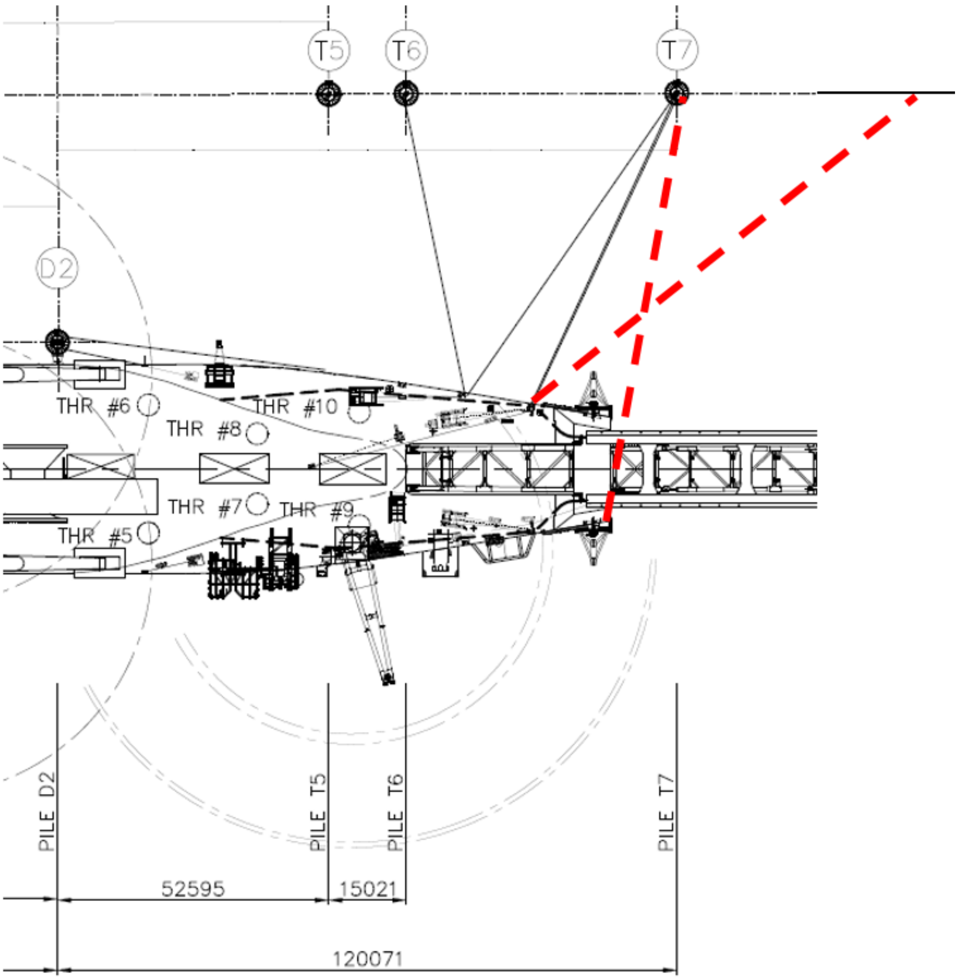


Figure 4.6: General aft mooring plan

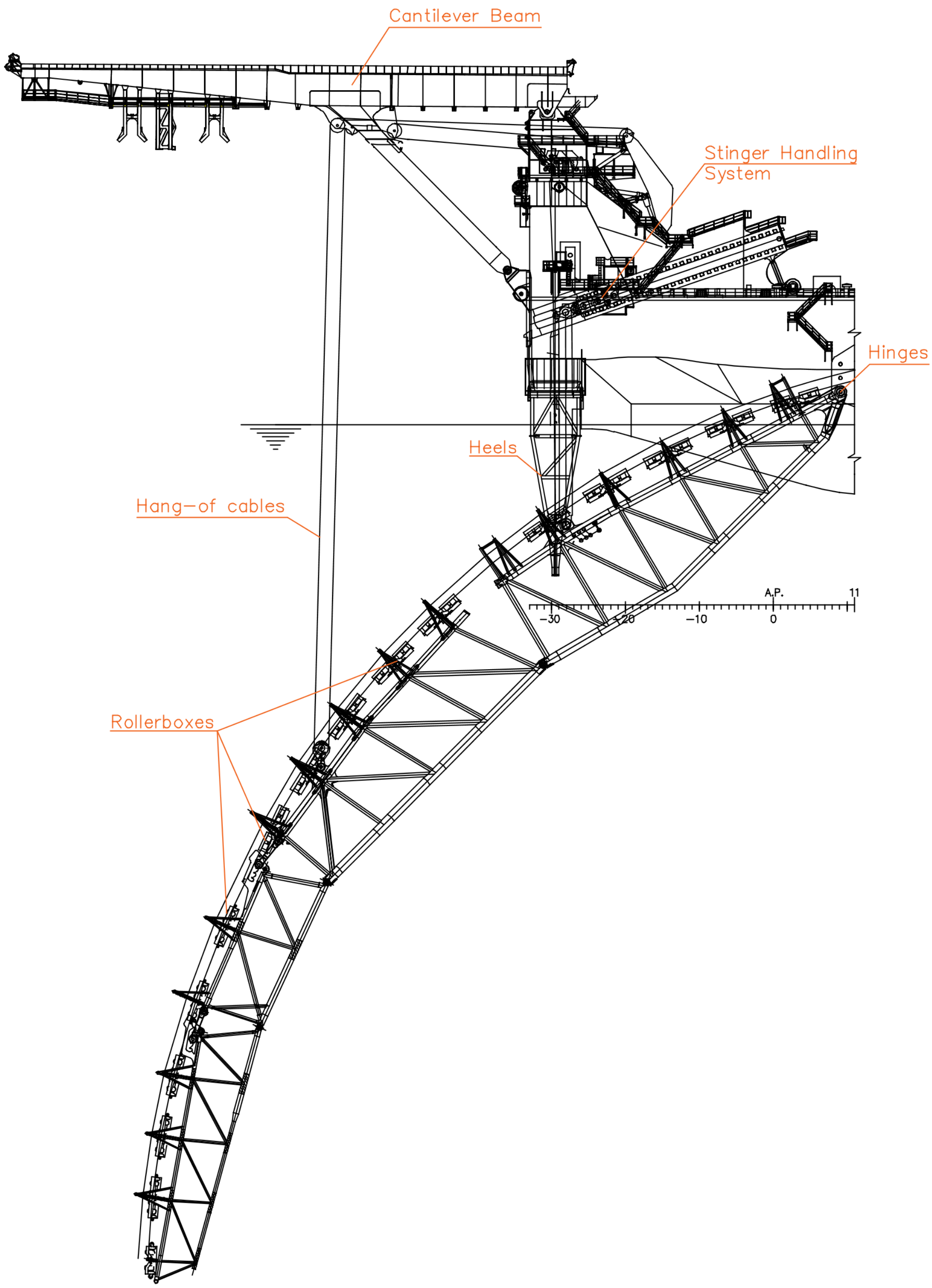


Figure 4.7: General overview of stinger and its components

5

Requirements analysis

Due to the characteristics of this project, a retrofit, certain specifications of the current design are input of the design requirements. Therefore, the overall performance of the vessel is not compromised by the new design. Other input of the requirements is the outcome of the current design analysis.

From chapter 4, it can be deduced that improvements have to be made. Certain operational deficiencies are critical and should be fixed as soon as possible, i.e.: the longitudinal strength. While others are not critical but have an important role in the performance of the vessel.

5.1. Current specifications

As mentioned in section 3.3, not all the components of a system become obsolete thus, only certain systems or parts are retrofitted. Also, the design scope of this thesis is only the aft of *Solitaire*. Therefore, part of the current specifications become requirements of the new design as reasoned in, while others need to be improved.

Operation		Possible change
- Diameter pipe	2 - 60 inch	
- Water depth	Ultra deep waters (≈3,000 m)	
- Installation configuration	S-lay	
- Area	Worldwide	

Main particulars		
- Lpp	248.65 meter	yes
- LWL	278 meter	yes
- Design Draught	8.5 meter	
- Breadth moulded	40.6 meter	
- Depth moulded	24.0 meter	
- Displacement (at T=8.5m)	73,679 ton	yes

Stinger		
- Length	140 meter	yes
- Nr. of Section	3	yes
- Nr. of roller boxes	17	yes

Tanks capacities		
- HFO	6,438 m^3	yes
- MDO	1,179 m^3	yes
- MGO	62 m^3	yes
- LO	50 m^3	yes
- Potable water	1,120 m^3	yes

Pipelay equipment		
• *Firing line*		
- Length	225 meter	yes
- Piggyback	up to 6 inch	yes
• *Double joint factory*		
Welding		
- Nr. welding stations	3 per side	
- Welding method	Phoenix automatic welding system	
NDT		
- Nr. NDT stations	1 per side	
• *Main firing line*		
Welding		
- Nr. welding stations	8	yes
- Welding method	Dual/ Triple torch Phoenix system	
NDT		
- Nr. NDT stations	1	yes
FJC		
- Nr. FJC stations	2	yes
• *Tensioner*		
- Nr. tensioner	3	
- Capacity	350 ton	
• *A&R winch*		
Single-wire system		
- Capacity	400 ton	
Four-wire system		
- Capacity	1,000 ton	

Table 5.1: Current specifications

5.2. Longitudinal strength

The longitudinal strength requirement can be related to the need of buoyancy that it is needed in the aft to maintain the Sill Water Bending Moment at a reasonable level while being able to install pipe and subsea structures at a certain water depth. The maximum water depth achieved by *Solitaire* was 2,775 in 2007. The Oil and Gas offshore market is evolving to deeper waters [15]. Also, it is expected that between 2019 and 2023 over 18,482 km of pipelines will be installed [16].

Therefore, not only is there a need to add buoyancy to meet the class requirements but also a need to be able to reach deeper waters to bid upcoming contracts. There might be a need to install a new structure in an unforeseen project. Thus, the longitudinal strength should be at least on the same level as it was before they issued the Condition of Class. Therefore, the Longitudinal strength should be at least 8% more, than the current situation.

5.3. Transit speed

When the location of consecutive projects is far apart, transit speed becomes crucial. As explained in chapter 4 transit days are considered lost days of operation. Therefore, the faster the vessel goes the better. But also, it is important to note that the transit time also becomes crucial when *Solitaire* has a lot of projects, since late penalty fees are quite high.

From section 4.5, it can be deduced that if the stinger slot is filled and the sponsons streamlined an increase of approximately 0.5 to 1.0 knots can be achieved, in Table 5.2 different transit times have been calculated, taking as starting point the port of Rotterdam.

		Time		
Port	**Distance**	@13.5 kn	@14.0 kn	@14.5 kn
Perth	9,575	29d 13h	28d 12h	27d 12h
Kakinada	7,530	23d 06h	22d 10h	21d 15h
Rio de Janeiro	5,243	16d 04h	15d 15 h	15d 02h

Table 5.2: Transit time comparison

As the current installed power remains the same, with 8 generators at a 80% utilisation, the increase in speed is approximately 0.7 knots. Therefore, an increase of approximately 0.5 knots is required.

5.4. Stinger

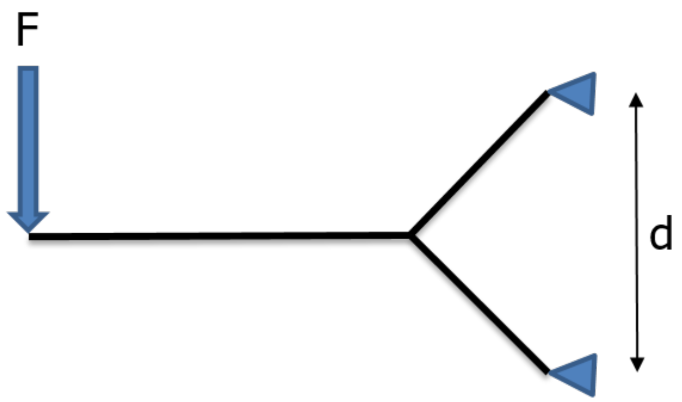


Figure 5.1: Free body diagram model of stinger

If we idealise the stinger under a lateral force "F" as pictured in Figure 5.1, Equation 5.1 is obtained. Where the load (F) that the supports can withstand increases as the distance between them also increases.

$$F \propto d \tag{5.1}$$

Therefore, a wide base stinger configuration is required. To handle this new stinger a simpler SHS is required, trying to avoid the use of the hydraulic yoke system. This simplification should keep the same functionalities as the current system and be able to conform the stinger to the required shape.

5.5. Deck space

To increase the deck space, multiple options are at hand. One of them is to widen the lines in the aft part. But if an extra station is to be fitted, the firing line should be extended by 12.2 m. With the current length, it would be placed on top of the stinger.

Therefore, it is required to have at least 122 m^2 of extra deck space (in pink on Figure 5.2), as the width of the firing line is 10 m and the nominal length of a joint is 12.2 m. But, this deck space must be placed after frame 11, to extend the firing line.

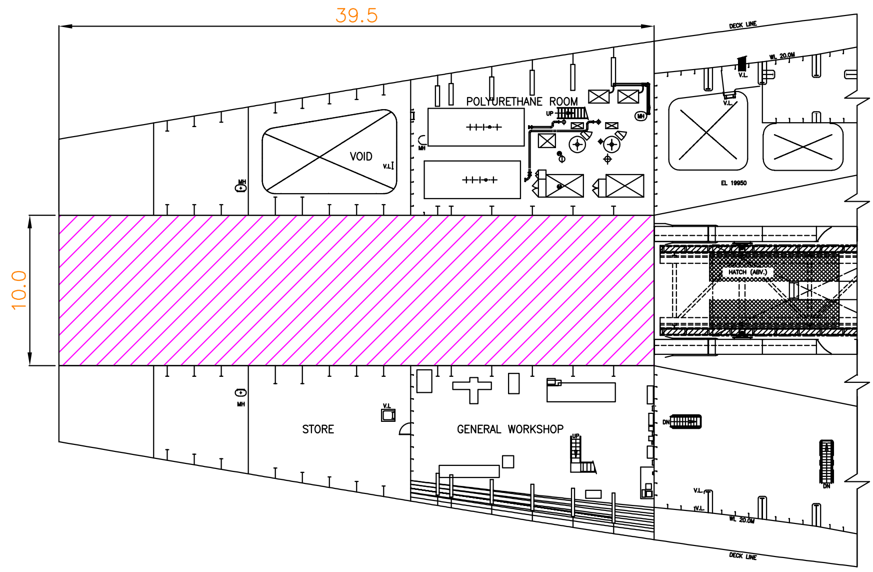


Figure 5.2: Possible extra deck space to extend firing line.

6

Functional definition

In the functional definition the critical functions that the design has to meet are identified. This functional definition should reflect the needs of the user. It precedes physical design to ensure an effective configuration of the functions. Furthermore, the design is broken down into a systems and sub-systems level. Which will result in the allocation of the functions that each system/sub-systems must perform.

6.1. Functional architecture

In order to fulfil the mission of the vessel and the different operational profiles, the design must achieve certain functions. Each function is broken down in different sub-functions to have a more comprehensive overview. Therefore, a functional tree (Figure 6.1) has been created to depict all the functions that the vessel must fulfil. But since the scope of this project is the aft, the associated parts are highlighted in orange and defined below:

- **Motions control:**
  - **Stability:** To maintain stability within allowable limits
  - **Station keeping (DP):** To maintain position during pipelaying operations and special installations.
  - **Seakeeping:** To maintain ship motions within allowable limits.
  - **Propulsion: to propel the vessel during transit.**
- **System support:**
  - **Buoyancy:** To provide enough buoyancy while the multiple operations.
  - **Spatial integration:** To provide enough space to integrate all equipment and processes.
  - **Structural integrity:** To provide with a structure able to cope with the loads met during the life of the vessel.
- **Pipe welding:**
  - **Coating:** to coat the newly made welds.
- **Pipeline installation:**
  - **Positioning:** To support the pipe in the overbend.

For the complete definitions refer to Appendix A.

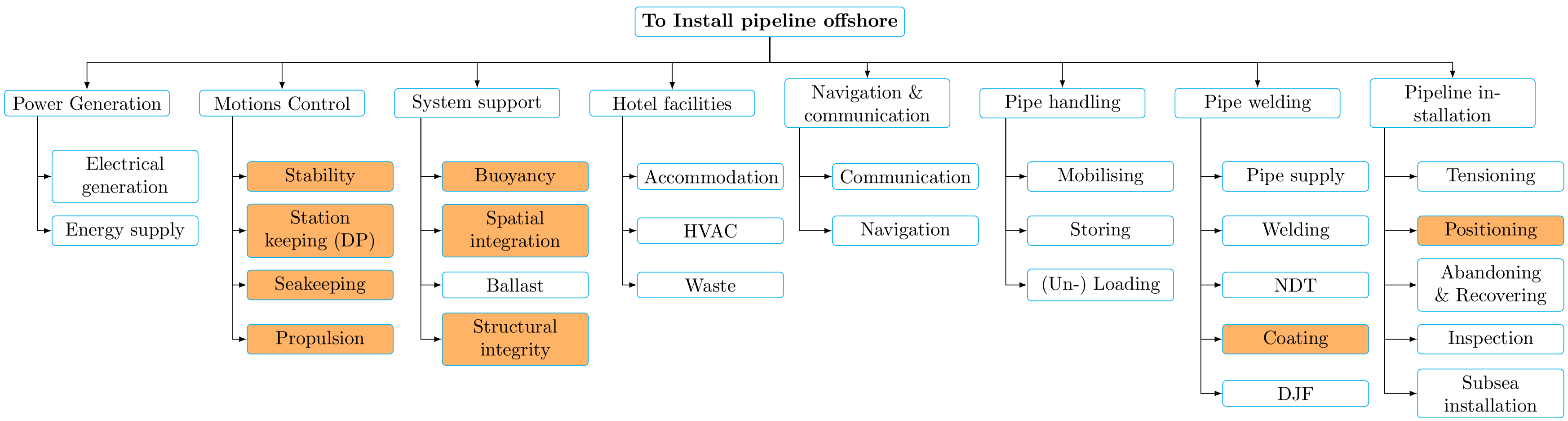


Figure 6.1: Functional Decomposition.

6.2. System architecture

In order to maintain a coherent decomposition of systems (Figure 6.2) the SFI coding system is used. "The SFI Technical Coding Solution is the most widely used classification system for maritime and offshore industries. It is an international standard providing a functional subdivision of technical and financial information, which can be applied to all aspects of a vessel or rig" [17].

As with the functional architecture, the systems that are related to the aft are marked in orange in Figure 6.2

- **Hull and Tanks:**
  - **Hull general:** the structure of the vessel and its components.
- **Production equipment:**
  - **Auxiliary systems and equipment for pipelay:** Firing line systems, line up systems, tensioners, stinger, A&R winch, piggyback equipment, et cetera.
  - **Field joint coating equipment:** Preheating, coating systems, etc.

For the complete definitions refer to Appendix A

6.3. Correlation matrix

Once the functions of the vessel are set and the systems that support those functions are determined. A correlation matrix is made, Figure 6.3. To correlate functions to systems is of utmost importance when designing a system. Therefore, it is possible to check that all the functions are met by at least one system. In this way, the systems architectures become modular is a certain degree, making the maintenance and retrofit easier.

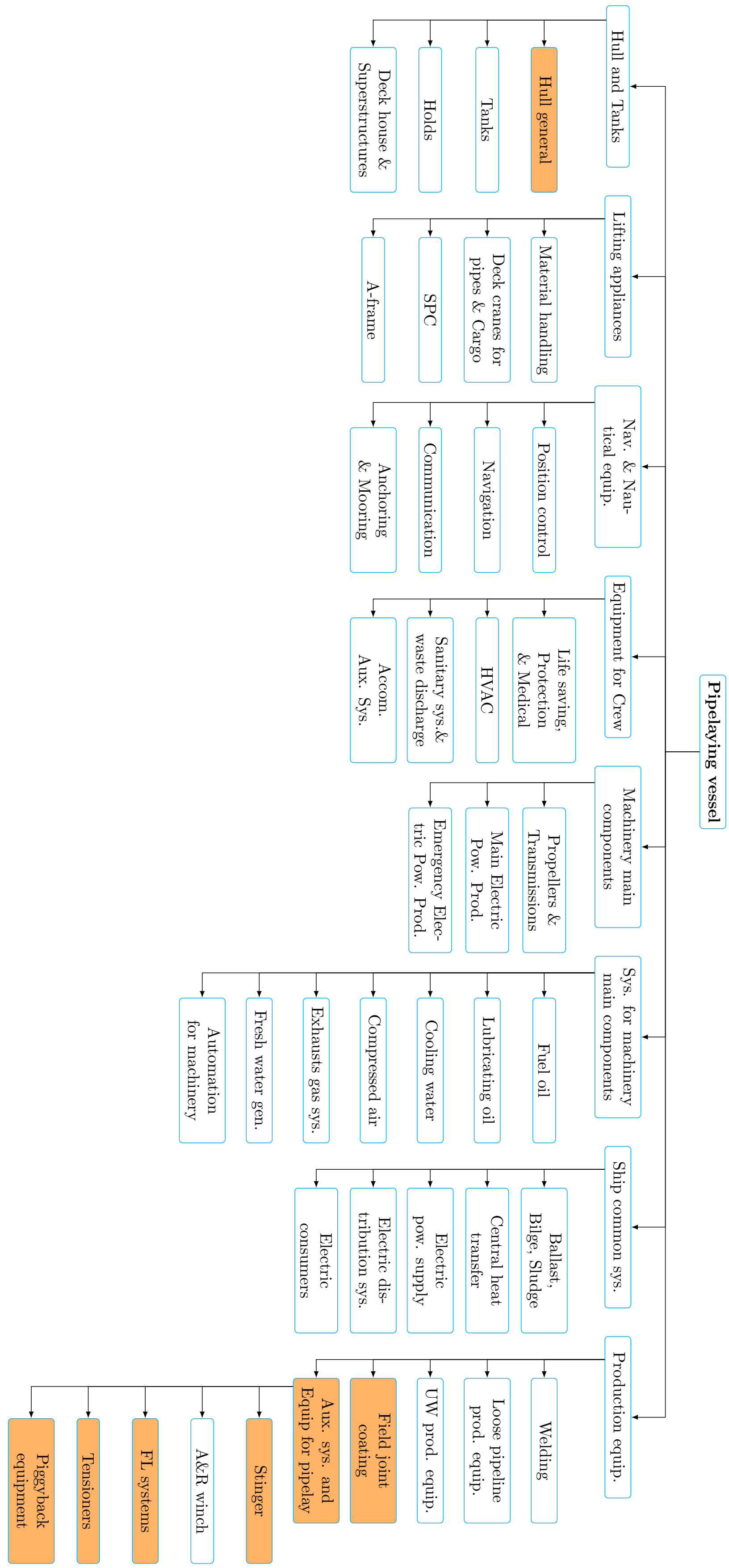


Figure 6.2: System Decomposition.

Functions		Hull and tanks				Lifting appliances				Navigation & nautical equipment				Equipment for Crew			
		Hull general	Tanks	Holds	Deck houses and superstructures	Material handling	Deck cranes for pipes and Cargo	Special purpose crane	A-frame	Position control	Navigation	Communication	Anchoring & Mooring	Life saving, protection & Medical	HVAC	Sanitary sys. & waste discharges	Accommodation Aux systems
Power gen.	Electrical generation																
	Energy supply		x														
Motions control	Stability	AFT	x	x	x					x	x						
	Station keeping	AFT								x	x		x				
	Seakeeping	AFT	x							x							
	Propulsion	AFT								x	x	x					
System support	Buoyancy	AFT															
	Spatial integration	AFT	x	x	x												
	Ballast		x														
	Structural integrity	AFT	x	x	x												
Hotel facilities	Accommodation				x									x			x
	HVAC														x		
	Waste		x													x	
Nav. & Comm.	Communication											x					
	Navigation									x	x						
Pipe handling	Mobilising			x		x	x						x				
	Storing			x		x	x										
	(Un-)Loading			x		x	x						x				
Pipe welding	Pipe supply			x		x	x										
	Welding																
	NDT																
	Coating																
	DJF																
Pipeline installation	Tensioning																
	Positioning																
	A & R																
	Inspection									x	x	x					
	Subsea installation					x		x	x	x	x	x					

Functions		Machinery main components			Systems For machinery Main components							Ship common systems					Production equipment				
		Propellers and transmissions	Main electric power production	Emergency electric power production	Fuel oil	Lubricating oil	Cooling water	Compressed air	Exhausts gas system	Fresh water generation	Automation for machinery	Ballast, Bilge, Sludge	Central heat transfer	Electric power supply	Electric distribution system	Electric consumers	Welding equipment	Aux. systems and equipment for pipelay	Loose pipeline production equipment	UW production equipment	Field joint coating
Power gen.	Electrical generation	x	x	x	x	x	x	x	x	x	x										
	Energy supply				x																
Motions control	Stability											x									
	Station keeping	x	x	x							x			x	x						
	Seakeeping	x										x									
	Propulsion	x	x	x	x	x	x	x	x	x	x	x		x	x						
System support	Buoyancy																				
	Spatial integration																				
	Ballast																				
	Structural integrity	x										x									
Hotel facilities	Accommodation												x			x					
	HVAC												x			x					
	Waste																				
Nav. & Comm.	Communication															x					
	Navigation															x					
Pipe handling	Mobilising	x																			
	Storing																				
	(Un-)Loading																				
Pipe welding	Pipe supply																	x			
	Welding						x			x							x	x	x		
	NDT									x								x	x		
	Coating																	AFT			AFT
	DJF						x			x							x	x	x		x
Pipeline installation	Tensioning	x														x		x			
	Positioning	x						x			x							AFT			
	A & R	x														x		x			
	Inspection																	x		x	
	Subsea installation	x																x		x	

Figure 6.3: Correlation matrix.

6.4. Requirements prioritisation

Due to the complexity of the vessel, the solutions of each requirement can be coupled. For example, to solve the Longitudinal strength, more buoyancy can be added to the aft by building bigger sponsons. This solution can be optimal for the longitudinal strength but is a detriment for the transit speed. Another example could be, that the closure of the stinger slot, which would be beneficial not only for transit speed but also for the longitudinal strength, but it would change drastically the aft configuration. Therefore, a locally optimal solution might not result in the best global solution. This conclusion leads to the need to prioritise the design requirements.

From chapter 5, it is clear that the most important requirement is the Longitudinal strength, since if *Solitaire* fails to meet this requirement, it will lose the Class certificate and it would not be able to sail.

The rest of the operational deficiencies are not as critical as the vessel can still operate if they are not met. Therefore, prioritisation has to be made.

The next requirement is the stinger, since it is a critical component for operation, without it the vessel can not lay pipe. Also, it has undergone multiple repairs and new sections have been retrofitted. Thus, a new design can decrease the number of repairs and have a longer lifetime.

On average, *Solitaire* expends 50 days in transit mode. The transit speed is not critical for normal operation, although it allows the vessel to arrive at the projects faster. Therefore, more operational days are available.

Deck space allows flexibility which for offshore operations is important not only on deck but also in the firing line. This requirement is also tied to the mooring aft arrangement. Even though this requirement is important, it is not crucial for operation.

6.5. Chapter conclusions

As with most of the complex designs, they are an integration of multiple systems. During their lifetime of operation, certain systems become obsolete. Due to this obsolescence, the effectiveness of the design decreases.

From the correlation of functions and systems (Figure 6.3), it can be seen that a few systems correlate to lots of functions. Which in some way reflects the reasoning to do a retrofit. Since by upgrading a few components, the effectiveness of the design increases greatly.

Some of the requirements are coupled with each other. Thus, it can lead to solutions that might be optimal for a certain operational deficiency but not for the other. Therefore, prioritisation has been made to escape from possible local optima and find global optima.

7
Analysis of alternatives

In this chapter, different solutions are investigated for each of the design requirements. As mentioned in the previous chapter, solutions that are optimal for one design requirement might not be globally optimal, as they might interfere with other requirements.

7.1. Aft definition

After gaining insights into the design of *Solitaire*, it has been decided, in conjunction with Allseas, that the scope of the retrofit is aft of frame 11. The main reason for it, is due to the amount of complex equipment installed forward of frame 11 (thrusters, special purpose crane, etc), see Figure 7.1. For example, in the case that the thrusters have to be moved to a different location, the power cables that connect them would have to be re-routed.

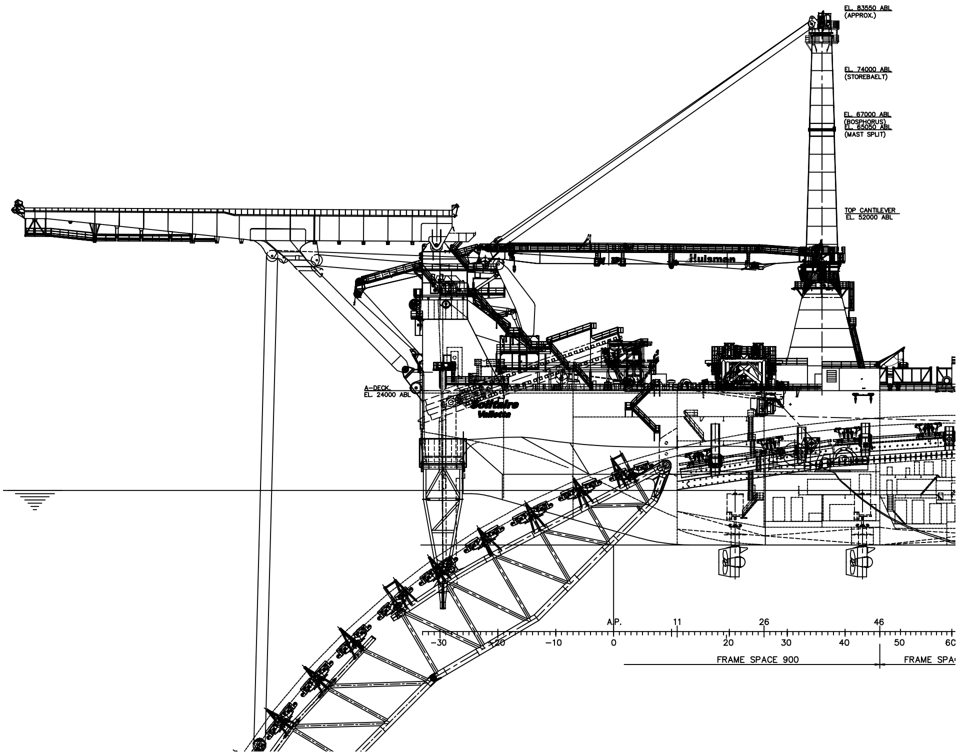


Figure 7.1: Profile general arrangement of *Solitaire*. ©Allseas B.V

7.2. Longitudinal strength

Due to the difference in weight and buoyancy distribution along the length, a ship experiences a longitudinal bending moment with its maximum at around the midships region. Therefore, different approaches can be taken to improve the longitudinal strength e.g. to lower the load on the hull girder by decreasing the weights, to increase the buoyancy at the aft or to strengthen the structure in the critical area. The following modifications are based on this approaches.

As pointed out in chapter 4, loading condition 20 -"Arrival ballast"- is the critical condition. This condition will be used as a benchmark for the modifications. Although it is possible that other loading conditions could become critical. Therefore, all other conditions will be checked.

7.2.1. Remove weights at the aft

One solution is to remove partially the cantilever beam structure at the aft, crossed out in red in Figure 7.2. This decreases the weight at the aft, partially unloading the hull girder. Also, the impact on stability is positive as the removed weight is quite high, Table 7.1.

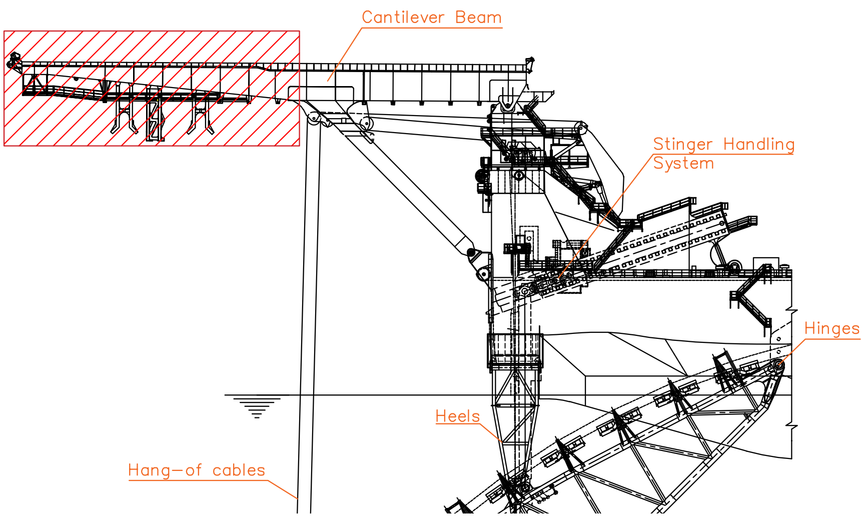


Figure 7.2: Removed part of the cantilever beam

Weight [ton]	≈ -184
VCG [m]	50
LCG [m]	-70
TCG [m]	0

Table 7.1: Approximate weight and CoG of the removed part of the cantilever beam

By performing this modification, the bending moment is improved by 5%, as shown in Figure 7.3.

Even though it is a simple solution, it eliminates the capacity to handle materials or equipment above the stinger, impacting in certain operations, which is not desirable. For example, guiding PLET, buoys, etc; before they are submerged.

This modification can be carried out at port without going into dry dock. Due to the simplicity of the modification and the ability to perform it in a short time, the costs involved in it are rather low.

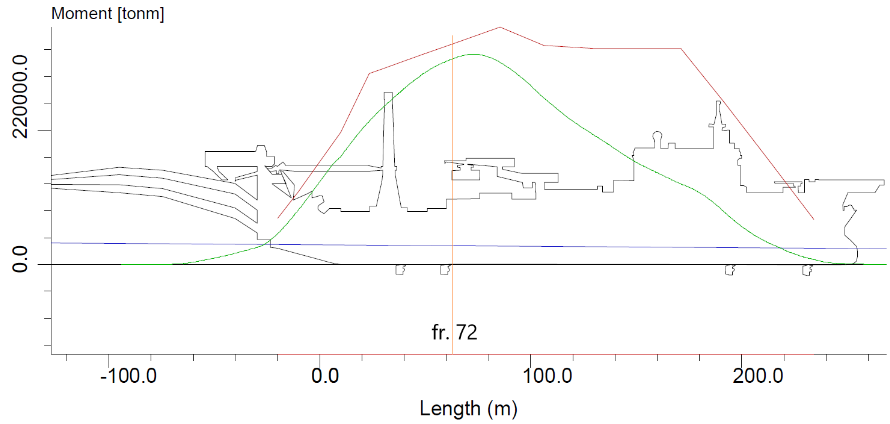


Figure 7.3: Bending moments LC 20 with modified cantilever beam

7.2.2. Enlarged sponsons

Due to the need of buoyancy another solution could be to enlarge the already installed sponsons, filling the gap until the heels. At a draft of 8.5 m, the added buoyancy is 2,843 m^3, Figure 7.4, adding approximately 600 tons of steel weight due to the new structure.

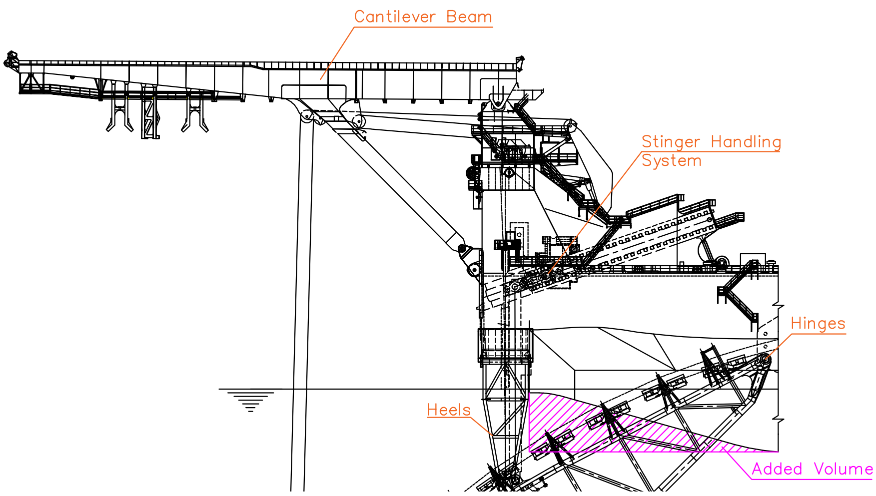


Figure 7.4: Enlarged sponsons modification

With this modification a large volume is added at the aft, which reduces the bending moment by 7% , as plotted in Figure 7.5.

In order to carry out this modification, *Solitaire* has to go into dry dock. The building of the sections can start before hand. But, cutting, preparation of surfaces, welding and painting have to be done during dry dock. The shape of the sponsons is also complicated. Therefore, the time and cost of this modification is quite high.

Due to the modification the hull forms vary, especially the lateral area. Therefore, the DP capabilities will be affected. Also, due to this change in hull forms the resistance will be increased, as there is more area exposed to the vortexes formed aft of frame 11.

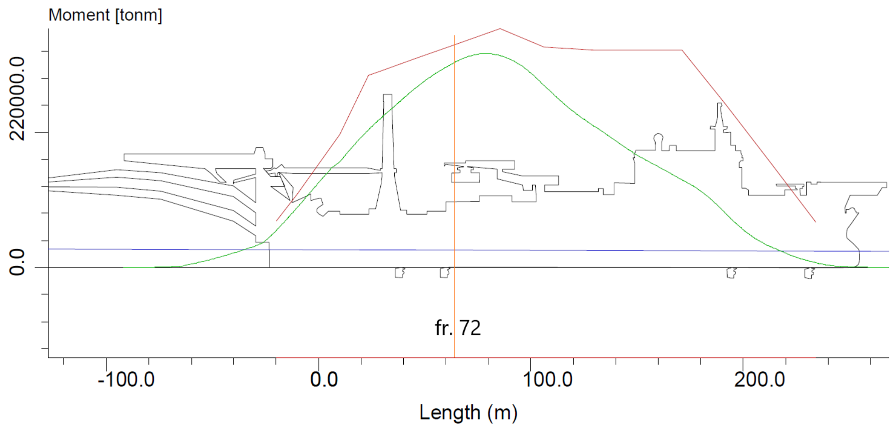


Figure 7.5: Bending moments LC 20 with enlarged sponsons

7.2.3. Close the stinger slot

Another modification to add buoyancy is to close the slot where the stinger moves during operation. With this modification 1,464 m^3 of buoyancy are added at a draft of 8.5 m, while the steel weight is approximately 200 ton, Figure 7.6.

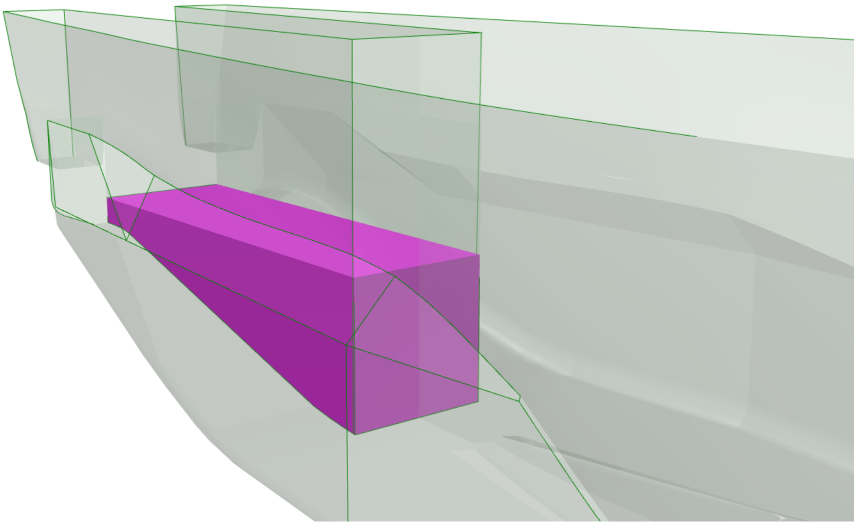


Figure 7.6: Added volume due to stinger slot closure

As shown in Figure 7.7 the longitudinal strength complies with the rules, obtaining a reduction of 14% on frame 72.

The use of dry dock is necessary to complete this modification. As with the previous modification, the building of the sections can be done before hand, but cutting, preparation of surfaces, welding and painting have to be done during dry dock. The shape of the structure is fairly easy, as only one side is curved.

By closing the stinger slot, the stinger has to be redesigned, with a different configuration. For example a wide base configuration similar as *Audacia*. But also, the different systems that are associated with the stinger as the SHS, the roller boxes, the firing line, etc.

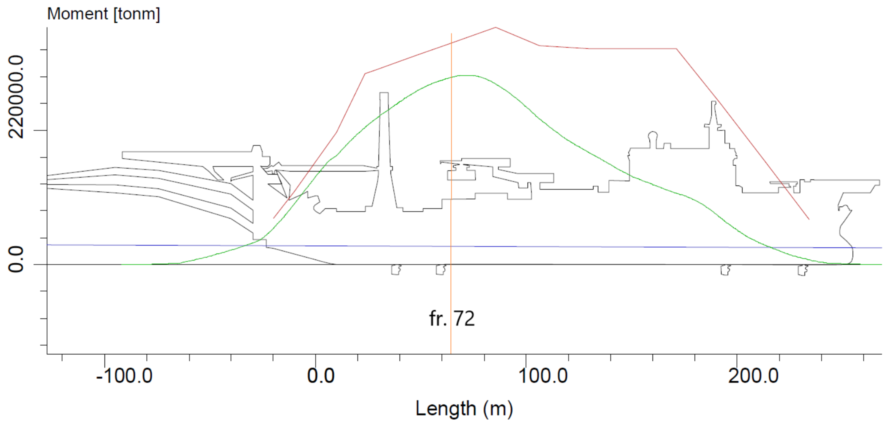


Figure 7.7: Bending moments LC 20 with stinger slot closed

As mentioned in chapter 5, the closing of the stinger slot improves the transit speed. Also, since the hull forms vary, the DP capabilities change, although they will most likely improve, as the flow is improved.

With this new structure, an area of 395 m^2 of potential deck space is added. Which potentially could increase the firing line up to 39 m in length. With this increased length, two/three additional stations could be added, Figure 7.8.

Cost wise this modification is expensive as it has associated works, such as new stinger configuration, adding more firing line components. But, it meets multiple design requirements. Regarding time, the execution is long as well as the engineering hours, as it has to go into dry dock.

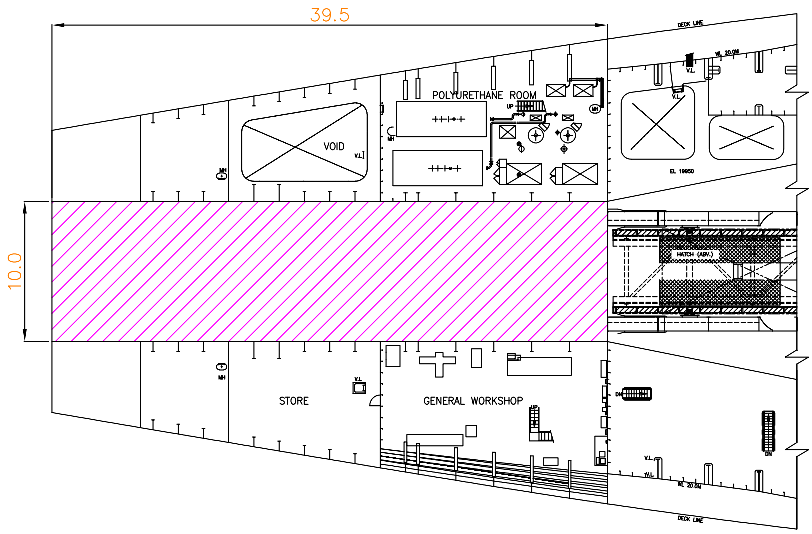


Figure 7.8: Plan view of Stinger Slot

7.2.4. Strengthening of the structure

To strengthen the structure at the aft does not help with this operational deficiency, as the most loaded sections are between frames 72 and 101, as can be seen in Figure 4.2. Therefore, by strengthening the structure of the aft it would only add more weight, without fixing the problem.

7.3. Stinger

The current design of the stinger (radius, length, loads of roller boxes) is preferred to not be changed[1]. Therefore, the new stinger configuration should be able to obtain the same departure angle as the current design.

By using a wide base stinger the loads transmitted to the hinges are less. As the lever arm is greater than with a straight base stinger. Therefore, the stinger can withstand higher loads and also the design of the main hinge can be simplified.

In the other hand, if the hinge is moved aft it has a negative impact on the longitudinal strength as the forces acting on the stinger are transmitted to the ship structure further from the midships section. Also, the DP capability will be lower as the forces acting on the stinger are further from the centre of gravity of the vessel. As the stinger tip is further apart from the CoG also the workability will decrease.

Within the wide base stinger concept, two configurations are investigated: the main hinges attached to the outside shell (Figure 7.9) and one where they are attached in the inside of the vessel (Figure 7.10).

7.3.1. Outside hinge

By relocating the hinges to the outside shell a wide base is obtained. This implies that a new general arrangement has to be made. Also, the Stinger handling system (SHS) has to be modified as well. This solution is similar to the one implemented in Allseas pipelaying vessel *Audacia*.

There are multiple modifications to the general arrangement due to the hinges being relocated to the outside shell, Figure 7.9.

By adopting this solution, the hinges would be moved backwards which would impact negatively the longitudinal strength of the vessel, as well as the DP capability and the workability. In the other hand, it would free the stinger slot to be used as deck space enabling an extra station to be installed. But also, more buoyancy would be added as the slot is closed, which would improve the longitudinal strength and decrease the vortex shedding, improving the resistance.

In order to carry out this modification, steel works are necessary. Although as they are above the waterline, it would not be necessary to do them in dry dock. A new stinger section and the consequent modification to the SHS has to be fabricated.

7.3.2. Inside hinge

As with the previous option, a wide base stinger is obtained although smaller, Figure 7.10. This solution is similar to the one implemented in Allseas pipelaying vessel *Lorelay*.

In order to install the wide base stinger, the general arrangement has to be modified to have enough space to install the new hinges as well as the stinger to rotate. Depending on the longitudinal position of the main hinges, the decrease of deck space and volume will vary. With this modification of the hull forms in principle the resistance of the vessel will increase.

A new stinger section has to be fabricated and the SHS has to be modified accordingly. *Solitaire* has to go into dry dock to carry out this modification, as the steel works involve the underwater ship.

[1] Raymond Vink, Manager of engineering at the Pipeline Engineering department, interviewed on July 1^{st} 2019 in Delft, Netherlands.

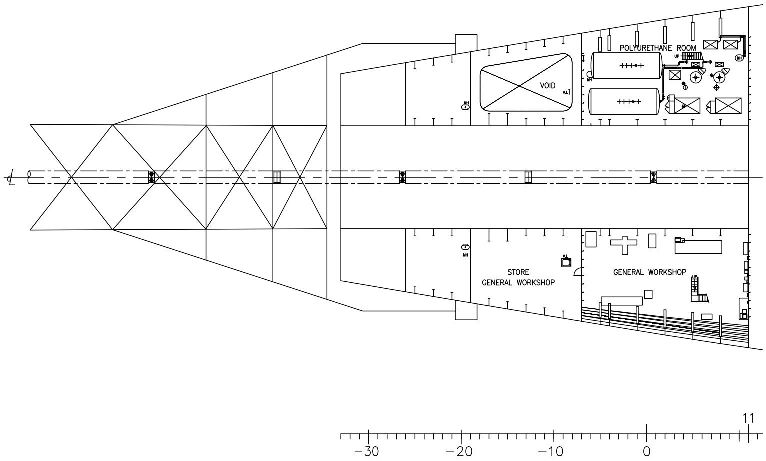


Figure 7.9: Sketch of possible outside hinge stinger configuration

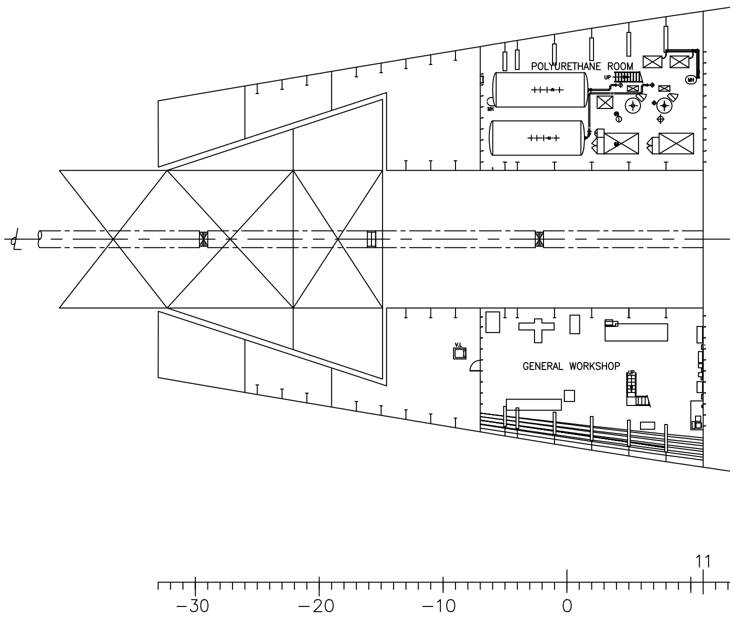


Figure 7.10: Sketch of possible inside hinge stinger configuration

7.4. Stinger handling system (SHS)

The new SHS should be a simpler design but also easier to operate, while being able to configure the stinger into the correct shape. Two systems are depicted below, although a combination of both could also be a solution.

7.4.1. Fixed support

The SHS of Saipem's *CastorOne* (Figure 7.11) is composed of four rigid beams. These beams are fixed to the stinger by means of a hinge and then attached to the vessel by a system of yokes that move and rotate the beam to the desired position.

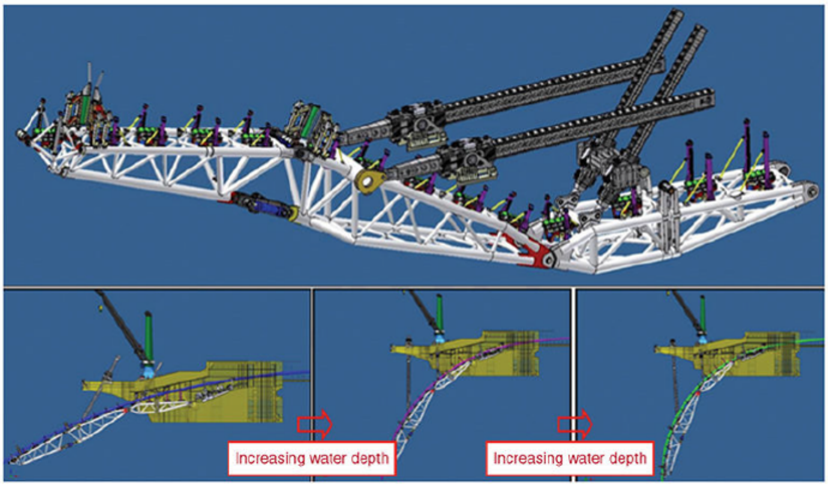


Figure 7.11: Stinger and SHS of *CastorOne* [3]

This system provides absolute control over the stinger and is able to transmit all the loads to the vessel, preventing uplift. In the other hand, the stinger has to be attached inside the vessel, which would decrease the length of the firing line, slowing the production time of the pipeline. Also, it is a quite complex system, which is not desired, as the yokes have to move but also rotate [3]. In order to install this system onboard, *Solitaire* does not have to go into dry dock. Although, the steel works are quite significant as the foundations to transmit the loads are large.

7.4.2. Wired support

The SHS of *Audacia* is mainly composed of Hang-off cable that support the stinger, Figure 7.12.

Figure 7.12: Stinger and SHS of *Audacia*. ©Allseas B.V

This design is simpler than the previous one as the cables are managed by winches, which simplify the operation significantly. Although it has a disadvantage, in the case that the stinger experiences a sudden uplift, afterwards cables might snap as they might not be able to cope with the extreme tension peak due to the stinger falling back to position. Therefore, a flipper system must be installed to keep the cables constantly under tension or certain operational guidelines must be set to avoid certain situations. Different factors influence the possibility of uplift to occur. The main factor is the pretension on the tackle wires due to the stinger weight itself.

As with the previous system going into dry dock is not necessary although the steelworks to reinforce the interface areas are significant.

7.5. Transit speed

In chapter 4, it has been noted, that the main component for resistance is due to the vortex being shed at the aft and the waves generated by the sponsons. During 2010 different design solutions where tested. As the shape of the hull is non-conventional, mainly due to the sponsons, applying statistical methods to obtain the resistance of the vessel is not realistic. Thus, the different options have been based on the features of the vessel and the model test of 2010.

As all the modifications are performed in the underwater part going into dry dock is necessary.

7.5.1. Close stinger slot

Fully closing the stinger slot (Figure 7.6) improves the flow at the aft, decreasing the resistance due to vortex shedding and to a lesser extent the friction resistance due to a decrease of wetted area. But, the wave-making resistance due to the sponsons will not decrease.

Also, the increase of buoyancy would improve the longitudinal strength and increase the deck space as aforementioned.

The complexity of the structure is rather small as there is only one curved side. It could be build before the vessel arrives at the yard decreasing downtime.

7.5.2. Faired sponsons

Fairing the sponsons would improve the wave-making resistance. But it would not improve the main resistance component of the vessel as the vortex shedding at the stinger slot would not be reduced. Therefore, it is considered that the improvement would be marginal in comparison.

The shape of the structure is rather complex as is composed of curved plates.

7.6. Deck space

To add an extra station to the firing line, it has to be extended. The scope of the thesis is the aft ship. Thus, the investigated option is to extend the firing line in the aft part.

The stinger is attached at frame 11, there are two main solutions: to add an extra station on the stinger or to move the hinge further aft to create enough space for an extra station.

7.6.1. Extra station on stinger

An extra station could be mounted at the beginning of the stinger, Figure 7.13. The current walkways (Figure 7.14) on the stinger are not sufficient to guarantee a safe workplace for the FJC workers or a suitable environment for the coating to be applied. Therefore, a movable structure should be designed such that it is strong and protective enough to guarantee the safety of the workers but also can move with the stinger. While also protecting the coating from being damaged due to water.

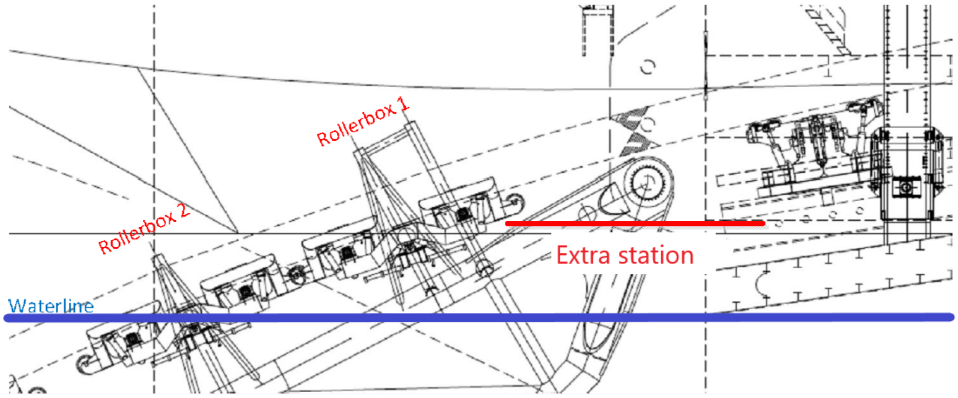


Figure 7.13: Possible location for extra station

Figure 7.14: Stinger slot and possible location for the extra station. ©Allseas B.V

7.6.2. Move stinger main hinge

Another option is to move the stinger further aft closing the gap that is left in the stinger slot. By doing so, not only the deck space is increased but also the buoyancy.

Another advantage of moving the hinge is that extra deck space is also added at main deck. Which allows having extra equipment and supplies. Allowing to rearrange the mooring equipment on deck.

7.7. Chapter conclusions

For each of the operational deficiencies, different solutions have been investigated. It can be observed that certain solutions solve each problem in the best/easiest way (local optima) but, if each of these local optima is implemented in the design, the global performance of the vessel is compromised. For example, the easiest way to fix the longitudinal strength of *Solitaire* is to remove part of the cantilever structure, but this would impact greatly the performance of the vessel as buoyancy modules or in-line structures can not be guided above the stinger, slowing down the production or even not being able to install them.

In Table 7.2, a summary of the different alternatives is presented. With the corresponding contribution to the different operational deficiencies. With '+' begin a positive contribution, '-' being a negative, and '+/-' meaning that it could be positive or negative depending on the design.

Table 7.2: Analysis of Alternatives summary

		Longitudinal Strength	**Transit speed**	**Deck space**	**Wide base stinger**	**Simplify SHS**
Longitudinal strength	**Remove weights aft**	+				
	Enlarge sponsons	+	-			
	Close the stinger slot	+	+	+	+	+
	Strengthen the structure	+				
Stinger	**Outside hinge**	-	+	+	+	
	Inside hinge	+/-	-	-	+	
SHS	**Fixed support**	+/-		-	-	-
	Wired support	+/-		+	+	+
Transit speed	**Close stinger slot**	+	+	+	+	+
	Faired sponsons	-	+			
	Trim vessel forward	-	+			
Deck space	**Extra station on stinger**					
	Move stinger main hinge	-		+		

Therefore, global optima must be found. In the upcoming chapter, integrated design is proposed based on the Analysis of Alternatives and Operational Needs.

8 Holistic design

After gaining insights into the current design through the needs analysis and the different alternatives proposed in the previous chapter. A holistic design is proposed based on the requirement prioritisation.

In the following chapters, different parts of the design are presented linearly. As the main nature of a report is a linear succession of chapters. But, it is important to note, that in most of the design problems this is not the case. This project can be an example. In Figure 8.1, an overview of the parts that compose this chapter is presented. As can be seen, all contribute to the integrated design, without being in linear order.

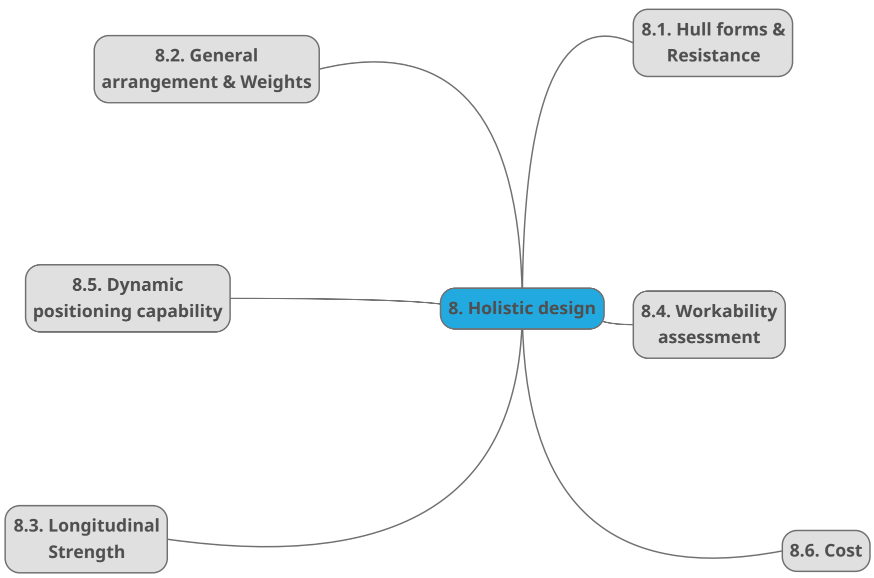


Figure 8.1: Parts of integrated design

8.1

Hull forms and Resistance

8.1.1. Hull forms

The hull forms have been designed taking into account the need for extra buoyancy, the necessary space for a wide base stinger and the increase of transit speed. In order to improve the longitudinal strength at least back to the original level. The buoyancy at the aft has to increase by at least 1,000 m^3 approximately. In order to achieve this, fuller hull forms are designed.

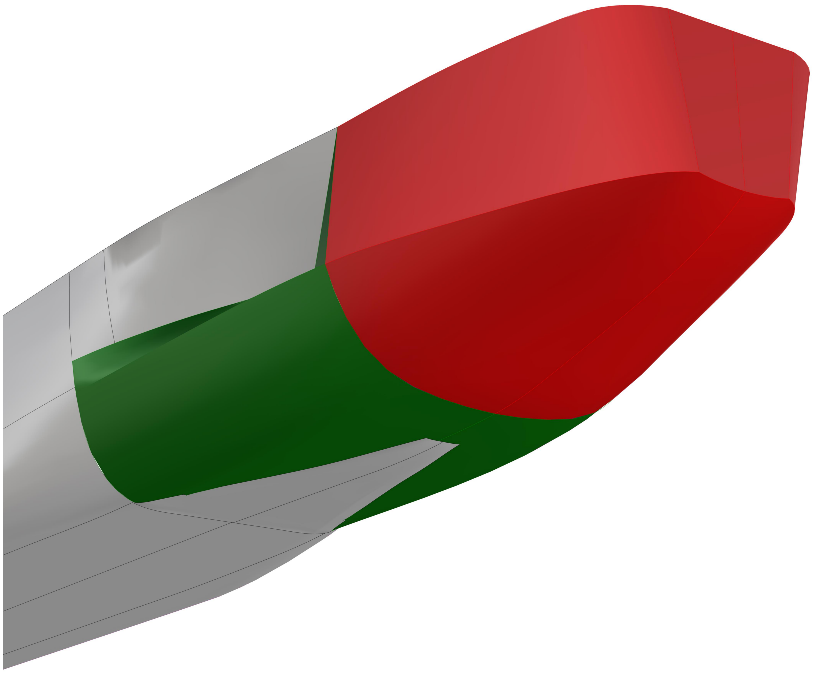


Figure 8.1.1: New aft hull forms. New structure in red, new shaped sponsons in green and Old structure in grey

The top connection between the sponsons (green) and the old structure (grey) has been designed with a curved plate. The main reason for this is the necessity to close the gap of 3.5 meters while at the same time limiting the added steel weight. The height of the connection is 14 meters above the base line. Which allows for a clearance of almost 4 meters while sailing at maximum draft.

The new hull lines have an added buoyancy of 1,080 m^3 (Table 8.1.1), which result in a smoother curve of areas, Figure 8.1.3. It is well known by ship designers that if the curve of areas has a smooth transition from the cylindrical body to the aft body, it will be less probable that flow separation occurs. Which translates to less resistance.

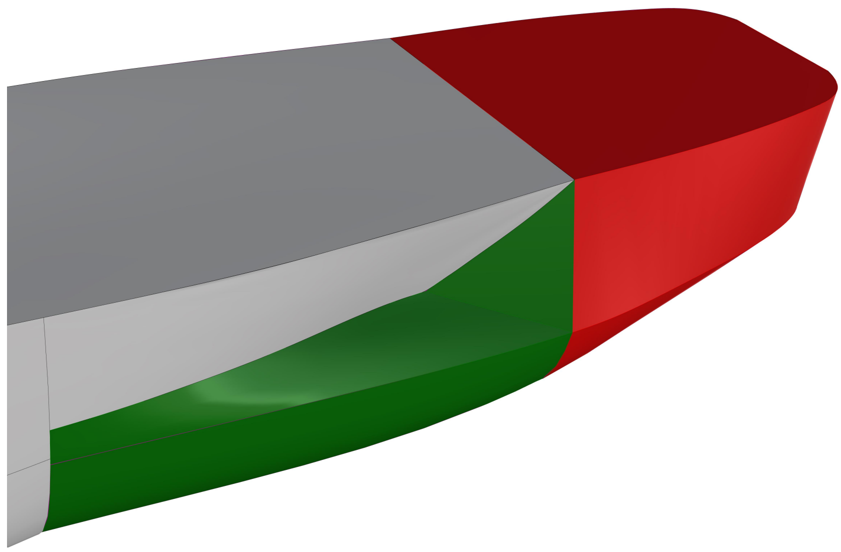


Figure 8.1.2: Top view of new aft hull forms. New structure in red, new shaped sponsons in green and Old structure in grey

Table 8.1.1: Length of the waterline and buoyancy comparison

	LWL [m]	Displacement [m^3]	Difference [m^3]
Current design (sponsons)	278	73,679	
New design	273	74,759	1,080

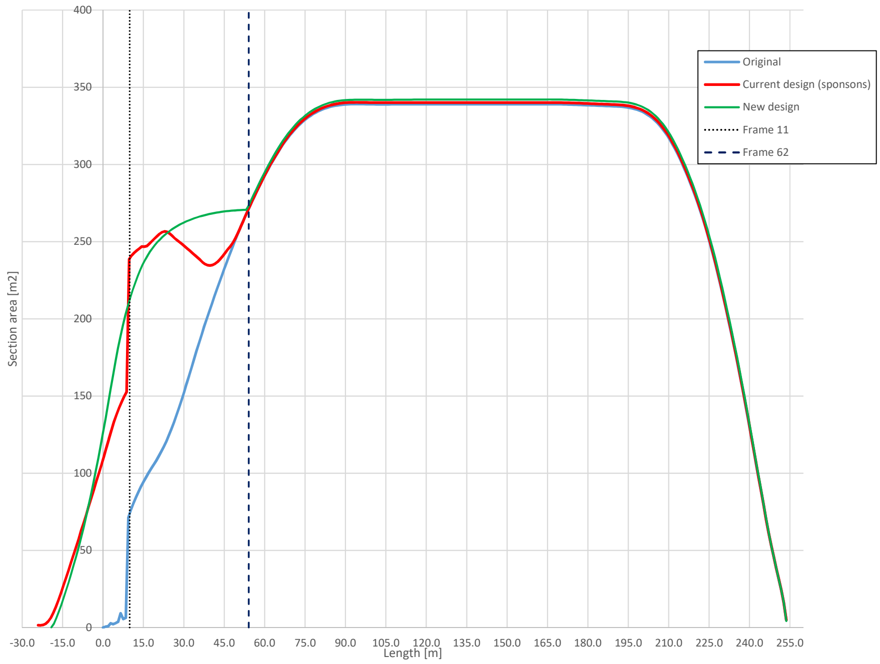


Figure 8.1.3: Curve of areas comparison.

The length on the waterline has decreased by 5 meters, Table 8.1.1. Although the difference is marginal (-2%). The SWBM will decrease, as the length of the hull girder is 5 m less. In the other hand, the Froude number will increase, translating into an increase in the wave making resistance.

8.1.2. Resistance

Due to the complex hull forms of the designs, mainly the current design with the sponsons. The resistance calculation using a parametric method, Holtrop-Mennen method, is not accurate enough. Although it can be used to make a qualitative comparison between designs.

A comparison between the current design (2A) and the new design (SOL23) was done and a difference of 0.3 knots is present when using 8 generators. Although the difference could be higher as the turbulence in full scale is higher than in the model test carried out.

8.1.3. Chapter review

The new hull forms have been designed taking into the account the need for more buoyancy at the aft, the necessity to have a wider stinger base and to improve the transit speed by reducing the resistance.

The new hull lines increase around 1000 m^3 of buoyancy in the aft. Also, an increase in transit speed of 0.3 knots can be achieved.

8.2

General Arrangement and weights

8.2.1. General arrangement

A wide base stinger with the hinges being attached to the outside shell has been selected. By implementing this option, the required deck space is obtained, but also it is possible to close the stinger slot to add the required buoyancy and decrease the resistance as mentioned in previous chapters.

8.2.1.1. Firing line and stinger configuration

The main reason to decide the location of the main hinge is to attach it to a strong point [1]. Since the hinge transmits the loads from the stinger to the vessel.

Ideally, the location of the main hinge should be as close as possible to the midships section. But as the hinge is attached on the sides of the vessel, certain deck equipment needs clearance to operate, i.e: Anchor rack, ROV platform, A-frame, Special purpose crane (SPC), mooring equipment. But also, the distance between the hinge and the first roller box should be such, that the weight of the stinger section is not too heavy. As it would add unnecessary weight which would have to be supported by the hinge and the tackle wires.

Thus, it has been decided to place the hinge close to a bulkhead, at frame 0, see General arrangement in Figure 8.2.1.

The main hinge height has been maintained at 12.415 m ABL. Therefore, the inner stinger has to be shifted to the aft. As it has to accommodate for the radius of the pipeline [2]. For this matter, the tween-decks have been moved aft. Therefore, the extra station (station 9) has been placed on one of the tween-decks.

As aforementioned in section 7.3, the new stinger should be able to achieve the same configurations as the current stinger. Therefore, sections 2 and 3 have been reused. Section 1 has been preliminary designed, given the fact that certain dimensions are dependant on the vessel, i.e width of the base, insertion angle, separation from the aft. Although these dimensions could change to better optimise the design of the stinger.

8.2.1.2. Main deck arrangement

[1] Yanrong Yu, Principal Structural Engineer at the Innovations department. Interviewed on July, 9^{th} 2019 in Delft, Netherlands.

[2] Raymond Vink, Manager of engineering at the Pipeline Engineering department, interviewed on July 1^{st} 2019 in Delft, Netherlands.

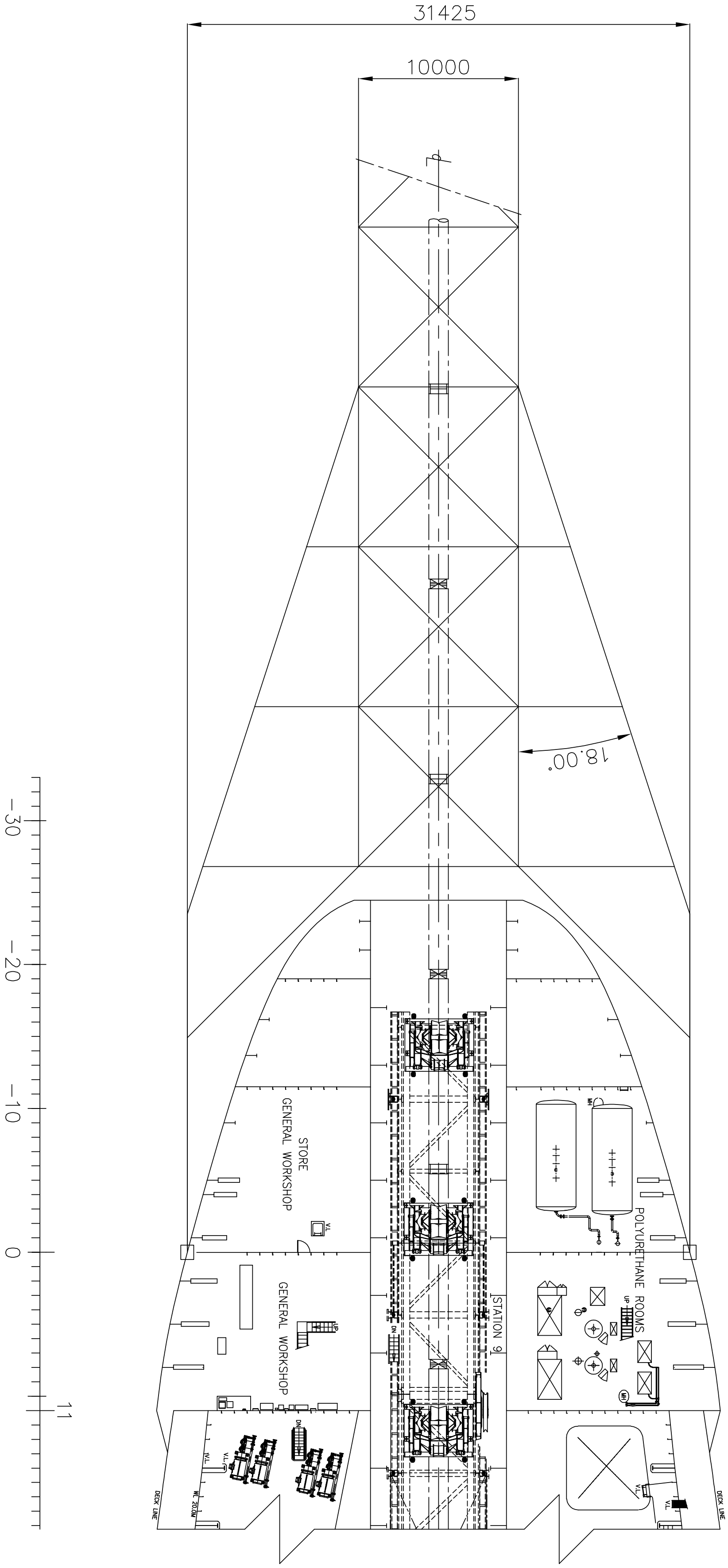


Figure 8.2.1: Firing line deck arrangement

Mooring system

Based on section 4.8, four split drum winches have been installed. By using the split drum winches, there is no need to have a level winder, as the tensioning of the line can be done on the split part of the drum. Thus, deck space is saved as there is no need to install level winders between the fairleads and winches, Figure 8.2.3. The mooring lines go in between the stinger and the hull to the quay side, taking into advantage the gaps that the stinger leaves.

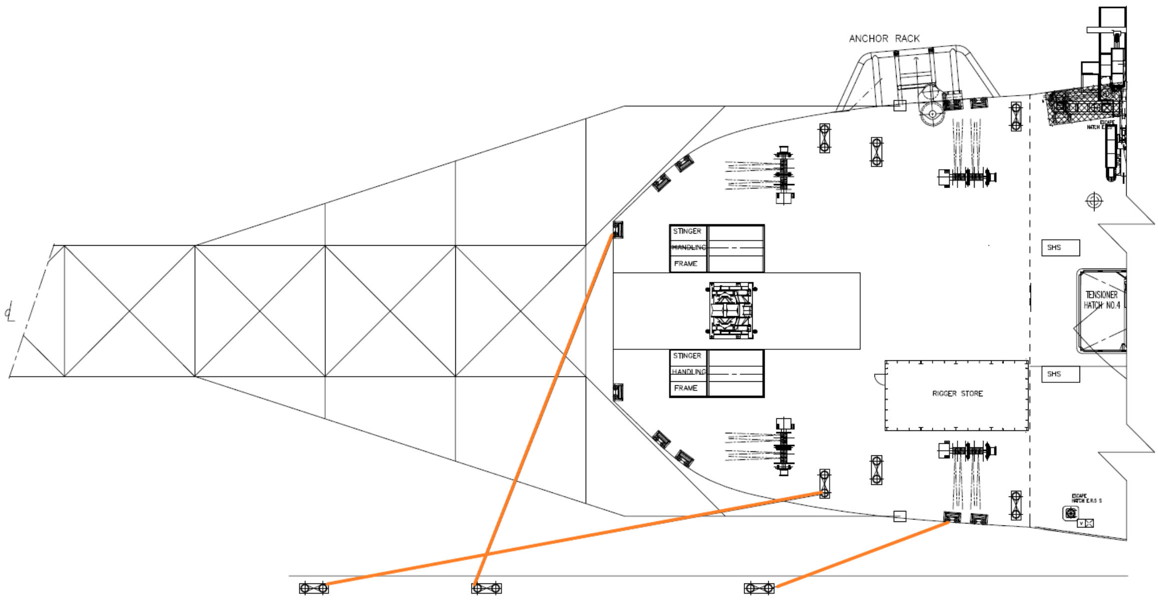


Figure 8.2.2: Example of aft mooring lines to quay side

Stinger handling system (SHS)

It has been decided that to simplify the SHS, a similar system as the one installed in *Audacia* is used. Therefore, the configuration of the stinger to the correct shape is done via two tackle wires, which are connected to sections 1 and 2. Section 3 is connected to section 2 via pup pieces.

The SHF transmits the loads from the tackle wires to the ship. To dimension the height of the SHF, it is necessary to be able to rotate the stinger out of the water with the configuration of R=110 m, and the tip of the stinger has to have a clearance of approximately 10 m. So that in stand-by mode the stinger tip is not being hit by waves (Appendix B).

The main reason to design the SHF similar to the one installed in *Audacia* is the possibility to spread the loads between two supports. Therefore, the loading on the hull girder due to the SHF is distributed. On top of this, the wind area can be reduced and moved closer to the centre of gravity. Also, the supports are not concentrated in the aft, therefore some space is created for the mooring system.

In certain conditions, the stinger might experience uplift. Therefore, to maintain constant tension on the tackle wires, a flipper system is installed. In case that the flipper system is not able to work, certain operational guidelines can be developed to not operate in those conditions.

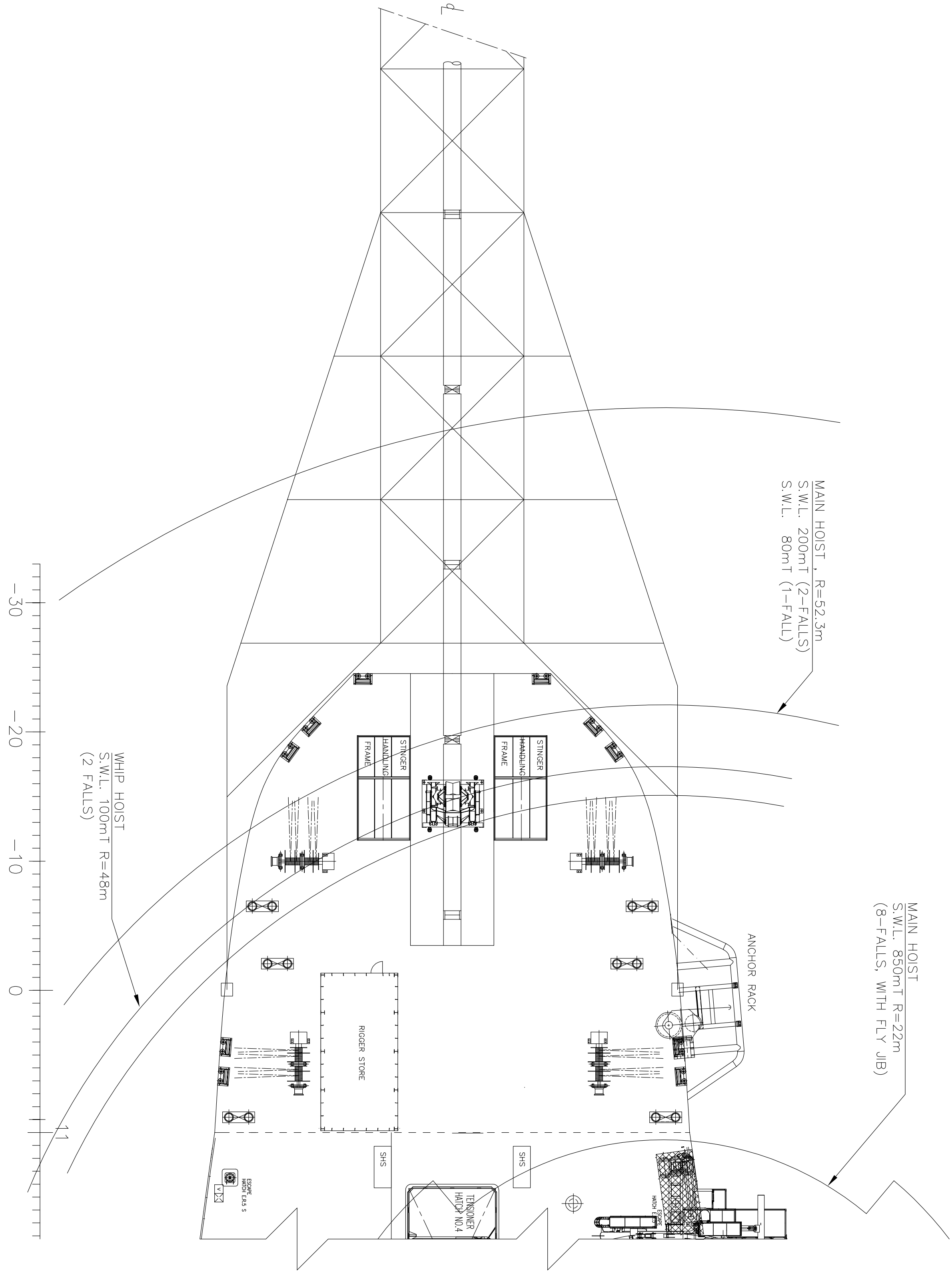


Figure 8.2.3: Main deck arrangement

8.2.2. Weight estimate

Before calculating the longitudinal strength of the new design, a weight estimate has to be done. The main changes in the design, concerning the current design, are the hull structure, the sponsons, the stinger and SHS, firing line equipment, and the mooring equipment. The rest of the weights onboard stay the same as only the aft is being retrofitted.

8.2.2.1. Weights aft of frame 11

As this part of the structure is completely new, the weight alteration is fairly simple.

To estimate the total weight of the new structure, different cross-section profiles have been used for the girders, stringers and longitudinal and transversal stiffeners. These reinforcements have been spaced accordingly to obtain adequate structure continuity. For the different decks and the hull shell, different thicknesses have been used accordingly with the current design, Table 8.2.1. Then, these weights have been added to the lightship weight by dividing them into strips, so the weight distribution is more accurate.

Table 8.2.1: New structure weight estimate

Component	Weight [ton]
Girders	484
Stringers	200
Longitudinal Stiffeners	242
Transversal Stiffeners	370
Decks	612
Shell	324
Total	**2232**

Firing line

With the new deck space the firing line has been elongated. Therefore, new equipment has been placed (roller boxes) and other have been moved (Tween decks), Table 8.2.2.

Mooring equipment

The new mooring arrangement consist of four electrical split drum winches, two roller fairleads per winch and an anchor rack, Table 8.2.2.

Table 8.2.2: Mooring systems & firing line components

Component	Weight [ton]	VCG [m]	LCG [m]	TCG [m]
Anchor rack	2	24	1.2	18.25
Fairleads	17.2	24	-6.21	0
Double Bitts	6	24	-2.351	-1.013
Split drum winches	66	24	-1.874	0
Roller boxes	80	16.25	42.186	0
Tween-decks	200	14.25	-3.687	0

Stinger & SHF

The stinger can attain different configurations depending on the necessities of the project. Therefore, it is considered as movable lightship weight since the CoG varies. As the stinger is supported

Table 8.2.3: Weight of the stinger sections and SHF components

Component	Weight [ton]
Stinger section 1	903
Stinger section 2	420
Stinger section 3	425
Steel structure SHF	850
Equipment SHF	400
Flipper systems SHF	320

Table 8.2.4: Weight of structural components of new sponsons

Component	Weight [ton]
Girders	147
Stringers	69
Longitudinal Stiffeners	95
Transversal Stiffeners	133
Shell	369
Total	**813**

by the tackle wires and the main hinge, to input the weight into the weight distribution in the PIAS model, the reaction forces due the different elements have to be calculated, see chapter 8.3.

As aforementioned in the previous section, sections 2 and 3 remain the same while section 1 changes due to the wide base, Table 8.2.3.

To obtain the weight of the Stinger handling frame (SHF), the structure has been modelled taking as reference the structural design of *Audacia*. Even though the dimensions and the accelerations are different it gives a rough estimate of the total weight (Table 8.2.3), to be used at this early stage.

8.2.2.2. Weight forward of frame 11

The only weights that have been added forward of frame 11 are due to the elongation of the firing line (2 extra roller boxes) and the new sponsons.

To obtain the weight of the new sponsons, the same method has been used with the new structure aft of frame 11. But in this case, previously designed sponsons have been used as a reference for the structural elements.

8.2.3. Removed weights

The removed weights are mainly the old sponsons and the rest of the structure aft of frame 11, Table 8.2.5.

8.2.3.1. New lightship weight

After all this changes, the new lightship weight can be calculated, Table 8.2.6.

There is a difference of around 1000 tons of lightship weight. Due to the modifications in the aft, which have made the LCG to more forward. The VCG has increased as the SHF is higher than the previous cantilever beam structure. This increase can harm the stability of the vessel. Although it

Table 8.2.5: Removed weights from *Solitaire*

	Weight [ton]
Structure aft fr.11	5171
Sponsons	785
Total	**5956**

Table 8.2.6: Lightship weight comparison

	Weight [ton]	VCG [m]	LCG [m]	TCG [m]
New lightship	51,667	18.82	127.05	0.18
Old lightship	52,796	18.75	124.30	0.18

will be softened by the dead weight and it is a marginal impact as the beam of the vessel is rather wide, 40 meters.

8.2.4. Chapter review

A new general arrangement has been done for the new aft. Including a preliminary design of the new stinger section 1. Furthermore, the aft mooring system has been changed.

With the new general arrangement, a weight estimate has been made. Which results in a new lightship weight distribution. The CoG has been shifting to the bow as a result in the change of the aft structure while the VCG has increased marginally.

8.3

Longitudinal strength

8.3.1. Stinger handling frame (SHF) reaction forces

The stinger is supported by the tackle wires and the main hinge. Depending on the stinger configuration and the pipeline that is being laid, the reaction forces vary. Due to the magnitude of these forces they have to be taken into account in the longitudinal strength of the vessel.

A free-body diagram has been made (Figure 8.3.1), as a first approximation of the forces acting on the hull girder.

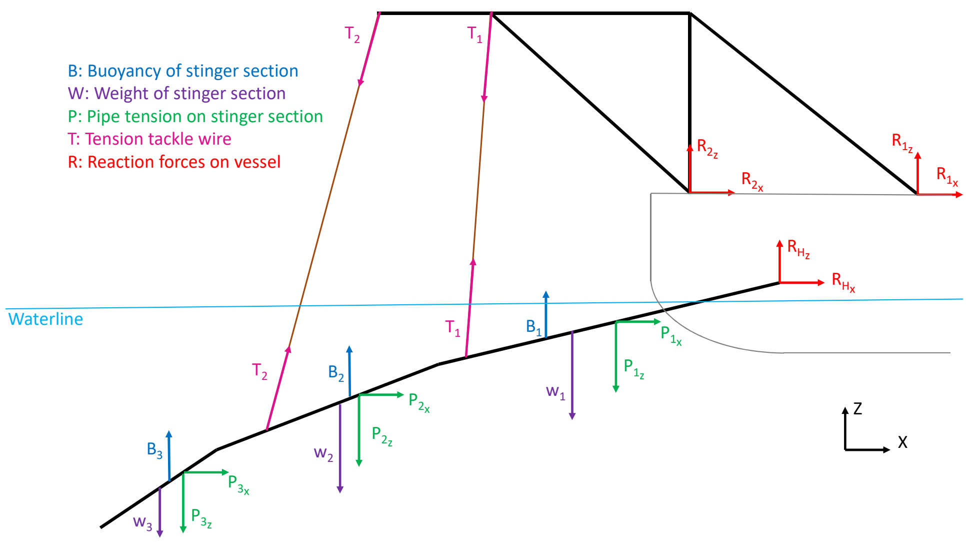


Figure 8.3.1: Free-body diagram of Stinger and SHF

The stinger can obtain multiple configurations. Thus, only three cases have been calculated: R100m, R300m and Survival.

Roller box loads are one of the important loads applied on the stinger structure. The magnitude of them will have a large impact on the stinger and the SHF design. Therefore, the loads on the stinger have been determined in different conditions by the installation department [18], the most critical loading is in deep water configuration. Which leads to the following results, Table 8.3.1.

Table 8.3.1: Reaction forces on vessel due to Stinger and SHF

	VCG [m]	LCG [m]	R110m Weight [ton]	R300m Weight [ton]	Survival Weight [ton]
Reaction force fr-12	20.40	-10.80	7259	6907	5689
Reaction force fr14	20.40	12.60	-3654	-3642	-3096
Reaction force hinge	12.15	0.00	-3025	-2805	-2017

Another important factor to take into account are the forces in the tackle wires, Table 8.3.2.

Table 8.3.2: Tackle wire forces

	R110m	R300m	Survival
T1 [ton]	2361	1212	2652
T2 [ton]	2937	2531	1470

The tension in the tackle wires is considered within normal limits. The tension of the tackle wires in *Audacia* for a deep water configuration is approximately 2600 tons, while the length of the stinger is only 80 meters. Which translates in carrying less pipeline load.

8.3.2. Longitudinal strength

With the new weight distribution, the longitudinal strength of the hull girder can be calculated using PIAS Loading module.

In Figure 8.3.3, it can be observed that the longitudinal strength for the benchmark loading condition (Arrival ballast) has improved.

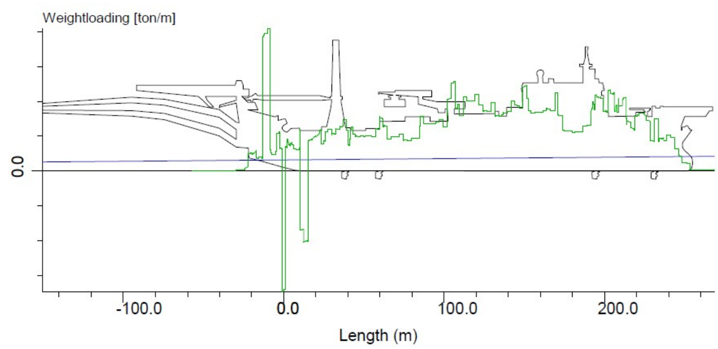
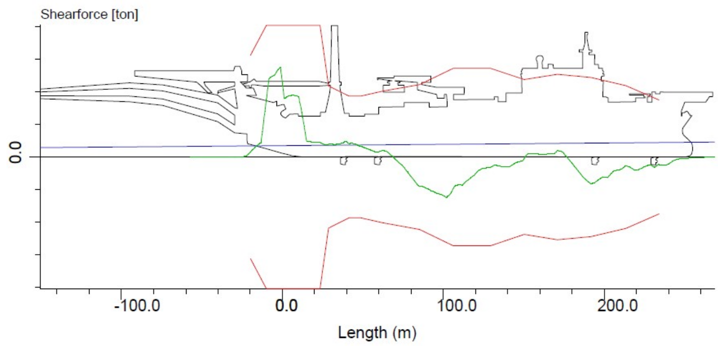


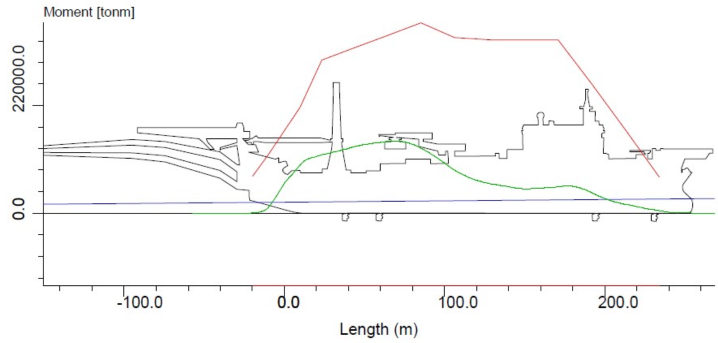
Figure 8.3.2: New weight distribution of loading condition "Arrival ballast"

The main reason for this change in the longitudinal strength is the new weight distribution, due to the reaction forces of the SHF and hinge, Figure 8.3.2.

Because of the new weight distribution other loading conditions become relevant, mainly due to the shear forces on the hull girder. In Figure 8.3.4, it can be observed that the shear forces are



(a) Shear force diagram



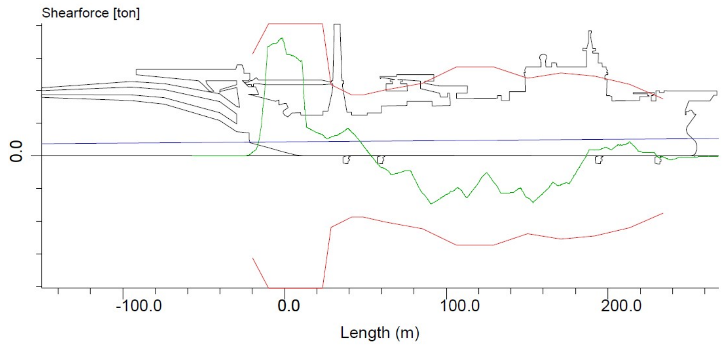
(b) Bending moment diagram

Figure 8.3.3: Longitudinal strength of loading condition "Arrival ballast"

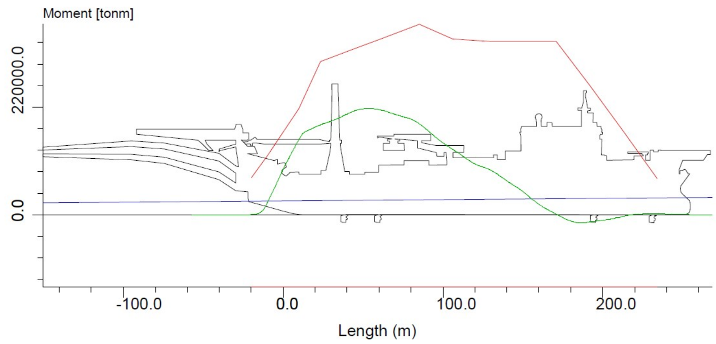
close to the allowable limit.

Two different solutions are identified to decrease the shear forces.

- To widen the SHF base. This would spread the loads over more sections.
- To strengthen the critical sections.



(a) Shear force diagram



(b) Bending moment diagram

Figure 8.3.4: Longitudinal strength of loading condition "100 % Bunkers, 100 % Pipes, Crane 850 T load 11.5 m to PS"

8.3.3. Chapter review

The forces due to the stinger weight, buoyancy and the pipe tension have been calculated with a free-body diagram.

The bending moments have been reduced in all the loading conditions. But, due to the change in the weight distribution, the shear forces become relevant. In order to decrease the shear force, two solutions have been identified. i.e, to widen the SHF base and to strengthen the critical sections.

8.4
Workability assessment

It is of utmost importance to asses the downtime of the new design. As it can be translated to the amount of time that a project will take to complete. First of all, a model of the new design is made. With this model the Response Amplitude Operator (RAO) are calculated. Lastly, with the RAOs a workability assessment is done at two different locations.

8.4.1. Cases subject to analysis

The objective is to obtain a better understanding of how the design changes affect the motions and workability of the new design:

- **Solitaire:** Current design.
- **Solitaire 2.3:** Change of hull forms, mass matrix and stinger tip location.

8.4.2. Hydrodynamic model

This assessment has been done using ANSYS AQWA software. The Response Amplitude Operator (RAO) have been calculated in the frequency domain solving the potential problem, considering the vessel to be free floating and neglecting non-linear and 2^{nd} order effects.

8.4.2.1. System of reference

The system of the reference considered is the one used by AQWA software, Table 8.4.1. Furthermore, waves coming from the stern are defined as 0 degrees direction and waves coming from the starboard are defined as 90 degrees direction.

Table 8.4.1: Global system of reference

Axis	Origin	Direction	Positive to
X	Aft perpendicular	Longitudinal	Forward
Y	Centre line	Transverse	Port
Z	Baseline	Vertical	Upward

8.4.2.2. Vessel models

An existing model of *Solitaire* has been used, with a maximum panel size of 2m in the underwater part (diffracting elements) and 3 m in the above water part. With this panel size, we are able to calculate the motions until 1.7 rad/s. The hull forms of *Solitaire 2.3* have been modelled in Rhinoceros.

And later on input into ANSYS APDL to mesh the model, with the same panel sizes as the previous model, Figure 8.4.1.

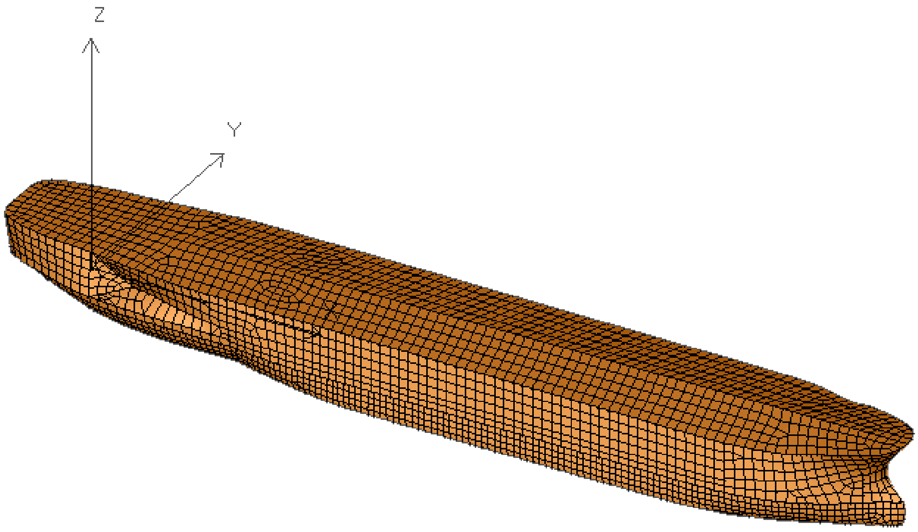


Figure 8.4.1: Mesh of *Solitaire 2.3* in AQWA

8.4.2.3. Roll damping

The mode which suffers most from the simplifications assumed in potential flow theory is the roll motion. The roll damping computed with potential theory only represents the energy dissipated by the radiated waves, but for roll the energy dissipated by viscous forces is relatively important.

Therefore, additional damping is introduced in the hydrodynamic calculations. As the hull forms only change in the aft, which is smaller than the total length of the waterline, the additional damping has been considered the same in all the cases.

A value of 5% of the critical damping have been used ($\kappa = 0.05$). As we have supposed linear behaviour, the additional linear roll damping is obtained by Equation 8.4.1.

$$B_{44} = 2 \cdot \kappa \cdot \sqrt{C_{44} \cdot (I_{xx} + A_{44})} \tag{8.4.1}$$

Where:

- I_{xx}: roll moment of inertia [ton m^2]
- A_{44}: roll added moment of inertia at resonance frequency [ton m^2]
- B_{44}: roll additional damping [kNm/rad]
- C_{44}: roll hydrostatic damping [kNm/rad]
- κ: critical roll damping [-]

8.4.3. RAOs and wave spectrum

The RAOs are calculated with AQWA-LINE every 15 degrees of wave coming direction and from a range of frequencies between 0.1 rad/s to 1.7 rad/s in 65 steps. The water depth has been maintained constant at 1,000 meter.

To estimate the 3 hours maximums at the stinger tip a JONSWAP spectrum has been used, with a wave of significant wave height of 3.5 m and peak periods between 2.5 s and 21.5 s. The peak enhance factor gamma has been maintained constant, following DNV recommended value, $\gamma = 3.3$

8.4.4. Limit criteria

In order to estimate the workability is necessary to define the limit criteria that governs it. In the case of *Solitaire* in pipelaying, one of the limit criteria related to vessel motions is the heave motions and the accelerations in Z direction at the stinger tip. The reason for choosing this criteria is the design limits of the stinger, roller boxes and the pipeline. If the limits are surpassed they could be damaged with the consequent toll into pipelaying.

Table 8.4.2: Stinger tip locations [1]

	x [m]	**y** [m]	**z** [m]
Solitaire	-70.4	0	-100.5
New design	-95.8	0	-103.88

From this it can be deduced that moving the stinger tip away from the centre of gravity will impact the workability.

To obtain the motions at the stinger tip, Equation 8.4.2 is used.

$$\begin{pmatrix} x_P \\ y_P \\ z_P \end{pmatrix} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \begin{pmatrix} 0 & -\psi & \theta \\ \psi & 0 & -\phi \\ -\theta & \phi & 0 \end{pmatrix} \cdot \begin{pmatrix} x_{b_P} \\ y_{b_P} \\ Z_{b_P} \end{pmatrix} \tag{8.4.2}$$

Where:

- x_P, y_P, z_P: Translation motions of desired point [m]
- X, Y, Z: Surge, Sway, Heave RAOs [m]
- x_{b_P}, y_{b_P}, z_{b_P}: Local coordinates of desired point [m]
- ϕ, θ, ϕ: Roll, Pitch, Yaw RAOs [rad/m]

Therefore, the main movements that have a greater impact in the motions of the stinger tip are roll, pitch and heave.

8.4.5. Response amplitude operators comparison

8.4.5.1. Roll

The greater differences are seen in the roll RAOs. The peak has been shifted to higher frequencies and at the same time it has increased. For the rest of the wave directions, similar tendencies occur but to a lesser extend. Therefore, in the case were the seas have higher frequencies the motion responses will be higher than in the current design.

The main reason for the difference is due to the Tranversal metacentric height (GM_T) increasing (+24%) , which influences the natural period of roll, Equation 8.4.3. A very large GM_T will have shorter periods of roll translating into higher natural frequencies.[19]

[1]With respect to the global reference system

$$T_{44} = 2\pi \cdot \sqrt{\frac{I_{xx} + A_{44}}{\rho g \cdot \nabla \cdot GM_T}} \tag{8.4.3}$$

Where:

- T_{44}: Roll natural period [s]
- g: Acceleration of gravity $[m/s^2]$
- I_{xx}: roll moment of inertia [ton m^2]
- A_{44}: roll added moment of inertia at resonance frequency [ton m^2]
- ρ: Density of sea water [ton/m^3]
- ∇: Displacement [m^3]
- GM_T: Traversal metacentric height [m]

8.4.5.2. Heave

The heave RAO are mainly dependent on the water plane area. Therefore, as the new hull lines close the stinger slot, the water plane area increases. As the increase in area is rather small the differences in the RAO are also small.

8.4.5.3. Pitch

Similarly as with roll, the pitch is affected by Longitudinal metacentric height (GM_L). With greater longitudinal metacentric heights the natural period of pitch is shorter which translates into higher natural frequencies.[19]

The increase of GM_L is only 9%, therefore the translation of the natural frequency can not be appreciated. What it can be appreciated is the decrease in the response at the natural frequency. This is because of the increase in the water plane area due to the stinger slot being closed. Which is an area that is quite far from the CoG.

$$T_{55} = 2\pi \cdot \sqrt{\frac{I_{yy} + A_{55}}{\rho g \cdot \nabla \cdot GM_L}} \tag{8.4.4}$$

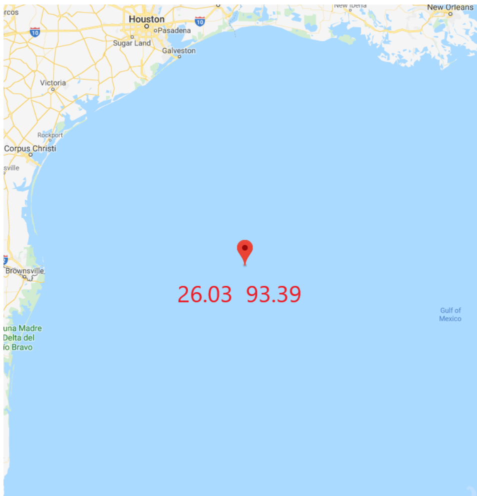
Where:

- T_{55}: pitch natural period [s]
- g: Acceleration of gravity $[m/s^2]$
- I_{yy}: pitch moment of inertia [ton m^2]
- A_{55}: pitch added moment of inertia at resonance frequency [ton m^2]
- ρ: Density of sea water [ton/m^3]
- ∇: Displacement [m^3]
- GM_L: Longitudinal metacentric height [m]

8.4.6. Location and environmental data

The downtime of Solitaire and the new design has been compared on two locations: in the north sea, Figure 8.4.2a and in the Gulf of Mexico, Figure 8.4.2b.

(a) North Sea location of wave scatter



(b) Gulf of Mexico location of wave scatter

Figure 8.4.2: Locations for workability assessment

8.4.6.1. North Sea

The meteocean data is based on 54 years of continuous hindcast from 1957 to 2011. At this location the scatter diagram of frequency of occurrence for T_p and H_s is available for the whole year and separately for each month.

From the scatter diagram it can be inferred that most of the energy is concentrated between peak periods of 5.5 s and 8.5 s and for wave significant heights up to 3.0 m. The seas in this location are influenced by wind but also by swells, which come from storms in the Artic.

8.4.6.2. Gulf of Mexico

The meteocean data is based on 35 years of continuous hindcast from 1980 to 2014. At this location the scatter diagram of frequency of occurrence for T_p and H_s is available for the whole year and separately for each month.

Most of the energy is concentrated between peak periods of 4.5 s and 6.5 s and for a wave significant heights up to 2.0 m.

8.4.7. Calculation method

Based on the operational experience the limiting significant wave height has been set at 3.5 m for *Solitaire*. Thus, the percentage of downtime is directly obtained form the H_s-T_p scatter diagram.

To asses the workability of the new design, an extrapolation has been done of the relative H_s for *Solitaire* as a function of the 3 hour maximum motions at the stinger tip. The calculation procedure is the following:

1. The 3 hours motions and accelerations at the stinger tip are calculated considering H_s=3.5m for every peak period in the scatter diagram. Using the RAOs calculated for deep waters.

2. For each T_p the average motions are considered.

3. Then, the corresponding H_s for which the new design would have the same motions as Solitaire is calculated. This is done assuming linear behaviour. For a variable "Z"

$$H_s(T_p, Z) = Limit\ H_s \cdot \frac{SOL_{avg}(T_p, Z)}{NewDesign_{avg}(T_p, Z)} \tag{8.4.5}$$

4. With these extrapolated H_s as a function of the T_p the percentage of downtime can be calculated from the scatter diagram.

This method has been applied for two variables at the stinger tip:

- Vertical motion: Z
- Vertical acceleration: accZ

8.4.8. Chapter conclusions

In this chapter, a simplified comparison of the dynamic behaviour between the different designs has been presented. First, the RAOs have been calculated for each model. Then, a workability assessment has been calculated at two different locations.

Differences in shape and mass distribution do not show significant changes in the vessel response.

The workability assessment has been done for two load conditions. Therefore, for different load conditions, the results will change and might lead to different conclusions.

As *Solitaire 2.3* has the stinger tip further from the centre of gravity, the motions for a given H_s and T_p are higher than those of *Solitaire*. It can also be concluded that the motions vary depending on the location, namely the sea state.

Annual workability decreases about 7% on harsh environments (North Sea). During winter this reduction is about 10% and during the summer months just 3-4%.

In a less severe environment, such as the Gulf of Mexico; the differences are smaller, ranging from 5% in the winter to 0% during summer. In the month of July, the workability is slightly improved.

8.5

Dynamic positioning capability

One of the most important systems onboard *Solitaire* is the Dynamic Positioning system (DP system). In this chapter, the DP capabilities of the new design are estimated; and compared with the current design. It is important to note that the thrusters have not been replace or moved.

The DP system is used to maintain position and follow an already defined track to lay the pipe. But also, it is used to keep the tension on the pipeline, which is crucial for the integrity of the pipeline. If the tension is not maintained, the pipeline could buckle and the consequences would be disastrous.

As the hull forms, stinger and SHF have changed, the forces that act on the vessel also change. Therefore, the DP capabilities of the new design have to be re-calculated.

Dynamic positioning is concerned with the control of the ship in the horizontal plane; surge (x), sway (Cy) and yaw (CR_z). Therefore, the changes in the design that affect the different force coefficients have to be calculated. The system of reference (Table 8.4.1) is the same as the one used in chapter 8.4, as some of the coefficients are calculated with ANSYS AQWA.

8.5.1. Changes in current coefficients

The current coefficients only involve the under water part of the ship.

$$C_{F_{x,current}} = \frac{F_{x,current}}{v_{current}^2} = \frac{1}{2}\rho_{sw} \cdot S_{frontal} \cdot C_{d_x} \tag{8.5.1}$$

$$C_{F_{y,current}} = \frac{F_{y,current}}{v_{current}^2} = \frac{1}{2}\rho_{sw} \cdot S_{transversal} \cdot C_{d_y} \tag{8.5.2}$$

$$C_{M_{z,current}} = \frac{M_{z,current}}{v_{current}^2} = \frac{1}{2}\rho_{sw} \cdot dS_{transversal} \cdot dx_{dS_{transversal}} \cdot C_{d_{Mz}} \tag{8.5.3}$$

Where:

- $C_{F_{x,current}}, C_{F_{y,current}}, C_{M_{z,current}}$: Partially dimensionalised current coefficients. $[\frac{kN}{(m/s)^2}]$, $[\frac{kNm}{(m/s)^2}]$
- $v_{current}$: current speed [m/s]
- ρ_{sw}: density of sea water. [kg/m^3]
- $S_{frontal}, S_{transversal}$: frontal and transversal area [m^2]
- $dS_{transversal}$: differential transversal area element [m^2]

- $dx_{dS_{transversal}}$: longitudinal distance from CoG to differential area element [m]
- C_{d_x}, C_{d_y} , $C_{d_{Mz}}$: drag coefficients [-]

The projected frontal area of the new design does not change, as the maximum beam and stinger did not change. In the case of the projected transversal area, it did change but marginally (Figure 8.5.1).

Figure 8.5.1: Aft lateral area comparison

Therefore, $C_{F_{x,current}}$ and $C_{F_{y,current}}$ can be assumed equal to the ones of *Solitaire*. In the other hand, the stinger has been moved backwards. Thus, $C_{M_{z,current}}$ has to be re-calculated. Usually, the current coefficients are obtained through model test. In this case, as we have the current coefficients of *Solitaire* and its stinger, and the only major change is the stinger position. We can use them to obtain the new coefficients, as follows:

We can decompose the yawing moment coefficient (C_{Mz}) in the contribution to the yawing moment of the vessel ($C_{Mz_{vessel}}$) and of the stinger ($C_{Mz_{stinger}}$), Equation 8.5.4

$$C_{Mz} = C_{Mz_{vessel}} + C_{Mz_{stinger}} \tag{8.5.4}$$

As aforementioned, the lateral area changes marginally. Therefore, Equation 8.5.5 can be assumed true.

$$C_{Mz_{vessel_{SOL}}} = C_{Mz_{vessel_{SOL23}}} \tag{8.5.5}$$

Thus, we only have to estimate the contribution of the new stinger position to the yawing moment coefficient.

$$C_{Mz_{stinger_{SOL}}} = \frac{1}{2}\rho \cdot C_{d_{SOL}} \cdot S_{s_{SOL}} \cdot dx_{SOL} \tag{8.5.6}$$

$$C_{Mz_{stinger_{SOL23}}} = \frac{1}{2}\rho \cdot C_{d_{SOL23}} \cdot S_{s_{SOL23}} \cdot dx_{SOL23} \tag{8.5.7}$$

As we assumed that the underwater part of the stinger has not been changed. We can conclude that:

$$C_{d_{SOL}} = C_{d_{SOL23}} \tag{8.5.8}$$

$$S_{s_{SOL}} = S_{s_{SOL23}} \tag{8.5.9}$$

Which leads to Equation 8.5.10.

$$C_{Mz_{stinger_{SOL23}}} = C_{Mz_{stinger_{SOL}}} \cdot \frac{dx_{SOL23}}{dx_{SOL}} \tag{8.5.10}$$

Therefore, the yawing current coefficient of *Solitaire 2.3* is given by Equation 8.5.11.

$$C_{Mz_{SOL23}} = C_{Mz_{vessel_{SOL}}} + C_{Mz_{stinger_{SOL}}} \cdot \frac{dx_{SOL23}}{dx_{SOL}} \tag{8.5.11}$$

It is important to note that the current coefficients vary depending on the stinger configuration. Three configurations are used: Deep, Shallow and Survival configuration.

8.5.2. Changes in wave coefficients

The wave coefficients are the horizontal wave-drift coefficients. They are proportional to the incident wave amplitude squared and are a function of the wave frequency. In this case, we are only interested on the forces in the horizontal plane; AQWA uses the "Far Field solution", which is calculated by considering the rate of change of the linear and angular momentum within a set domain. [20]

Therefore,the coefficients change, as the hull forms have changed.

The wave drift force is given by the sum of the product between the coefficients and the wave spectrum (Equation 8.5.12). [21]

$$F^{(2)}_{1_{mean}} = 2\int_0^\infty S_\zeta(\omega)\cdot P(\omega,\omega)\cdot d\omega \tag{8.5.12}$$

Where:

- $P(\omega,\omega)$: mean drift force coefficients in regular waves [N/m^2]
- S_ζ: JONSWAP wave spectrum [$\frac{m^2}{rad/s}$]

8.5.3. Changes in wind coefficients

The wind coefficients for *Solitaire* were obtained via model test. In this case, the data available is not divided in components, as it was the case for the current coefficients. Also, in Figure 8.5.2 it can be seen that the lateral area of the new design is less than the current one. In addition, the centre of pressure of the new SHF is closer to the centre of gravity.

Therefore, the wind coefficients have been maintained the same. By doing so, the wind forces acting on the vessel are slightly overestimated.

$$C_{F_{x,wind}} = \frac{F_{x,wind}}{v^2_{wind}} = \frac{1}{2}\rho_{sw}\cdot S_{frontal}\cdot C_{d_x} \tag{8.5.13}$$

$$C_{F_{y,wind}} = \frac{F_{y,wind}}{v^2_{wind}} = \frac{1}{2}\rho_{sw}\cdot S_{transversal}\cdot C_{d_y} \tag{8.5.14}$$

$$C_{M_{z,wind}} = \frac{M_{z,wind}}{v^2_{wind}} = \frac{1}{2}\rho_{sw}\cdot dS_{transversal}\cdot dx_{dS_{transversal}}\cdot C_{d_{Mz}} \tag{8.5.15}$$

Where:

- $C_{F_{x,wind}}, C_{F_{y,wind}}, C_{M_{z,wind}}$: Partially dimensionalised wind coefficients. [$\frac{kN}{(m/s)^2}$], [$\frac{kNm}{(m/s)^2}$]

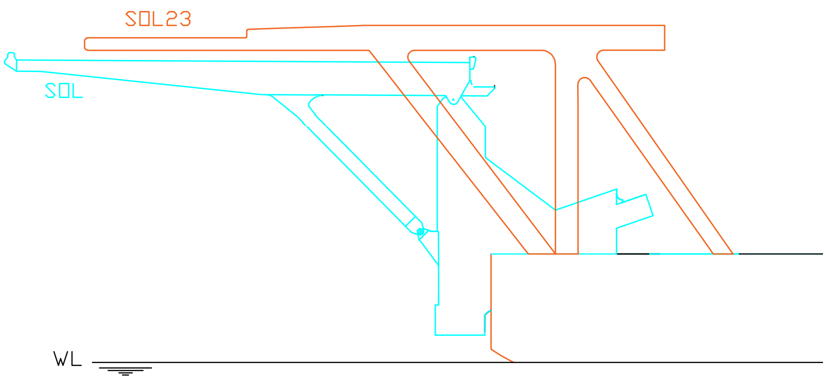


Figure 8.5.2: Aft lateral area (above water) comparison.

- v_{wind}: wind speed [m/s]
- ρ_{air}: density of air. [kg/m^3]
- $S_{frontal}, S_{transversal}$: frontal and transversal area [m^2]
- $dS_{transversal}$: differential transversal area element [m^2]
- $dx_{dS_{transversal}}$: longitudinal distance from CoG to differential area element [m]
- $C_{d_x}, C_{d_y}, C_{d_{Mz}}$: drag coefficients [-]

8.5.4. Chapter conclusions

The Wind DP capability presents no differences between both designs. Although, the wind coefficients should be slightly lower for the new design as the area has decreased and is closer to the centre of gravity.

The current DP capability presents some differences when the direction of the current is between 105 and 165 degrees. Although this differences start appearing when the current speed is above 3 knots. Therefore, for operational conditions it could be considered as there is no differences, as most of the times the currents do not reach 3 knots.

Therefore, not changing the thrusters or their location does not impact operations within normal weather conditions. The modifications in the aft of *Solitaire* do not affect the DP capability; and therefore the operability for DP governing situations is not reduced.

8.6 Cost

A cost estimate is essential to asses the feasibility of a project. Even though, it is a concept design a preliminary cost estimate can be done to have a better idea of the main expenditures in the project.

8.6.1. Unit price

In Table 8.6.1, the different prices per kilogram of structure are shown. In these prices, the material costs for the steel, the man-hours needed for fabrication, the costs of protection against corrosion and placement on board are included within the price.

Table 8.6.1: Price in euros per kg of structure

Structural steel	5	[€/kg]
Equipment steel	10	[€/kg]
Complex structures	15	[€/kg]

It is important to take into account that the prices, mainly the man-hours vary significantly between countries. For example it is cheaper to build in China or Singapore than in The Netherlands or Spain. To obtain the prices above, Spanish prices have been used as a guidance.

8.6.2. Cost Calculation

Based on the General Arrangement and the weight estimate of chapter 8.2, and the unit prices of Table 8.6.1. The total cost of the retrofit can be calculated, Table 8.6.2.

It is important to note that the transit cost to a shipyard in order to carry out the retrofit have not been included, depending on the chosen location the final price will vary.

In the dry dock cost, it has been included the layrate and the daily service cost of the vessel, 3,450 €/day. Also, the first and last day of dry dock, as the cost due to the use of tugs, installation of blocks, etc; is significant (120,000€)

For the cutting of the sponsons and the old structure, in consultation with the Technical Department, a cost of 1,5 M€ has been set. This includes all the man-hours and equipment needed for the safe removal of the structures.

Table 8.6.2: Cost calculation

Item	Price [€/kg]	Amount [ton]	Total [€]
Structural steel weight new structure	5	2322	€11,610,000
Structural steel weight Sponsons	5	813	€4,065,000
SHF steel weight	5	850	€4,250,000
New stinger section 1	15	903	€13,545,000
New equipment:	10	841.2	€8,412,000
Equipment SHF		350	
Flipper Systems		320	
Anchor rack		2	
Fairleads		17.2	
Double bitts		6	
Split drum winches		66	
Rollerboxes		80	
Remove sponsons + Structure aft of fr.11			€1,500,000
Dry dock (2 months)			€327,000.00
Total			**M€ 43.7**
Total + 25% contingency			**M€ 54.6**

8.6.3. Chapter review

A total price of approximately 55 M€ is estimated. Although, the price could vary depending on the chosen shipyard to carry out the retrofit, as the labour cost vary per country. Also, the transit cost are not included in the calculation.

9 Design evaluation

The complete design is evaluated in terms of requirements, and performances.

9.1. Specifications

Operation	Solitaire	Solitaire 2.3
- Diameter pipe	2 - 60 inch	idem
- Water depth	Ultra deep waters (≈3,000 m)	idem
- Installation configuration	S-lay	idem
- Area	Worldwide	idem
Main particulars		
- Lpp	248.65 meter	idem
- LWL	278 meter	273 meter
- Design Draught	8.5 meter	idem
- Breadth moulded	40.6 meter	idem
- Depth moulded	24.0 meter	idem
- Displacement (at T=8.5m)	73,679 ton	74,759 ton
Stinger		
- Length	140 meter	160 meter
- Nr. of Section	3	idem
- Nr. of rollerboxes	17	idem
Tanks capacities		
- HFO	6,438 m^3	idem
- MDO	1,179 m^3	idem
- MGO	62 m^3	idem
- LO	50 m^3	idem
- Potable water	1,120 m^3	idem
Pipelay equipment		
• *Firing line*		
- Length	225 meter	240 meter
- Piggyback	up to 6 inch	idem

• *Double joint factory*		
Welding		
- Nr. welding stations	3 per side	idem
- Welding method	Phoenix automatic welding system	idem
NDT		
- Nr. NDT stations	1 per side	idem
• *Main firing line*		
Welding		
- Nr. welding stations	5	idem
- Welding method	Dual/ Triple torch Phoenix system	idem
NDT		
- Nr. NDT stations	1	idem
FJC		
- Nr. FJC stations	2	3
• *Tensioner*		
- Nr. tensioner	3	idem
- Capacity	350 ton (each)	idem
• *A&R winch*		
Single-wire system		
- Capacity	400 ton	idem
Four-wire system		
- Capacity	1,000 ton	idem

Table 9.1: Comparison between current and new specifications

9.2. Longitudinal strength

The longitudinal strength of the vessel is under the maximum allowable limits. Although, with the new design the shear forces are closer to the limit. Therefore, the critical sections have to be reinforced.

9.3. Deck space, extra station and mooring system

As the stinger slot has been closed the deck space has been increased by 250 m^2 in the firing line deck and by 130 m^2 in the main deck.

The firing line has been extended to install an extra station. This extra station can be used as a second coating station or the whole firing line can be rearranged so that an extra welding station is installed. Allowing more flexibility to divide the workload between stations, which can lead to decreasing cycle times.

The aft mooring system has been redesign, using split drum winches. These winches allow to tighten the lines without a level winder.

9.4. Workability

As mentioned in chapter 8.4, the workability on the new design is less than for the current design, as the stinger tip has been moved further from the centre of gravity of the vessel. Although for harsh environments the difference is big, around 7%. For mild environments the difference is rather small.

9.5. DP capability

The DP capability of both designs is similar, as shown in chapter 8.5, for normal conditions. For harsh conditions specially under unfavourable angles (stern quartering seas) the DP capabilities decrease for the new design.

Therefore, changing or moving the thruster is not necessary as long the design operates in normal conditions.

10 Conclusion and recommendations

The objective of this research was to create insight into the possibility to retrofit the aft of *Solitaire* to improve its capabilities and performances. An operational analysis has been done in order to pinpoint the critical parts of the design and obtain insight about the current design. Furthermore, a requirements analysis was also done based on the different operational deficiencies. Which led to a functional definition of the whole design, highlighting the parts involved in the aft.

With the previous analyses and the functional definition, a distinction was made between the aft and the rest of the ship. This lead to an analysis of alternatives for each of the previously defined requirements. The outcome of this analysis created the need to make an integrated design, as a global optima was needed.

10.1. Systems Engineering for a retrofit

The Systems Engineering principles provided a solid base to manage the complexity of the design process. It gives a logical structure to follow and document the whole process, which is essential for a retrofit as the constraints increase the complexity of the design. As the structure was built at the beginning, it gives an important overview. Which is fundamental as you dive into more specific parts of the design. Therefore, the overall objective of the research is not lost.

One of the key aspects of SE is that in the process you have to decompose the problem in smaller/easier problems so that they can be solved. But also, after they are solved it gives you the structure to build the problem back up again. Thus, obtaining the solution to the complex problem.

Therefore, in my humble opinion, Systems engineering is a useful method to tackle complex problems, especially when the requirements are all interconnected. This method can be of great help in the design of complex vessels.

In the other hand, to obtain a good result extra care should be taken at the beginning of the process. If the main objective is not well defined, the rest of the process is compromised. This can also happen with the functional definition or the requirement analysis. For example, I did not realise that by having a wide base stinger, the hinge had to be moved further aft. This meant that the workability of the design decreased. This problem aroused from not having in the requirement analysis the workability.

Anyhow, taking everything in to account everything. I can conclude that using SE as a design method has been quite helpful for me throughout this project.

10.2. Conclusions

Based on this concept feasibility study, insight has been given on the possibility to retrofit the aft. It can be concluded that is it economically and technically feasible to do so. Although, in certain aspects of the design improvement has not been made or it is not clear.

The longitudinal strength of the vessel has been improved. Although at the cost of certain sections being under high shear forces. Even though these sections are highly loaded, they are within the limits approved by the classification society also, they are part of the new structure to be retrofitted. Therefore, the structure can be designed accordingly to better support those loads, if necessary.

A wide base stinger has been primarily designed, which can withstand more lateral loads. Although, extra calculations have to be made to quantify the improvement and to obtain the maximum working operational limit. The SHS has been simplified by using just winches and tackle wires to support the stinger. Although, the possibility for uplift and its consequence of lowering the workability has not been assessed.

The transit speed has been improved by at least 0.3 knots. Although extra analysis should be done to better estimate the total improvement, as it has been identified that a higher improvement could be achieved. The deck space has been increased by more than 122 m^2, and an extra station has been added at the end of the firing line. The new mooring systems allows to tension the mooring lines properly.

The workability of the new design has decreased for harsh environments around 7% and for less severe seas around 3%. This is due to the stinger tip being further away from the centre of gravity. Although for summer conditions the decrease is minimal. The DP capability of the design has not been affected by the new aft and therefore, the operability for DP governing situations is not reduced. The cost of all of the modifications taking into account a contingency of 25% is around 55 million euros. Although, the price might vary as depending on the shipyard and the country that it is in. This price is reasonable for the size of the retrofit.

Certain aspects of the design have been improved while others have worsened, Table 10.1. Even though there are more improvements, it is hard to estimate the overall improvement as not all the deficiencies are equally important. Thus, more studies have to be made.

Operational deficiency	Improvement
Global strength	+
Transit speed	+
Deck space	+
Stinger	+
Workability	-
DP capability	=

Table 10.1: Summary of improvements

10.3. Recommendations

Bellow different recommendations can be found regarding future research:

- **Operational analysis:** Due to the amount of activities that *Solitaire* performs, they had to be group together to have a better overview. This helped understand the problem better. But it also obstructs the definition of gains, as they are harder to identify. Thus, it is recommended to perform a more exhaustive analysis. Also, it would be of interest to perform a future outlook into the market of pipelaying. Which would give insights into the most critical parts of the design.

- **Requirement analysis:** The ultimate goal of the vessel is to operate as long as possible. Thus, all the different design characteristics that impact workability should be incorporated, such as, vessel motions, DP capability, etc.

- **Requirement prioritisation:** the prioritisation of the requirements has been done based on an operational analysis. It would be interesting to use a mathematical method to decrease the designers opinion. For example, the Analytical Network Process method (ANP) could be used to solve this problem. Although extreme care should be taken into quantifying the interdependent coefficients.

- **Stinger design:** in this project, the stinger has been maintained almost the same. As it is an essential part of the whole design, more effort in the design of the stinger should be taken.

- **Resistance calculation:** as the resistance component that influences the transit speed is due to the shedding of vortexes, CFD calculations should be made in order to properly assess the decrease in resistance.

- **Longitudinal strength:** Due to the limiting time of this research, an estimate of the weights has been done. Better estimates could be achieved by a detailed design. Also, the effects of the shear forces in the new design should be checked.

- **DP capability:** to better assess the changes in the DP capability, it is recommend to recalculate the wind coefficients.

10.4. Personal reflection

This thesis has allowed me to learn about pipelaying and the offshore world. It has been quite an interesting journey.

To be able to carry out a thesis at a company can be a great opportunity but it also can have some disadvantages. In one hand, you can get a lot of help from engineers around you, a lot of information and tools are available, and you are somewhat forced to put in the hours every week, which for those who sometimes lack discipline can be of great help. In my case, I have been able to benefit from all.

In the other hand, managing stakeholders (University and Allseas) can be a little bit of a challenge. It can be hard to change the direction of the thesis. In my case, I have been lucky in this aspect as the University and Allseas were almost aligned.

I have learned a lot about complex ship design. Especially, I have been able to exercise my way of thinking about complex problems. Which I believe to be one of the most important outcomes of this thesis, even though it is not tangible.

I think I have had good communications with my supervisors at the company and at the university, which I believe is one of the key aspects for a successful thesis.

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A
Definitions of vessel functions and systems

A.1. Definition of functions

- **Power generation:** to generate power and supply with fuel generators and other machines.
    - **Electrical generation:** To generate enough electric power to operate the vessel.
    - **Energy supply:** to supply with fuel the engines and also the distribution of electricity onboard.
- **Motions control:** to maintain vessel motions within the allowable limits to ensure the operability and survivability. And to provide mobility to the vessel.
    - **Stability:** To maintain stability within allowable limits
    - **Station keeping (DP):** To maintain position during pipelaying operations and special installations.
    - **Seakeeping:** To maintain ship motions within allowable limits.
    - **Propulsion:** To propel the vessel during transit.
- **Systems support:** general support of systems, but also to support them physically.
    - **Buoyancy:** To provide enough buoyancy while the multiple operations.
    - **Spatial integration:** To provide enough space to integrate all equipment and processes.
    - **Ballast:** To provide enough ballast to maintain the correct
    - **Structural integrity:** To provide with a structure able to cope with the loads met during the life of the vessel.
- **Hotel facilities:** to accommodate crew and personnel on-board and their needs.
    - **Accommodation:** to accommodate all the crew and personnel in the best possible way, as to have necessary supplies.
    - **HVAC:** to maintain a healthy environment across the vessel.
    - **Waste:** to manage all waste products within the ship.
- **Navigation & Communication:** To be able to navigate and communicate with other vessels, ROVs, or platforms.
    - **Communication:** to communicate within the vessel, third parties, ROVs, etc.

  - **Navigation:** to navigate and position the pipeline in the correct way..

- **Pipe handling:** to handle sections of pipe before production of the pipeline starts.
  - **Mobilising:** To be able to mobilise for a project anywhere.
  - **Storing:** to store all consumables onboard.
  - **(Un-)loading:** To be able to load and unload supplies in port or at sea.

- **Pipe welding:** to weld sections of pipe to the pipeline. Also, to test and coat them.
  - **Pipe supply:** to supply the different workstations with pipe.
  - **Welding:** to be able to weld pipe joints and other structures on board.
  - **NDT:** to test the quality of the welds before installation.
  - **Coating:** to coat the newly made welds.
  - **DJF:** To be able to produce double joints.

- **Pipeline installation:** to install the pipeline on the seafloor and its associated structures as well as to check that the installation has been done in the predicted way.
  - **Tensioning:** To apply enough tension to the pipe to prevent buckling.
  - **Positioning:** To guide the pipe to the correct location.
  - **Abandoning & Recovery:** To be able to abandon the pipeline and later on recover it.
  - **Inspection:** To inspect that the installation of the pipe is correct.
  - **Subsea installation:** To install subsea structures.

A.2. Definition of systems

- **Hull and Tanks**
  - **Hull general:** the structure of the vessel and its components
  - **Tanks:** tanks, sounding pipes, valves, service tanks, settling tanks, etc.
  - **Holds:** holds, hatches to them, etc
  - **Deck houses and Superstructures:** houses in deck, helideck, etc.

- **Lifting appliances**
  - **Material handling:** equipment to move materials around. Like forklift, conveyors, etc
  - **Deck cranes for pipes and cargo:** overhead cranes, pipe loading cranes, etc.
  - **SPC:** Special purpose crane
  - **A-frame:** A-frame, rigging and its equipment.

- **Navigation and Nautical equipment**
  - **Position control:** GPS, radar, etc
  - **Navigation:** ECDIS, AIS, etc
  - **Communication:** VHF, Satellite phone, etc.
  - **Anchoring and Mooring:** Anchor windlasses, mooring winches, anchor winches, sheaves, fair leads, et cetera.

- **Equipment for crew**
  - **Life saving, protection and medical:** life boats, rescue boat, FiFi, medical equipment, PA/GA system, et cetera.
  - **HVAC:** Air conditioning, heating and ventilation system, pumps, et cetera.
  - **Sanitary systems and waste discharge:** Hot water, black waster systems, drain system accommodation, sewage treatment systems, et cetera.
  - **Accommodation auxiliary systems:** furniture, entertainment systems, laundry equipment, galley equipment, etc.
- **Machinery main components**
  - **Propellers and Transmissions:** propellers, azimuth thruster transmissions, etc.
  - **Main Electric Power Production:** main diesel generators, alternators, etc.
  - **Emergency Electric power production:** emergency diesel generators, alternator, etc.
- **Systems for machinery main components**
  - **Fuel oil:** Fuel oil transfer, centrifuge, drain systems, etc.
  - **Lubricating oil:**
  - **Cooling water:** Sea water cooling systems, fresh water systems, etc.
  - **Compressed air:** Compressed air bottles, compressors, start air systems, working air system, clamp air system, etc.
  - **Exhausts gas systems:** pipes, exhaust gas boiler, silencer, spark arrestor, expansions joints, etc.
  - **Fresh water generation:** Fresh water generators, evaporators, pump, sea chest
  - **Automation for machinery:** data logging system, computers, actuators, et cetera.
- **Ship common systems**
  - **Ballast, bilge, Sludge:**
  - **Central heat transfer:** heat exchangers, evaporators,
  - **Electric power supply:** main switchboards, circuit breakers, etc.
  - **Electric distribution system:** power cables, switches, transformers, etc.
  - **Electric consumers:** lighting, general appliances, et cetera.
- **Production equipment**
  - **Welding systems:** automatic welding system, shielding gas systems, etc.
  - **Auxiliary systems and equipment for pipelay:** Firing line systems, line up systems, tensioners, stinger, A&R winch, piggyback equipment, et cetera
  - **Loose pipeline production equipment:** Internal clamp, bead stall line up, grit blasting, bevel machines
  - **UW production equipment:** ROV, tether management system, launch and recovery system, etc
  - **Field joint coating:** Preheating, coating systems, etc.

B

Stinger and SHF configuration drawings

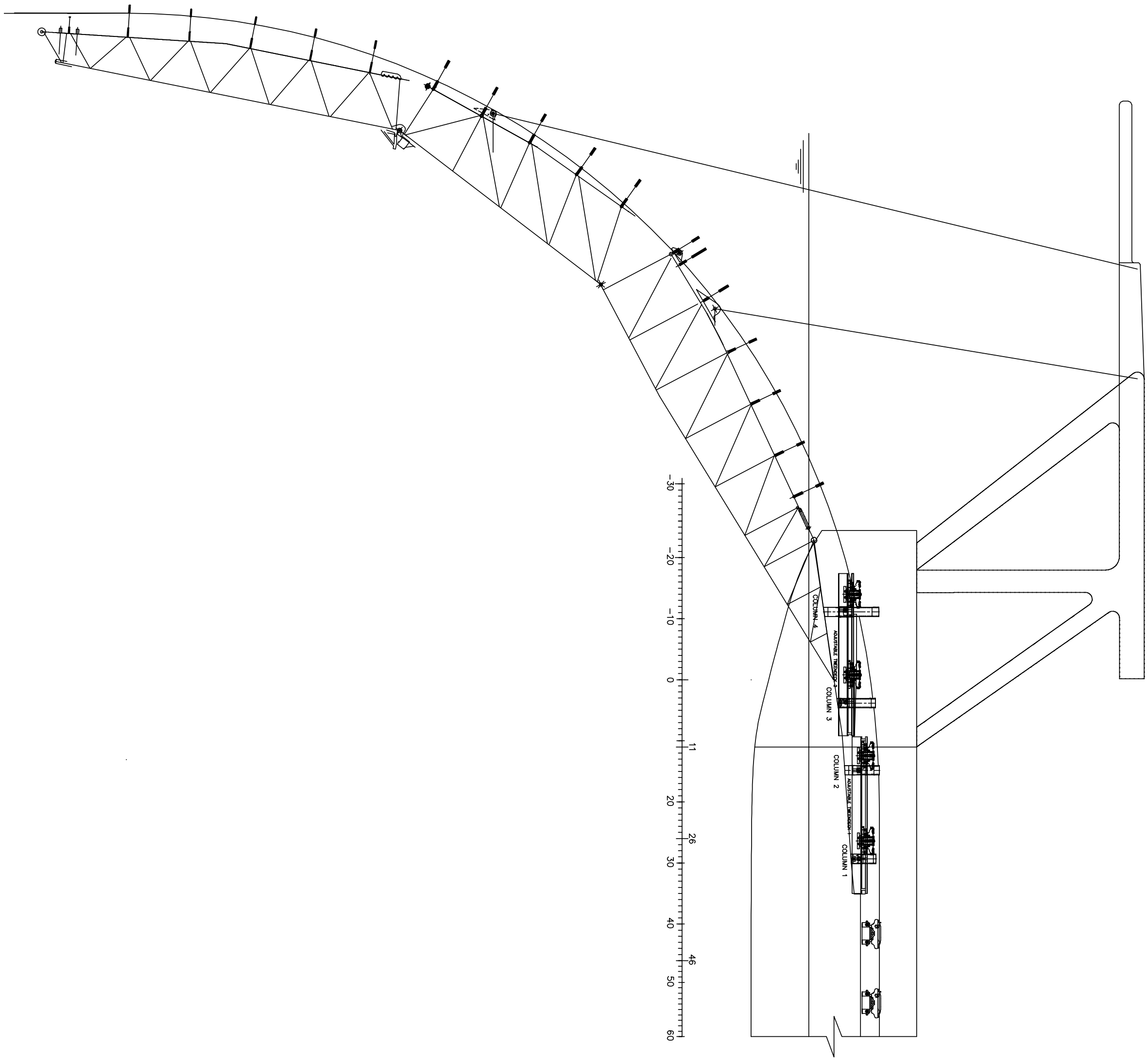

Figure B.1: R110m stinger configuration

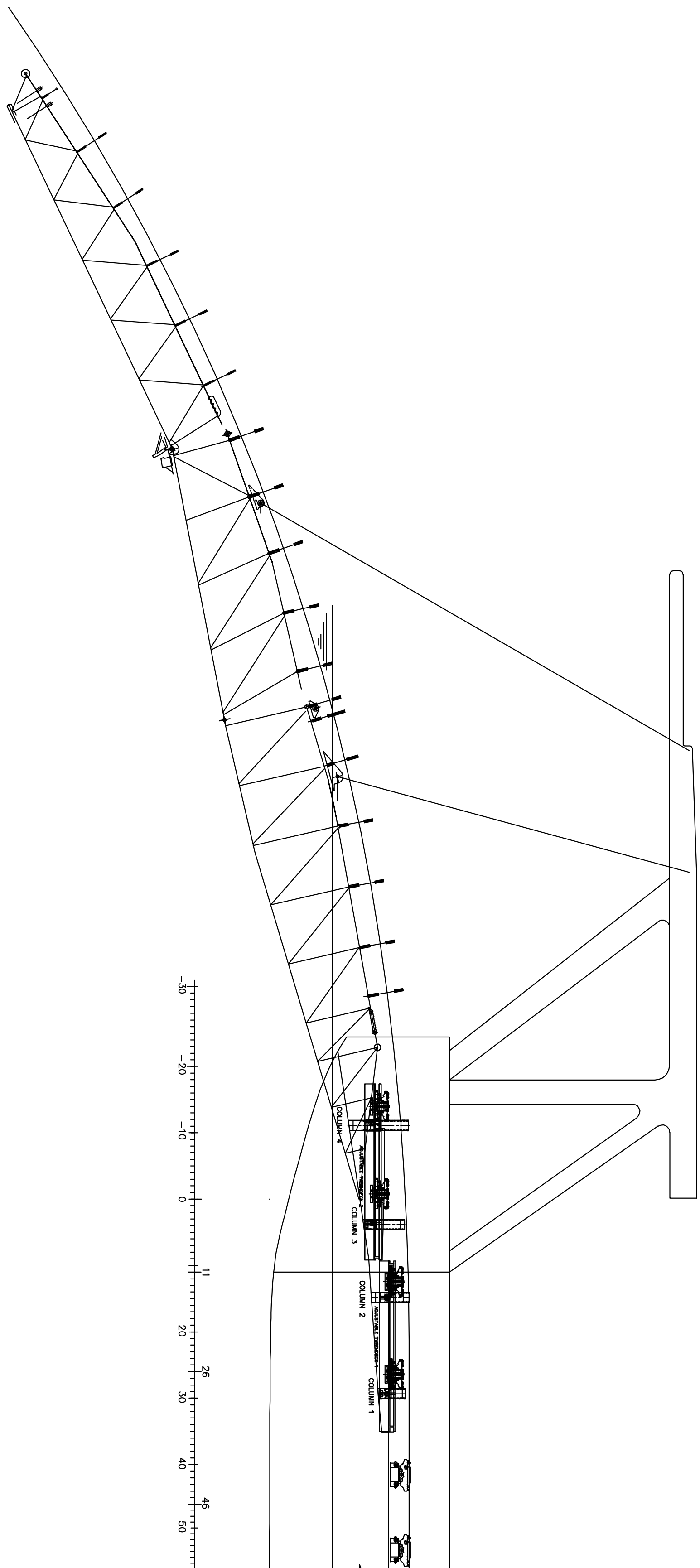

Figure B.2: R300m stinger configuration

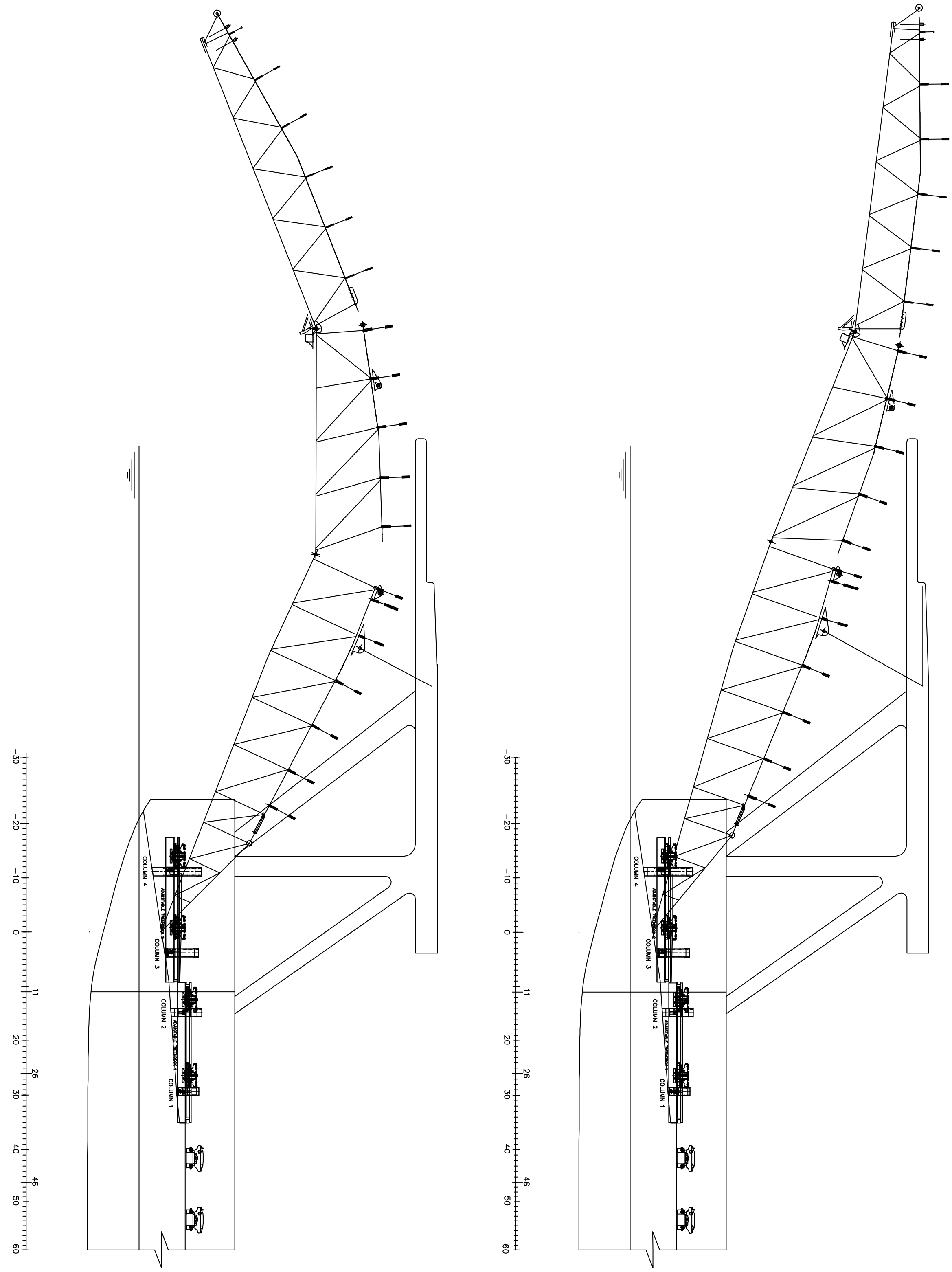

Figure B.3: Survival configuration (top) and